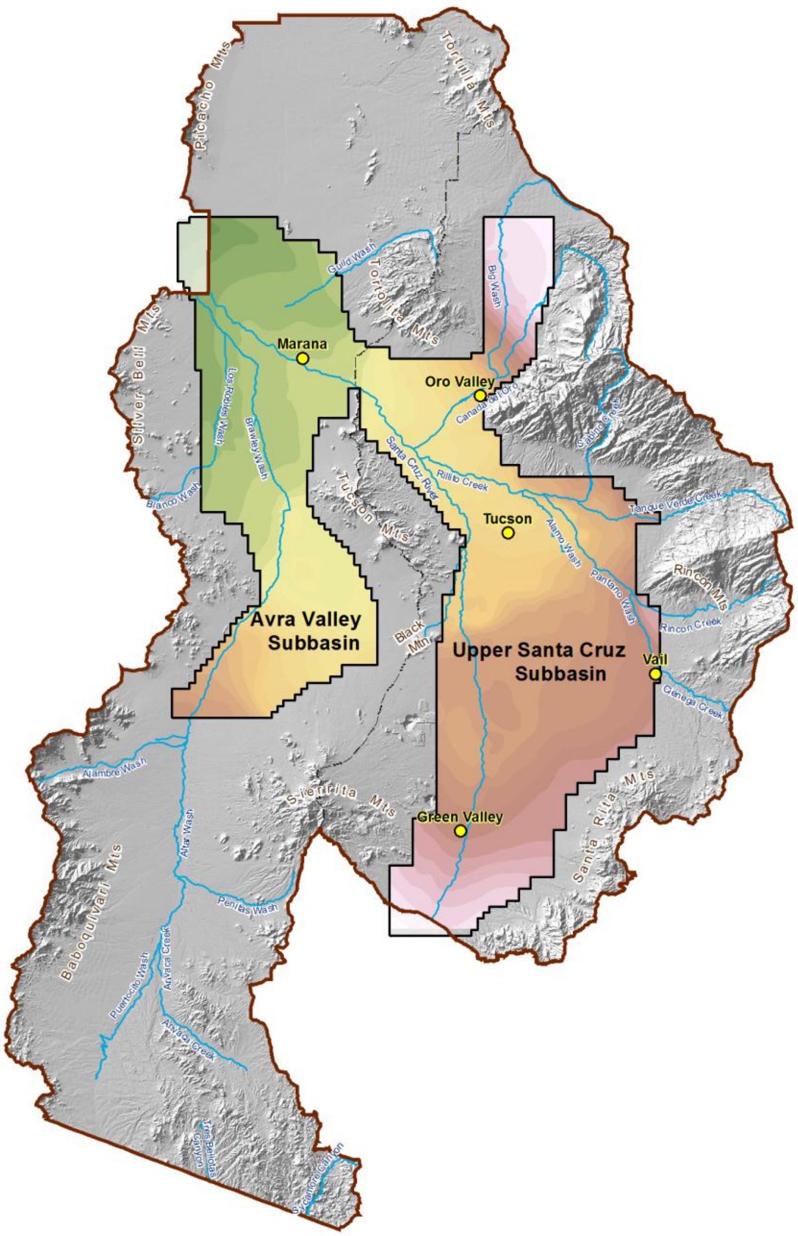
ARIZONA DEPARTMENT OF WATER RESOURCES

REGIONAL GROUNDWATER FLOW MODEL
OF THE TUCSON ACTIVE MANAGEMENT AREA, ARIZONA

MODEL UPDATE AND CALIBRATION



MODELING REPORT NO. 24

BY

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List of Acronyms

AAWS	Assured and Adequate Water Supply
ADWR	Arizona Department of Water Resources
AMA	Active Management Area
AMSL	Above Mean Sea Level
AZGS	Arizona Geological Survey
BAS	Basic Package
BLS	Below Land Surface
CAP	Central Arizona Project
CHB	Constant Head Boundary
CHD	Time-Variant Specified-Head Package
DIS	Discretization Package
DTW	Depth to Water
ET	Evapotranspiration
GFR	Grandfathered Right
GSF	Groundwater Savings Facility
GWSI	Groundwater Site Inventory
HOB	Hydraulic-Head Observation Package
HYDMOD	MODFLOW Hydrograph program
IGFR	Irrigation Grandfathered Rights
K_x	Horizontal Hydraulic Conductivity
K_z	Vertical Hydraulic Conductivity
MAE	Mean Absolute Error
ME	Mean Error
RCH	Recharge Package
RMSE	Root Mean Squared Error
ROGR	Registry of Grandfathered Rights
TAMA	Tucson Active Management Area
UPW	Upstream Weighting Package
USBR	United States Bureau of Reclamation
USF	Underground Storage Facilities
USGS	United States Geological Survey
WEL	Well Package
WWTP	Waste Water Treatment Plant

Abstract

Managing regional aquifer systems within groundwater basins in the arid southwestern U.S. requires the appropriate tools to understand and predict how recharge and withdrawals impact the systems, both spatially and temporally. Groundwater modeling has become a key tool used by water managers to address complex regional hydrologic interactions and their potential impacts on aquifer systems. The Arizona Department of Water Resources (ADWR) Tucson Groundwater flow model was updated in an on-going effort to provide the best tools possible for the long-term management of the water resources in the Tucson Active Management Area (TAMA).

The previous ADWR Tucson groundwater model simulated the period from 1940 to 1999. The model has been updated to simulate conditions from 1940 to 2010 and includes several major updates. The updates include: a defined elevation for the model bottom, the addition of annualized stream infiltration distributed along the major drainages to improve simulated stream recharge, improved historical pumping volumes and distribution, and improved historical agricultural recharge volumes. The model was re-calibrated using the latest well-specific water level data.

The transient calibration simulated regional water level fluctuations during the 71 year period. The model calibration was evaluated by comparing well specific water level elevations from 1940 to 2010 to simulated heads, time-series simulated heads to observed heads at wells with long-term records, and by comparing hand-drawn measured water level contours with model simulated head contours. Approximately 66 percent of the simulated heads had a weighted residual error (simulated head – observed water level) of ± 10 feet or less, and about 97 percent of the weighted residuals were ± 50 feet. The model-wide mean residual error (ME) was 3.7 feet, the ME for the Avra Valley sub-basin was 1.6 feet, and the ME for the Upper Santa Cruz sub-basin was 4.2. feet. The mean of the absolute value of all weighted residuals (MAE) was 11.3 feet. The MAE for the Avra Valley sub-basin was 10.1 feet and the MAE for the Upper Santa Cruz sub-basin was 11.6. feet. The cumulative simulated water budget maintained a zero percent discrepancy between simulated inflows and outflows.

1.0 Introduction

Since the inception of Arizona's Groundwater Management Act of 1980, the ADWR's focus within the Tucson AMA (TAMA) has been to manage the regional groundwater aquifer to reach the goal of safe yield by 2025. Groundwater flow models have proven to be effective tools in understanding how various stresses can interact and affect an aquifer, and can aid in predicting future impacts from projected development. To assist the TAMA in the management of its water resources, ADWR has developed a series of groundwater flow models that covered the key portions of the AMA (Figure 1). Travers and Mock (1984) developed the first generation ADWR model that simulated the TAMA regional aquifer from 1960 to 1984. The Travers and Mock model simulated groundwater flow in the regional aquifer as two-dimensional using a single layer. Mason and Bota (2006) redefined the regional aquifer into three layers, incorporated new pumpage data, and expanded the simulation period to include 1940 to 1999. This report documents the updating and refining of the Mason and Bota (2006) model by expanding the transient calibration period to 2010, adding new groundwater demand and supply data, and incorporating improved methods for simulating some of the aquifer stresses.

1.1 Objective and Scope

The purpose of the Tucson model update was to upgrade the previous numerical groundwater flow model and provide the ADWR with a more current tool to assist in the management of the TAMA water resources. The model data also serves as a repository of hydrologic and geologic data in a database format that can be spatially displayed. Upgrades to the model include:

- ✓ Adding bottom elevations to model Layer 3 (the bottom layer of the model)
- ✓ Revised quantity and distribution of historical pumping
- ✓ Revised quantity and distribution of historical recharge
- ✓ Updated pumping and recharge values from 1984 to 2010
- ✓ Applying annualized stream infiltration to major drainages
- ✓ Incorporated the latest MODFLOW code
- ✓ Model recalibration

1.2 Project Setting

The TAMA is located in the basin and range physiographic province of southeastern Arizona and covers approximately 3,900 square miles (mi^2). The TAMA consists of two broad alluvial basins that are surrounded by mountains (Figure 1). The two alluvial basins are used as natural divisions to separate the TAMA into the Upper Santa Cruz (USC) and Avra Valley sub-basins. The two alluvial basins are surrounded by the Santa Catalina, Rincon, Santa Rita,

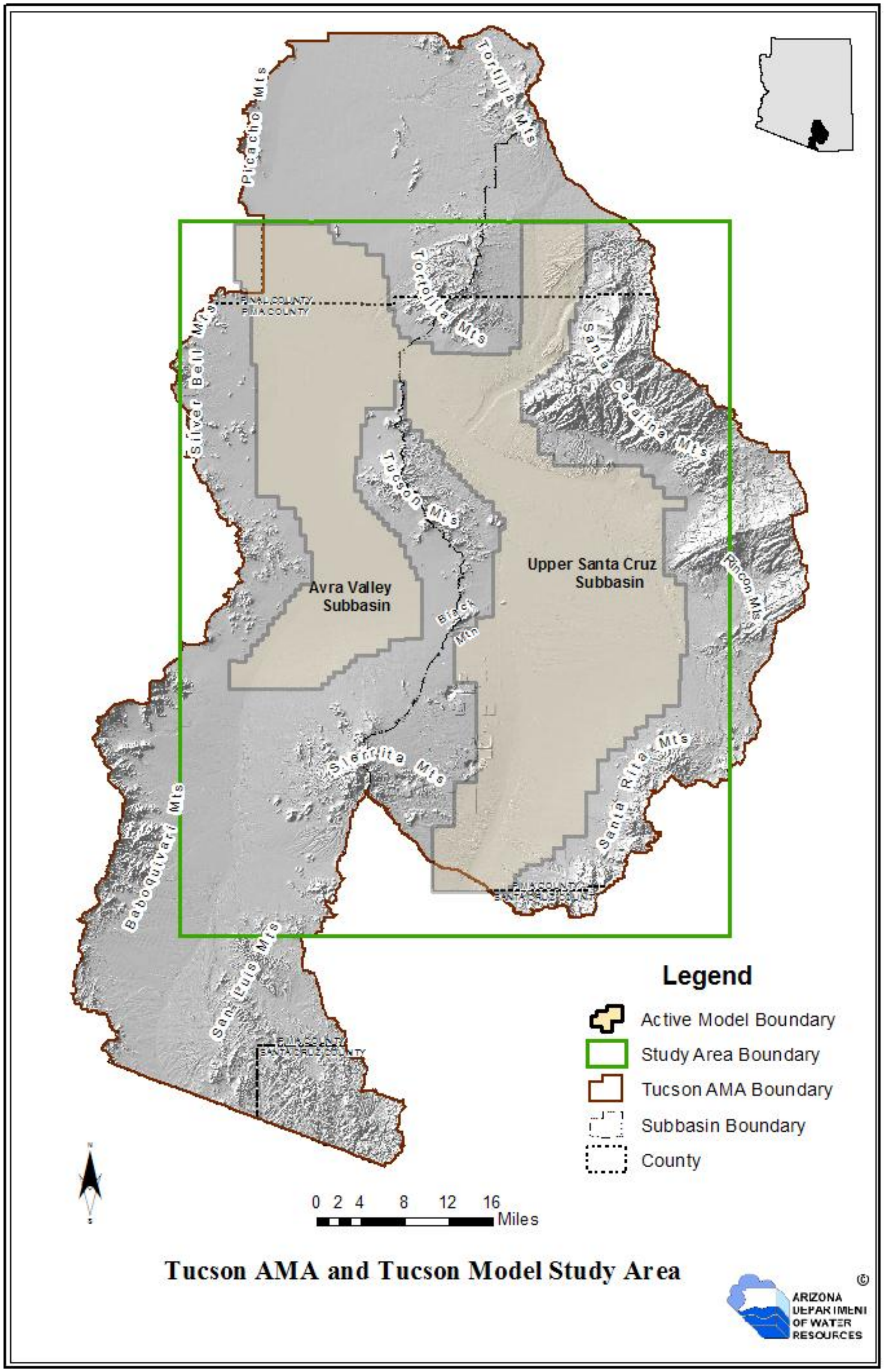


Figure 1. Tucson AMA model study area.

Sierrita, San Luis, Baboquivari, Black, Tucson, Silver Bell, Picacho, Tortilla and Tortolita Mountains (Figure 1).

The Tucson model domain contains approximately 3,200 mi^2 and includes portions of the USC and Avra Valley sub-basins (Figure 1). The model domain encompasses the major urban centers within the TAMA as well as a portion of the San Xavier Reservation (Figure 2). The active model domain contains the majority of the population and hydrologic stresses to the regional aquifer that occur within the TAMA.

1.3 Previous Investigations

The geology, hydrology, and the water resources of the TAMA have been extensively studied with published reports starting in the early 1900s. For an extensive list of previous geologic and hydrologic investigations in the Tucson area see Mason and Bota (2006). The TAMA groundwater flow system was first simulated using groundwater modeling techniques by the U. S. Geological Survey (USGS) in the early 1970s and then again in the early 1990s. Moosburner (1972) and Hanson and others (1990) simulated groundwater flow in the Avra Valley sub-basin, and Anderson (1972) and Hanson and Benedict (1994) simulated groundwater flow in the USC sub-basin. The ADWR developed and released its' first generation groundwater flow model of the TAMA in 1984 that combined the two sub-basins into a single model (Travers and Mock, 1984). Since its original development in 1984, the ADWR's TAMA regional groundwater flow model has undergone several major improvements that have increased its usefulness as a management tool. The model upgrades combined with on-going data collection efforts by the ADWR and other entities within the TAMA have increased the understanding of the regional aquifer and the impacts development stresses have had on the TAMAs water resources.

1.4 Acknowledgements

A project as complicated as a groundwater flow model requires input and assistance from many sources, and although only two names are credited as authors this report could not have been completed without the assistance of many other people who gave of their time and expertise. The authors would like to acknowledge those individuals and organizations that have provided information, guidance, and comments during the development of this update to the Tucson AMA groundwater flow model.

Special thanks go to the following ADWR personnel: J. Scott Miller the AMA Director for his time and many helpful suggestions, Lisa Williams and Pam Muse from AMA Planning for their help with data retrieval and water budget issues, Tracy Carpenter for answering our many questions regarding recharge issues, E. Frank Corkhill and Keith Nelson for their suggestions and guidance during model development, and Diane Yunker for her assistance drafting the many figures in the report.

The Tucson Groundwater Users Advisory Committee (GUAC) was instrumental to the project by providing funds to support model development. Institutions that have provided data and other expertise helpful to model development include the Cortaro-Marana Irrigation District (CMID), Farmers Investment Co-Op (FICO), City of Tucson Water Division, Flowing Wells Irrigation District (FWID), and Metropolitan Water Improvement District (MWID). Numerous individual have provided information, suggestions, comments, and encouragement during the development for the model. Special thanks go to Wally Wilson of Tucson Water, Peter Mock, Bradley Prudhom of the U.S. Bureau of Reclamation, and Gary Burgess of MWID for their review comments on the draft model report; Marla Odom and Hail Barter of E.L. Montgomery and Associates for sharing data and their many helpful suggestions; and Matt Bailey of Farmers Water Company for his interest and encouragement.

And a very special thanks to the ADWR Field Services Unit who collected the water level data that made it possible to generate the maps and statistical analysis of the final model results. Without the hard work of the Basic Data personnel there would be no water levels to help calibrate this or any other model.

2.0 Regional Groundwater Flow System

Mason and Bota (2006) used previous geological, hydrological, and modeling studies to develop a conceptual model of groundwater flow in the regional aquifer system in the TAMA. That conceptual model was then used to construct the basic framework of the ADWR Tucson regional groundwater flow model (Mason and Bota, 2006). This study continues the evolution of the TAMA groundwater flow model by adding more time to the transient period, further refining model recharge and pumpage distributions, and by modifying the model's layer geometry.

The USC sub-basin and the Avra Valley sub-basin of the TAMA are typical of alluvial basins in the Basin and Range physiographic province, characterized by block-faulted mountains separated by basins filled with alluvial sediments. The basin-fill sediments are composed of consolidated to unconsolidated sedimentary material of Tertiary to Quaternary age. The alluvial basin-fill sediments are saturated at depth and form the regional aquifer system that provides groundwater for municipal, agricultural, and industrial uses within the TAMA (Figure 3). The mountains surrounding the TAMA are composed of crystalline and consolidated sedimentary rocks that generally yield only small amounts of water and are not considered part of the regional groundwater flow system. Groundwater in the regional aquifer is generally unconfined to semi-confined to depths of about 1,000 feet below land surface (bls) (Davidson, 1973, Hanson 1988, 1989). Localized confining conditions and perched zones have been observed in areas where fine-grained materials in the basin-fill sediments either inhibit the downward percolation of water or the upward movement of water.

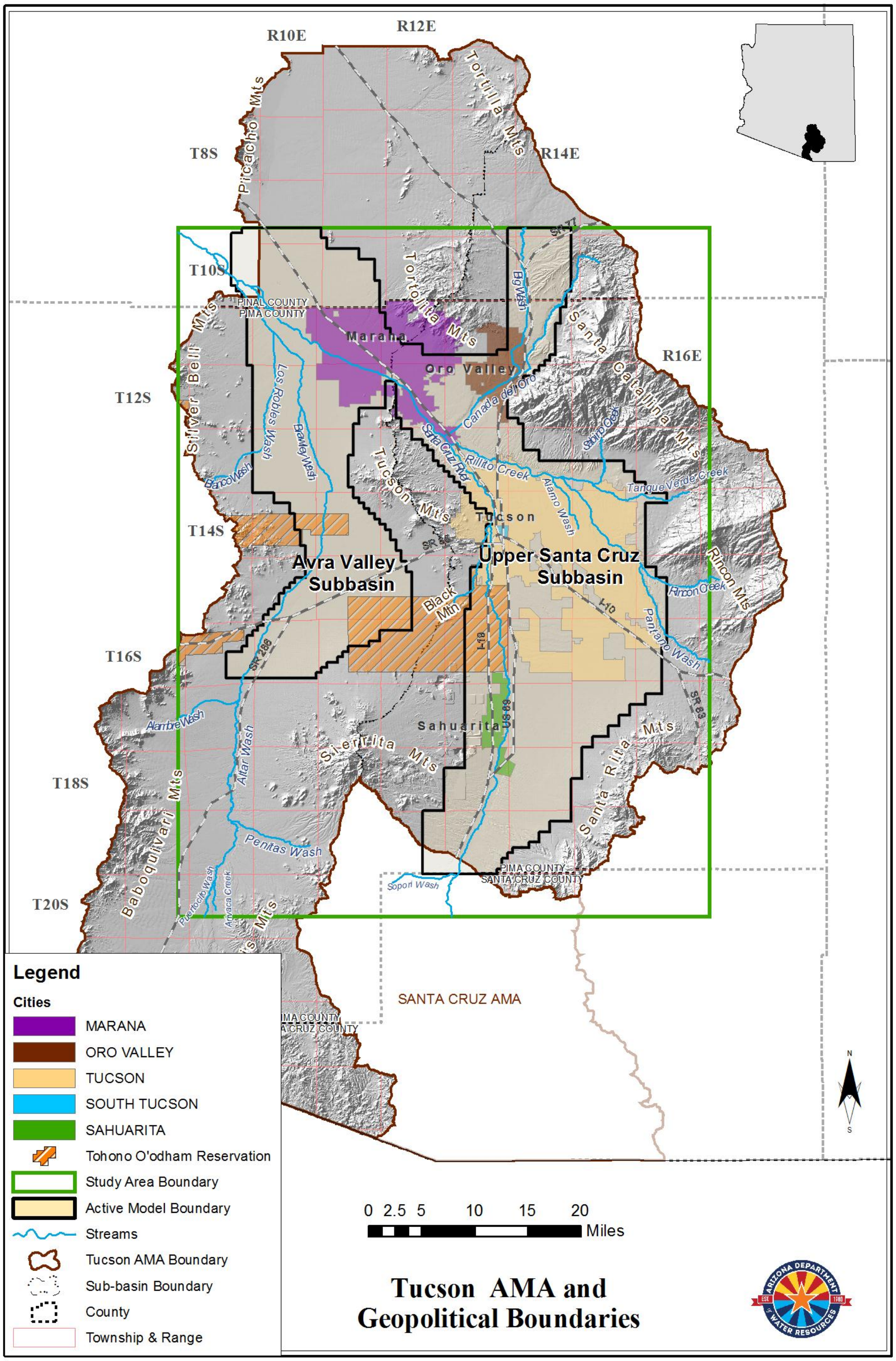


Figure 2. Geopolitical boundaries within the Tucson AMA.

Groundwater flow within the regional aquifer is generally to the north and northwest, except in the Cañada del Oro drainage, where groundwater flows south before entering the main part of the USC sub-basin (Figure 3). Groundwater in the USC sub-basin flows to the north-northwest and exits the sub-basin into the northern part of the Avra Valley sub-basin through the Rillito narrows between the Tucson and Tortolita Mountains (Figure 3). Groundwater in the Avra Valley sub-basin also flows to the north-northwest from Altar Valley to northern Avra Valley where it turns to the northwest and exits the TAMA into the Pinal AMA through the gap between the Silver Bell and Picacho Mountains. Stresses imposed on the flow system by groundwater development since the 1940s have impacted the regional flow system creating localized complexities in the flow regime. In some areas heavy, localized pumpage has created cones of depression and long-term groundwater declines. In other areas CAP surface water recharged at artificial recharge projects has created groundwater mounds.

2.1 Hydrogeologic Framework

The thickness of the basin-fill deposits in the TAMA range from a thin veneer along the mountain-fronts to as much as 9,000 feet thick in the Avra Valley sub-basin and at least 12,500 ft. thick in the USC sub-basin (Figure 4). Previous investigations divided the basin-fill sediments into an upper basin-fill unit that was assigned a thickness of as much as 1,000 feet, a lower basin-fill unit that was as much as 8,000 feet thick, the Pantano Formation, and other older undifferentiated Tertiary aged sediments. Davidson (1973) identified three sedimentary units as comprising the regional aquifer in the Tucson Basin, which is equivalent to the ADWR's USC sub-basin. Upper basin-fill sediments were assigned to the Fort Lowell Formation, lower basin-fill sediments were named the Tinaja beds, and the Pantano Formation was identified as the basal sedimentary unit. Anderson (1987a, 1987b, 1988) expanded Davidson's layering into the Avra Valley sub-basin, and divided the Tinaja into an upper, middle, and a lower unit. The upper Tinaja beds were assigned to the upper basin-fill and the middle and lower Tinaja beds were designated as the lower basin-fill sediments.

2.1.1 Revised Basin Statigraphy

Recent work by Houser and others (2005) has led to a revised interpretation of the depositional history and stratigraphy for the Tucson Basin. Detailed analysis of well cuttings and geophysical logs from the Exxon State (32)-1 well (Figure 4) indicate that the upper basin fill unit may be much thicker than was assumed by either Davidson (1973) or Anderson (1987a, 1987b, 1988). The Exxon State (32)-1 well was drilled in 1972 in one of the deepest sections of the Tucson basin to a total depth of 12,556 feet, penetrating 12,500 feet of sedimentary and

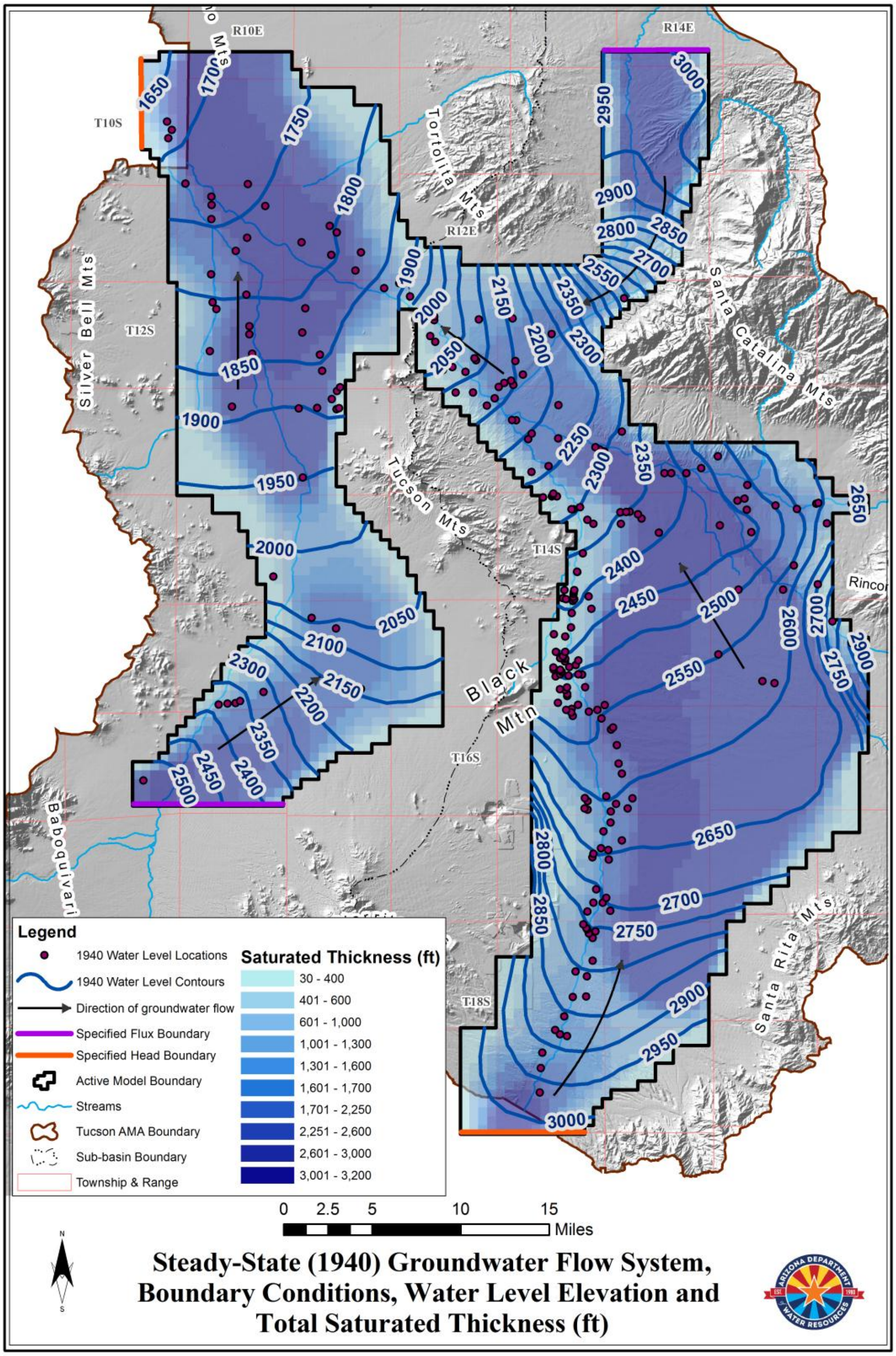


Figure 3. Pre-development groundwater flow system, boundary conditions, and total saturated thickness map of the regional aquifer, Tucson model area.

volcanic rocks before bottoming out in the basin's granitic basement rocks (Houser and others, 2005). As a result, the well provides a nearly complete record of basin-fill sediments for the Tucson basin.

Houser developed the following stratigraphy for the Exxon State (32)-1 well based on well cuttings and geophysical logs: upper basin-fill sediments from 0 to 2,980 feet, lower basin-fill sediments from 2,980 to 6,170 feet, Pantano Formation from 6,170 to 8,255 feet, undifferentiated early Tertiary volcanic and sedimentary rocks from 8,255 to 10,025 feet, the Bisbee Group, which is a group of related limestone, shale, sandstone, and conglomerate formations from 10,025 to 12,000 feet, and granitoid plutonic rocks from 12,001 to 12,556 feet (Houser and others, 2005). The upper and lower basin-fill sediments are divided into four distinct and recognizable units. They are in descending order: Units A and B of the upper basin-fill and Units C and D in the lower basin-fill. For a more detailed discussion of the revised stratigraphy and tectonic history of the Tucson basin based on the Exxon State (32)-1 well the reader is referred to Houser and others, 2005.

Upper Basin-Fill Sediments

The upper basin-fill sediments identified in the Exxon State (32)-1 are flat lying, unfaulted alluvial fan, alluvial plain, and fine grained playa deposits that are 2,980 feet thick (Houser and others, 2005). Houser (2005) divided the upper basin-fill is divided into two units based depositional environment. Unit A, the upper most upper basin-fill unit, is 1,850 feet thick and consists of interbedded siltstones, sandstones, and sandy conglomerates. The depositional environment for Unit A is interpreted as a medial alluvial fan and an alluvial plain (Houser and others, 2005). Unit B is about 1,130 feet thick and is composed of sandy and limey muds and muddy sandstones that were deposited in a distal alluvial fan and playa-marine environment (Houser and others, 2005).

Pantano Formation

The contact between the lower basin-fill and the Pantano Formation in the Exxon State (32)-1 well is sharply defined and may be an erosional unconformity representing a considerable loss of sediments. The Pantano Formation is about 2,300 feet thick and consists of well consolidated fine to coarse-grained alluvial fan and playa deposits, volcanic flows, and rock-avalanche beds. The upper 1,500 feet of the Pantano Formation contains alluvial fan and playa deposits that consist of conglomerates, muddy sandstones, and evaporite sequences. There is avolcanic flow that occurs near the middle of the formation. The rock-fall deposits mark the bottom of the formation and are about 615 feet thick. The Pantano Formation is faulted and the lower rock-fall section may be dipping at a considerable angle (Houser and others, 2005).

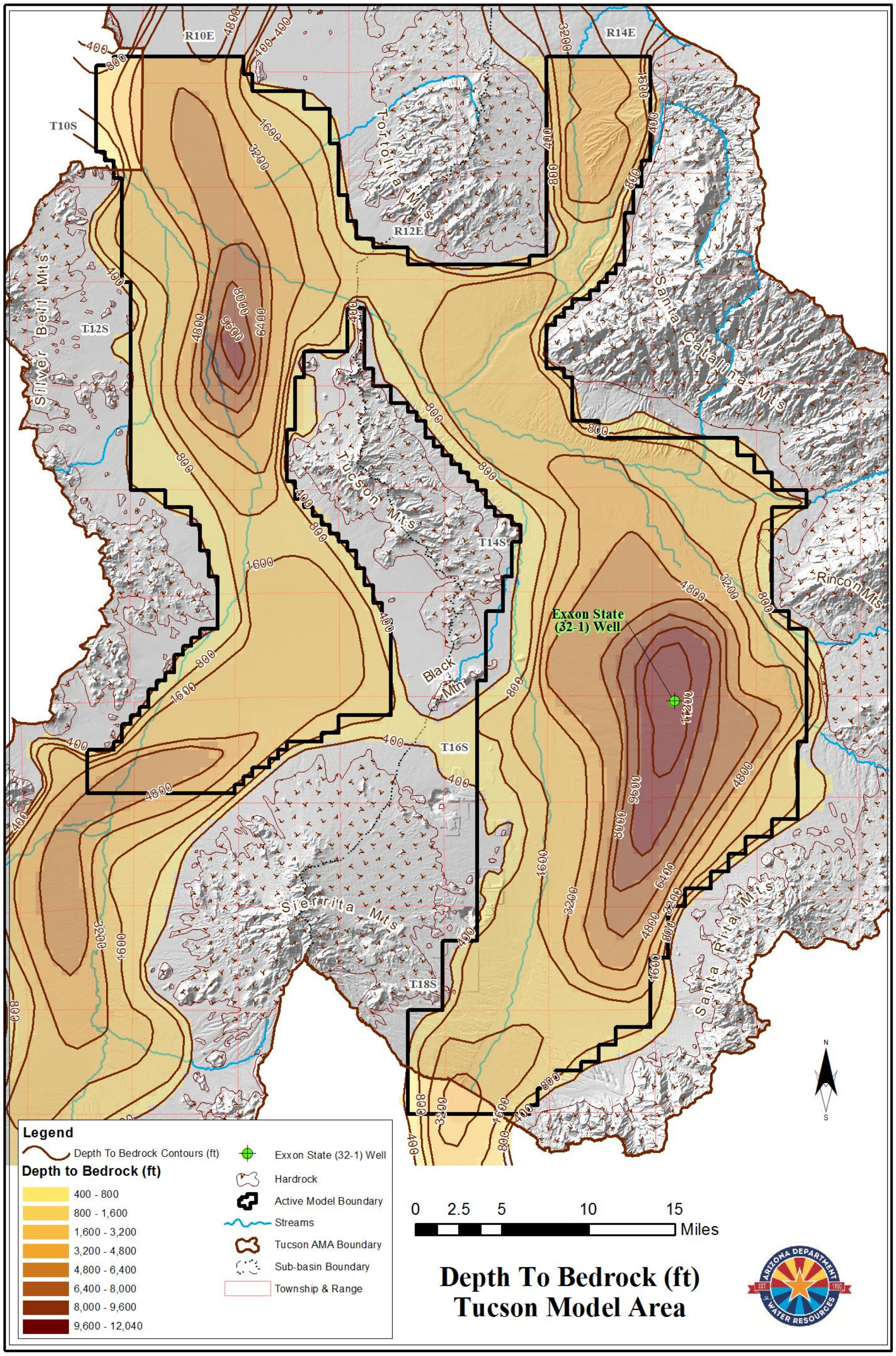


Figure 4. Depth to bedrock map, Tucson model area.

Undifferentiated Volcanic and Sedimentary Rocks

In the Exxon State (32)-1 well Houser (2005) identified a 1,770 feet thick section of alternating volcanic and sedimentary rocks between the Pantano Formation and the Bisbee Group. These rocks were divided into six separate units and are collectively referred to as the middle Tertiary volcanic and sedimentary rock unit. The individual units are in descending order: 1) an igneous intrusive dike or sill, 2) a volcanic lava flow that may be highly fractured, 3) a conglomerate composed of volcanic and sedimentary rock chips, 4) a thick volcanic tuff, 5) a second conglomerate composed of mostly of limestone clasts, and 6) a basal volcanic flow identified as a pyroxene trachyte (Houser and others, 2005).

Bisbee Group

The Bisbee Group consists of Lower Cretaceous to Upper Jurassic interbedded shales, sandstone, conglomerates, and limestones. The type section has been described in the Mule Mountains, and the group has also been recognized in the Empire and Whetstone Mountains in southeastern Arizona (Houser and others, 2005). Sediments that represent the Bisbee Group are difficult to identify in the Exxon State (32)-1 well due to contamination from overlying sediments (Houser and others, 2005). However, Houser (2005) identified a 1,975 foot sediment sequence that may represent the Bisbee Group sediments. The formations that make up the Bisbee Group in the Exxon State (32)-1 well are in descending order: 1) the Turney Ranch Formation, a sequence of shales, siltstones, and sandstones, 2) the Shellenberge Canyon Formation also composed of shales, siltstones, and sandstones, 3) The Apache Canyon Formation containing limestones, shale, and sandstones, 4) the Willow Canyon Formation a sequence of shales and sandstones, and 5) the basal Glance Conglomerate that contains shales, sandstones, and conglomerate beds (Houser and others, 2005).

Granitic Basement

The Bisbee Group sediments rest on the granitic basement of the Tucson basin. The Exxon State (32)-1 well penetrated 555 feet of granitic crystalline bedrock that is referred to as granitoid due to the difficulty in describing its composition Houser and others (2005).

2.2 Regional Aquifer System

As redefined by Houser and others (2005) the TAMA regional aquifer system consists of the upper and lower basin fill sediments, the Pantano Formation, the undifferentiated Tertiary sedimentary and volcanic rocks, and the sedimentary rocks of the Bisbee Group as described above. In deeper sections of the Avra Valley and USC sub-basins the upper basin-fill sediments may be as much as 3,000 feet thick and are the major aquifer providing groundwater to wells (Figure 3). Along the basin margins, where the upper basin-fill sediments thin, the lower basin-fill sediments, the Pantano Formation, or the Tertiary sedimentary rock unit are saturated and provide water to wells. Dickinson (1994) placed the age of the basin-fill sediments in Oro

Valley, a sediment trough between the Tortolita and Santa Catalina Mountains drained by the Canada del Oro and Big Wash, as correlative to the Tinaja beds of Davidson (1973) and Anderson (1987). This would make them equivalent to Unit B of the upper basin-fill and the lower basin-fill sediments (Units C and D) of Houser and others (2005).

The discussion in this report concerning the TAMA regional aquifer system is a general summary. For a more detailed description of the regional aquifers hydrologic parameters and related studies detailing the TAMA regional aquifer see Mason and Bota (2006) and Houser and others (2005).

2.3 Groundwater Budget

Water recharges the TAMA regional aquifer system as natural recharge from local precipitation and as groundwater underflow moving into the TAMA. Natural recharge is produced by precipitation and snow melt infiltrating along the mountain-fronts and by streambed infiltration from flow events in the Santa Cruz River and its' major tributaries. Underflow enters the TAMA regional aquifer from the south across the TAMA - Santa Cruz AMA (SCAMA) boundary (Figure 3). Small amounts of underflow enter the model study area from Falcon Valley, located in the north where Big Wash enters the study area, and through bedrock gaps where Pantano Wash and Tanque Verde Creek enter the TAMA. In the southern part of the Avra Valley sub-basin underflow enters the study area from Altar Valley (Figure 3). Groundwater discharges from the regional aquifer include groundwater withdrawals, underflow out of TAMA into the Pinal AMA (PAMA), and evapotranspiration (ET) (Figure 3).

During the development period some components of recharge in the TAMA regional aquifer have changed and new recharge components have been created. Groundwater withdrawals have changed groundwater flow directions within the regional aquifer (Figure 5), and changed gradients across inflow and outflow boundaries either increasing or decreasing underflow volumes (Mason and Bota, 2006). Water level declines of 150 to 200 feet have occurred in both the Avra Valley and USC sub-basins as a result of increased groundwater withdrawals. Water-level declines under streams and rivers have created a deeper vadose zone decreasing ET from phreatophytes but increasing potential storage for stream flow infiltration. New recharge sources include infiltration of effluent released into the channel of the Santa Cruz River, artificial recharge of effluent and Central Arizona Project (CAP) surface water at artificial recharge facilities, and seepage from mine tailing ponds. A more detailed discussion about the regional aquifer's pre and post-development groundwater budget components and their annual volumes is presented in the simulated inflows and outflows section of Chapter 3.

2.3.1 Pre-development Water Budget

There is a general consensus among previous investigators that the TAMA regional aquifer system was still in a state of dynamic equilibrium until about 1940 (Anderson, 1972;

Moosburner, 1972; Davidson, 1973; Hanson and others, 1990; Hanson and Benedict, 1994). Prior to 1940, pumpage was relatively small and generally confined to areas along the Santa Cruz River and its major tributaries (Schwalen and Shaw, 1957; Davidson, 1973). By 1940, the combination of streambed entrenchment, lowering of the water table near the Santa Cruz River due to groundwater withdrawals, and development in the floodplain had significantly reduced the areal extent of the remaining bosques and their associated ET losses (Mason and Bota, 2006). The decreased evapotranspiration is believed to have approximately equaled the amount of pumpage plus a small loss of aquifer storage (Davidson, 1973). This would have allowed the regional aquifer system to adjust to groundwater withdrawals and maintain an approximate state of equilibrium between inflows and outflows (Davidson, 1973, Hanson and Benedict, 1994). For this modeling study the condition of the TAMA regional aquifer system in 1940, is considered generally representative of predevelopment times and is used as the steady-state simulation period.

Pre-development recharge included natural recharge, groundwater underflow and agricultural recharge. Table 1 presents the conceptual steady-state groundwater components and annual rates. Natural recharge includes mountain-front recharge and infiltration of stream flow events in ephemeral washes and in major stream drainages. Mountain-front recharge occurs at the margins of basins where rainfall and snowmelt generate surface flows that infiltrate into the alluvial material under the streams and washes that flow from the mountains and across alluvial fans located at the base of the mountains. The groundwater then flows into the regional aquifer system through the alluvial fans.

Stream recharge occurs at the lower elevations when precipitation or spring snow melt creates flow events that infiltrate into the regional aquifer through the normally dry beds of ephemeral washes and the Santa Cruz River and its tributaries. In general, summer thunder storm events in July, August, and September generate short-term flow events of limited aerial extent and short duration. However, some large summer monsoonal storms can produce sustained flows that can last several days. During the fall and winter large frontal storms and cyclonic systems that originate from the Pacific Ocean can generate large flow events that may last for several weeks. The spring snow melt can also produce significant flow events that can last for a week or more.

The amount of stream recharge in the TAMA is extremely variable from year to year and is dependent on both regional and local climatic conditions. Mason and Bota (2006) used estimated long-term average stream recharge values for their 1940-1999 model simulation. However, hydrographs of model simulated heads were not always able to match hydrographs of observed heads from wells near the Santa Cruz River and its' major tributaries. This report used flow data available from the U.S. Geological Survey (USGS) stream gage data network (Figure 6) and precipitation data to generate estimates of the annual infiltration volumes for the Santa Cruz River, Tanque Verde, Rillito, and Rincon Creeks, and Pantano Wash. By using annual infiltration estimates the model should be able to more accurately replicate the variability in stream recharge volumes during the model simulation period. Table 2 provides a list of the

USGS stream gages and Figure 6 shows the location of gages that were used to develop estimates of the annual infiltration volumes. A detailed discussion of the stream flow analysis methodology is provided below in Chapter 3.

Groundwater underflow enters the study area from the Santa Cruz AMA (SCAMA), from Altar Valley, from Falcon Valley, and from bedrock gaps where Pantano Wash and Tanque Verde Creek enter the study area (Figure 3). Underflow from bedrock gaps where Pantano Wash and Tanque Verde Creek enter the study area are believed to be small and are included in the assigned mountain-front recharge estimates for those areas. Analysis of the groundwater gradient across the northern boundary from Falcon Valley into the study area indicates the inflow volume is also relatively small (Figure 3). Hydrographs of wells near the southern model boundary in Avra and Altar Valleys show fairly consistent water- levels through time; therefore, groundwater underflow into the model domain from Altar Valley is not believed to have changed significantly over time (Mason and Bota, 2006).

Irrigated agriculture began in the TAMA in the early 1900s with surface water diverted from the Santa Cruz River and its main tributaries (Schwalen and Shaw, 1957). By the 1920s irrigation wells had begun supplementing surface water diversions, providing a more stable supply of irrigation water. This report simulates agricultural recharge during the steady-state period from water applied to crops by the Cortaro-Marana Irrigation District, Flowing Wells Irrigation District, Farmers Investment Co-operative, and numerous small independent farms.

Pre-development groundwater discharge from the TAMA regional aquifer occurred as underflow, evapotranspiration, and groundwater withdrawals. Groundwater underflow exits the TAMA into the PAMA through the gap between the Silverbell and Picacho Mountains in the northwest corner of the study area (Figure 3). Evapotranspiration loss is a result of water utilized by phreatophyte plants, primarily along riparian corridors. Prior to the 1890s, water levels in the USC sub-basin along the Santa Cruz River and its major tributaries were shallow enough to support extensive mesquite bosques and cienegas (Bryan, 1922; Schwalen and Shaw, 1957; Parker, 1993). By 1940, the combination of streambed entrenchment, lowering of the water table near the Santa Cruz River due to groundwater withdrawals, and development in the floodplain had significantly reduced the areal extent of the remaining bosques and associated ET losses (Mason and Bota, 2006). Groundwater withdrawals for agriculture, industrial, and municipal uses were the largest source of groundwater discharge to the TAMA regional aquifer during the pre-development period. Total annual recharge and discharge to the TAMA regional aquifer is estimated to be about 103,000 ac-ft per year (Table 1). As discussed above the conceptual steady-state water budget assumes that overall the TAMA regional aquifer was in a state of quasi-equilibrium in 1940.

2.3.2 Post-development Water Budget

Most recharge and discharge groundwater budget components vary with time during the post-development (1941-2010) period. Mountain-front recharge and groundwater underflow into the model from Altar and Falcon Valleys are the only groundwater budget components that were held constant for the post-development period.

As discussed above, annual stream infiltration along the Santa Cruz River and its major tributaries varies greatly. Stream recharge was varied annually during the post-development period to more accurately simulate the impact of wet and dry periods on the regional aquifer. Annual volumes of stream recharge were assigned to river segments established between the USGS gages based on observed and estimated annual flows past a gage (Figure 6). A detailed description of the methodology used to develop the initial annual infiltration estimates is provided in Chapter 3.

Table 1. Conceptual steady-state groundwater budget, Tucson model area.

	Upper Santa Cruz Sub-Basin	ac-ft/yr.	Avra Valley Sub-Basin	ac-ft/yr.	AMA Totals ac-ft/yr.
Inflows					
	Mountain-Front Recharge	**26,600**	Mountain-Front Recharge	**3,500**	**30,100**
	Stream Infiltration	**32,500**	Stream Infiltration	**6,000**	**38,500**
	Ag Recharge	**10,800**	Ag Recharge	**4,700**	**15,500**
	Underflow from		Underflow from		
	Santa Cruz AMA	8,600	Altar Valley	10,000	
	Pantano	200	USC sub-basin [1]	15,000	
	Total Underflow	**8,800**	Total	**25,000**	**18,800**
	Total Inflows	**78,700**	Total Inflows	**39,200**	**102,900**
Outflows					
	Pumpage	**55,700**	Pumpage	**12,000**	**67,700**
	Evapotranspiration	**8,000**	Evapotranspiration	**0**	**8,000**
	Underflow to Avra Valley [1]	**15,000**	Underflow	**27,200**	**27,200**
	Total Outflows	**78,700**	Total Outflows	**39,200**	**102,900**
	In – Out	**0**	In - Out	**0**	**0**

1. Underflow from the USC sub-basin to the Avra Valley sub-basin is internal to the study area and is not included in the AMA total calculations.

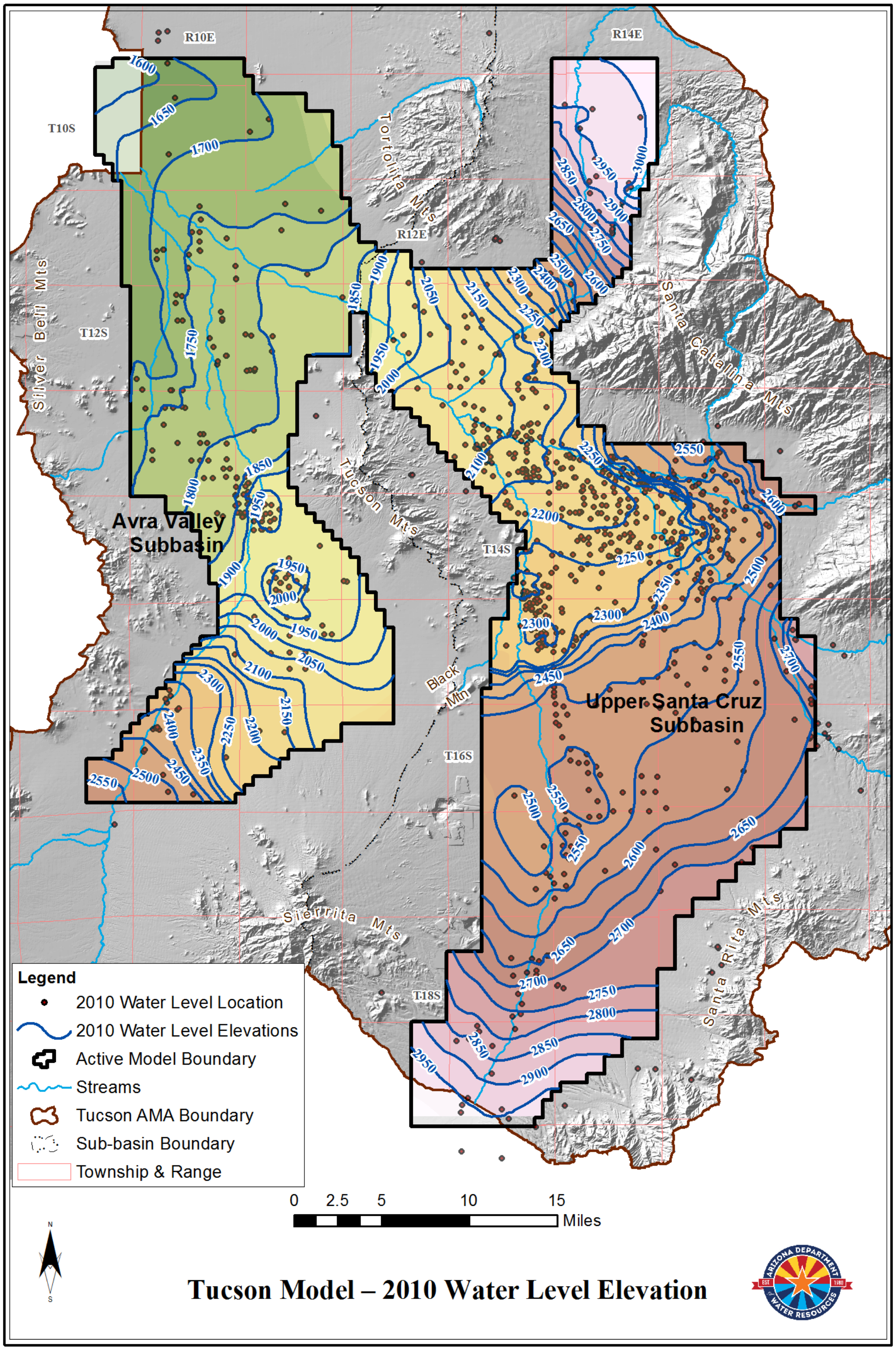


Figure 5. Water level elevation in the fall of 2010, Tucson model area.

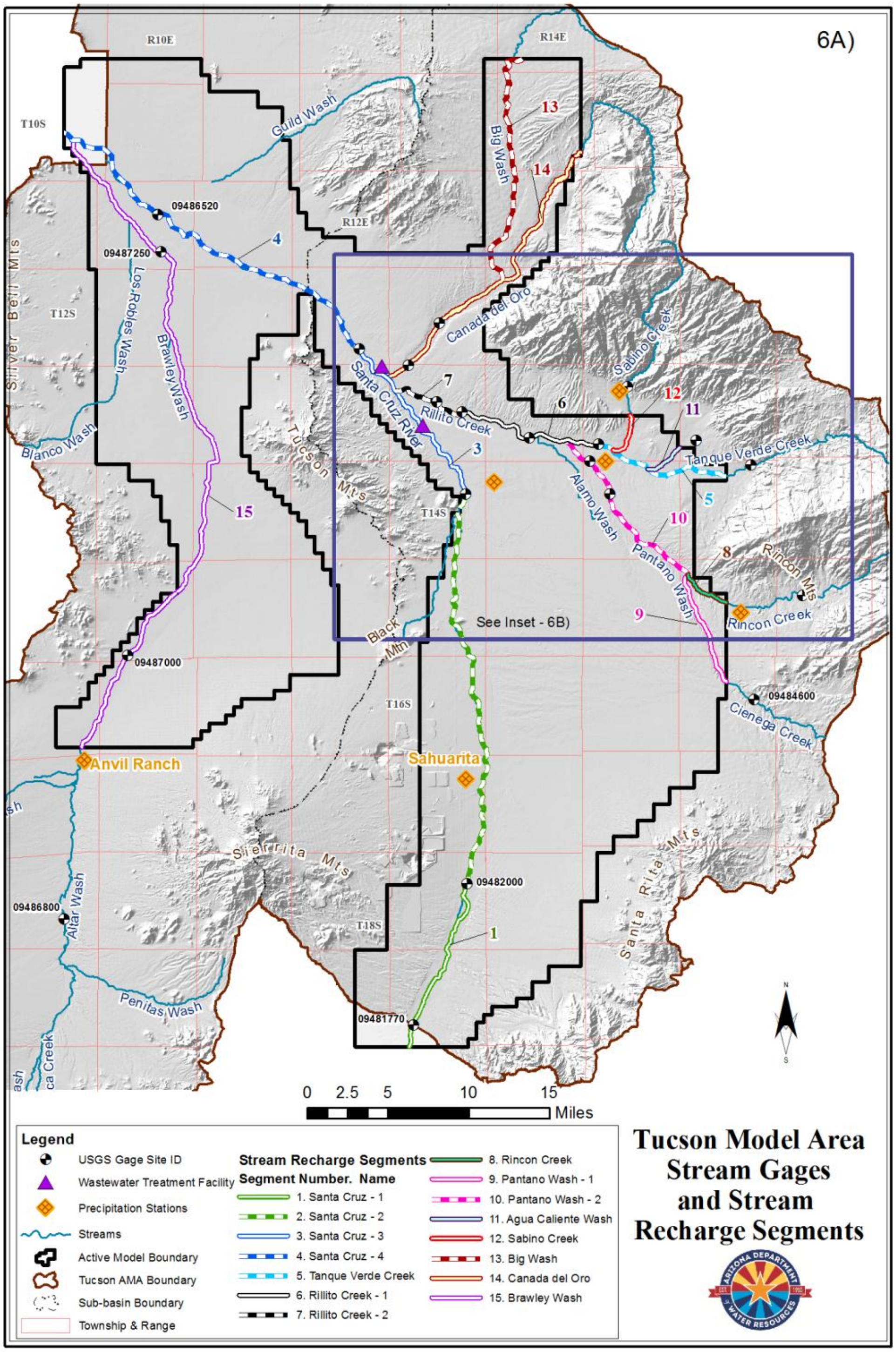


Figure 6. Stream gage locations, stream recharge segments, wastewater treatment plants, and precipitation stations, Tucson model area. 6A, AMA area; 6B inset area.

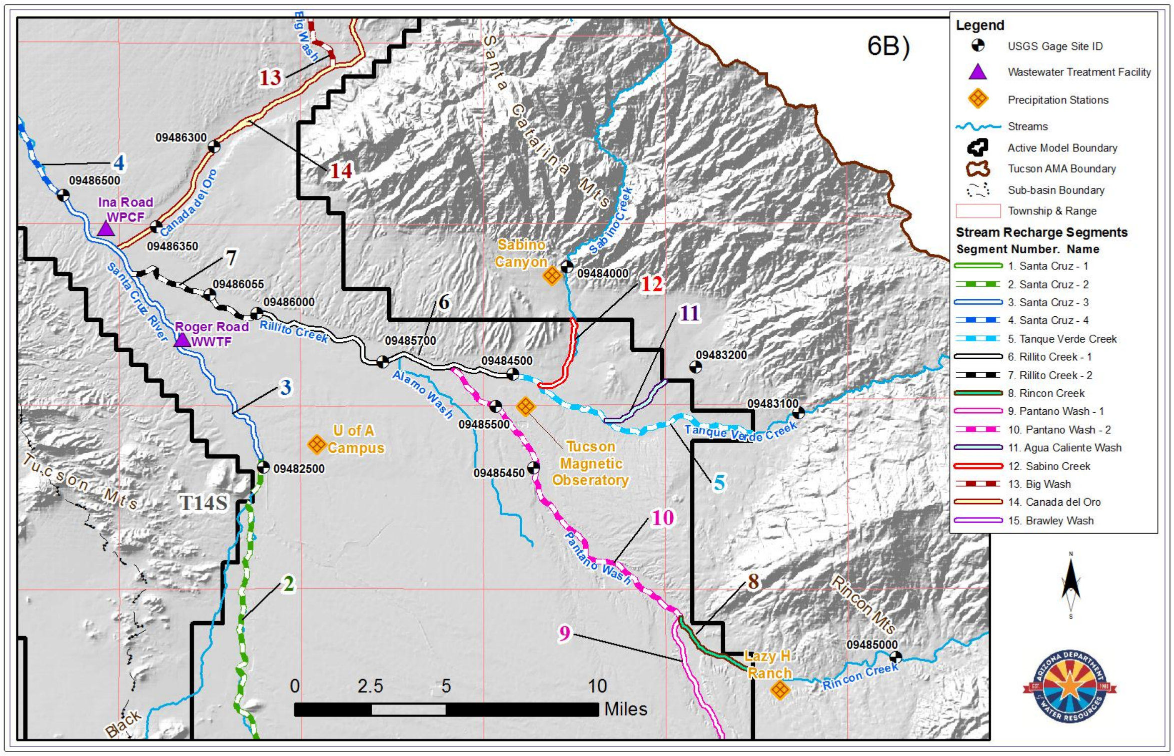


Figure 6B. Stream gage locations, stream recharge segments, wastewater treatment plants, and precipitation stations, Tucson model area.

Groundwater underflow into the study area across the TAMA - SCAMA boundary is believed to have varied over time due to water-level fluctuations caused by pumping on both sides of the boundary and infiltration of water from large stream flows and effluent released from the Nogales International Waste Water Treatment Plant (NIWWTP). All these factors have combined to impact the water-level gradient across the model boundary during the development period (Mason and Bota, 2006; Nelson, 2007).

Incidental recharge is defined as water that recharges an aquifer during the course of its use for agricultural, industrial, or municipal purposes. In the TAMA this includes water that is recharged as a result of irrigation activities, wastewater effluent released into the Santa Cruz River, and water infiltrating from mine tailings ponds. Historically, one of the larger components of incidental recharge was agricultural recharge. Agricultural recharge is the result of water applied to crops that is not utilized by the plant for consumptive use, lost to evaporation, or held by the soil. Through deep percolation the excess water eventually reaches the water table recharging the regional aquifer. The total annual water applied to crops and turf facilities (parks and golf courses) includes pumped groundwater, CAP surface water, and effluent (Mason and Bota, 2006).

Table 2. USGS Stream Gages in the Tucson Model Area.

USGS Gage ID	USGS Station Name	Gage Records [1]	Flow Data Available [2]
9483200	Agua Caliente Wash Trib near Tucson, Ariz.	1965 - 1980	Peak Flows
9486800	Altar Wash near Three Points, Az	1966 – 2012 1966 - 2011	Daily flows Peak flows
9487000	Brawley Wash near Three Points, Az	1991 – 2012 1940 – 2011	Daily Flows Peak Flows
9487250	Los Robles Wash near Marana, Az	1932 - 1983	Peak Flows
9486300	Canada Del Oro near Tucson, Az	1965 – 1990 1959 - 1983	Daily Flows Peak Flows
9486350	Canada Del Oro Blw Ina Road, near Tucson, Az	1992 – 2012 1992 - 2011	Daily Flows Peak Flows
9484600	Pantano Wash near Vail, Az	1959 – 2012 1958 - 2011	Daily Flows Peak Flows
9485450	Pantano Wash At Broadway Blvd. at Tucson, Az	1998 – 2012 1978 - 2011	Daily Flows Peak Flows
9485500	Pantano Wash near Tucson Az [3]	1940 – 1977 1940 - 1983	Daily Flows Peak Flows
9485700	Rillito Creek at Dodge Boulevard, at Tucson, Az	1987 – 2012 1988 - 2011	Daily Flows Peak Flows
9486000	Rillito Creek near Tucson, Az	1914 – 1983	Peak Flows
9486055	Rillito Creek at La Cholla Blvd near Tucson, Az	1990 – 2012 1990 – 2011	Daily Flows Peak Flows
9485000	Rincon Creek near Tucson, Az	1952 – 2012 1953 - 2011	Daily Flows Peak Flows
9484000	Sabino Creek near Tucson, Az	1932 – 2012 1932 - 2011	Daily Flows Peak Flows
9481770	Santa Cruz River near Amado, Az	2003 – 2009 2004 – 2009	Daily Flows Peak Flows
9482000	Santa Cruz River at Continental, Az	1940 – 2012 1940 - 2011	Daily Flows Peak Flows
9482500	Santa Cruz River at Tucson, Az	1905 – 2012 1914 – 2011	Daily Flows Peak Flows
9486500	Santa Cruz River at Cortaro, Az	1939 – 2012 1940 – 2011	Daily Flows Peak Flows
9486520	Santa Cruz River at Trico Road, near Marana, Az.	1989 – 2012 1989 – 2011	Daily Flows Peak Flows
9483100	Tanque Verde Creek near Tucson, Az	1959 – 1974 1960 – 1974	Daily Flows Peak Flows
9484500	Tanque Verde Creek at Tucson, Az	1940 – 2012 1940 – 2011	Daily Flows Peak Flows

1) Some sites may have gaps in the recorded flow data.
2) Flow data available as of December, 2012.
3) The Pantano Wash near Tucson gage has only 5 years of flow between 1940 and 1977

Mine tailing recharge is water that is returned to the aquifer through seepage from tailing ponds associated with copper mining. The study used estimates of mine withdrawals and incidental recharge from tailings ponds from Travers and Mock (1984) and Hanson and Benedict (1994) for the period 1952 to 1983. Additional estimates of tailings pond recharge volumes and their locations were developed based on information from Arizona Department of Environmental Quality (ADEQ) reports provided to the ADWR by Montgomery and Associates (2009).

Artificial recharge is currently the largest source of recharge to the TAMA regional aquifer. CAP surface water and treated effluent are both recharged into the regional aquifer at constructed or managed underground storage facilities (USFs) permitted by the ADWR (Figure 7). CAP surface water is also used to reduce agricultural pumpage by allowing farmers to use CAP water in lieu of pumping groundwater at permitted groundwater savings facilities (GSFs). A detailed account of how CAP and effluent have been utilized in the TAMA can be found in Mason and Bota (2006), and Chapter 3 of this report discusses artificial recharge locations and volumes since 2000.

Effluent from wastewater treatment plants has been released into the Santa Cruz River starting in the early-1950s (Figure 6B). Effluent has also been directed to USFs for recharge to the aquifer and wheeled through a city-wide distribution system to irrigate parks, golf courses, and other turf facilities in the greater Tucson metro area.

Groundwater withdrawals for agriculture, municipal, and industrial purposes are the single largest source of discharge from the regional aquifer during the post-development period from 1941 to 2010. The volume and location of post-development groundwater withdrawals are not well known prior to about 1960. After about 1960, the amount and location of groundwater withdrawals there is better understood because more agricultural and municipal users in the TAMA began to keep well-specific pumpage records. The adoption of the Groundwater Management Act with and the reporting of well-specific pumpage for all groundwater right holders after 1984, provides accurate withdrawal volumes and locations for the last 26 years of the model simulation period.

Groundwater underflow exits the Tucson AMA into the PAMA through the gap between the Silverbell and Picacho Mountains in the northwest corner of the study area (Figure 3). Underflow out of the Tucson AMA has varied through the developed period (1941-2009) due to changing water levels along the AMA boundary. Water levels in northern Avra Valley generally began declining in the late 1940s and continued to decline into the mid-1970s. In the mid-1970s water levels stabilized and then began to rebound. This decline-recovery pattern is illustrated in Figure 8 presenting the hydrograph of well D-11-10 08DDD located in the northwest corner of the model area (Figure 7). Underflow out of the model area is believed to have declined from the 1950s to the mid-1970s due to the loss of saturated thickness in the aquifer at the outflow point, and then increased after the mid-1970s as water levels recovered to present levels.

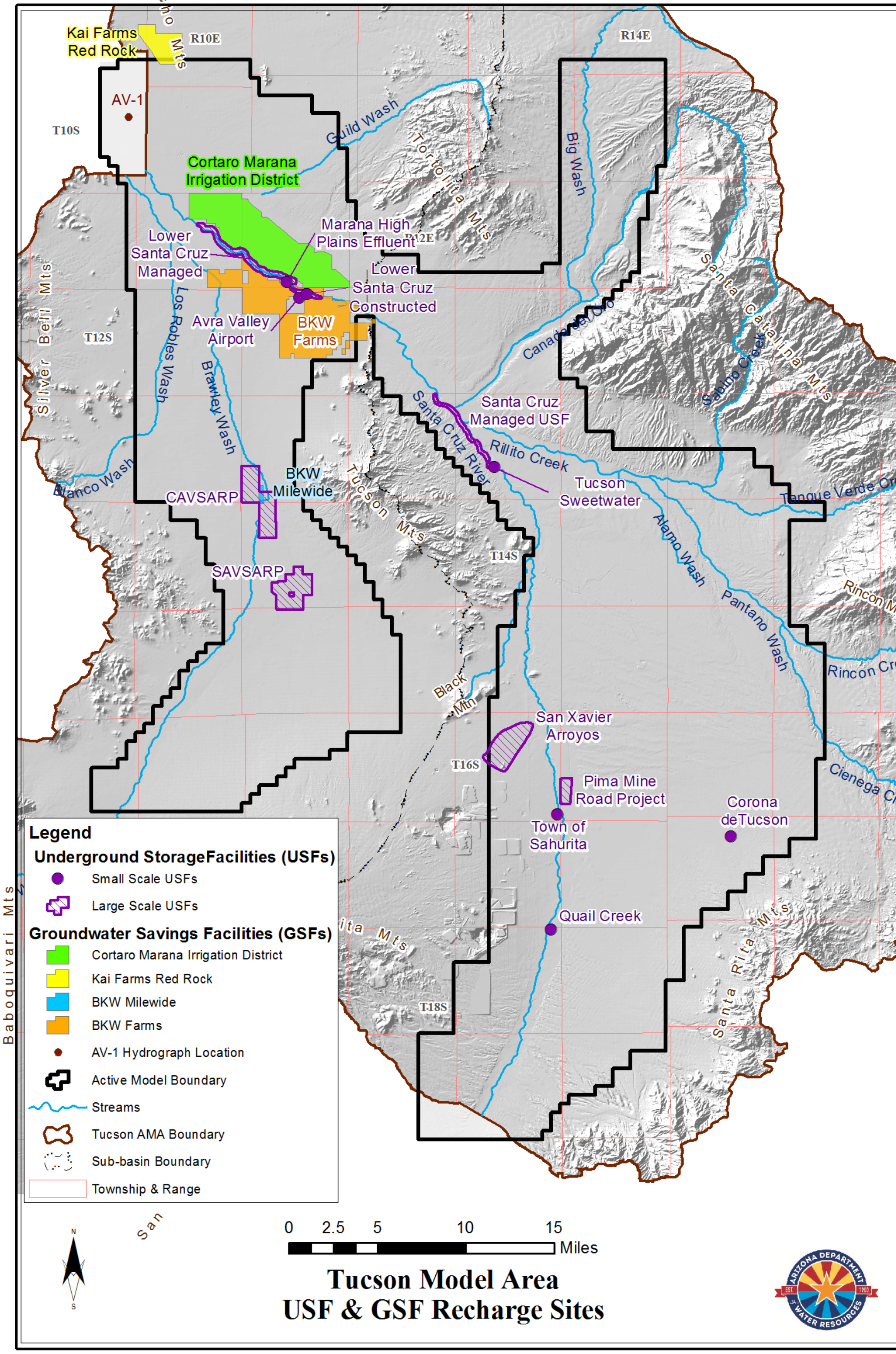


Figure 7. Underground Storage Facilities and Groundwater Storage Facilities recharge locations, Tucson model area.

The overall ET loss from riparian vegetation has declined during the developed period as water levels have dropped along the Santa Cruz River and its tributaries. There are no published estimates of ET available for the Avra Valley sub-basin. Previous investigators have either assumed that ET in Avra Valley was negligible due to deep water levels or did not estimate that component in their water budgets (Mason and Bota, 2006).

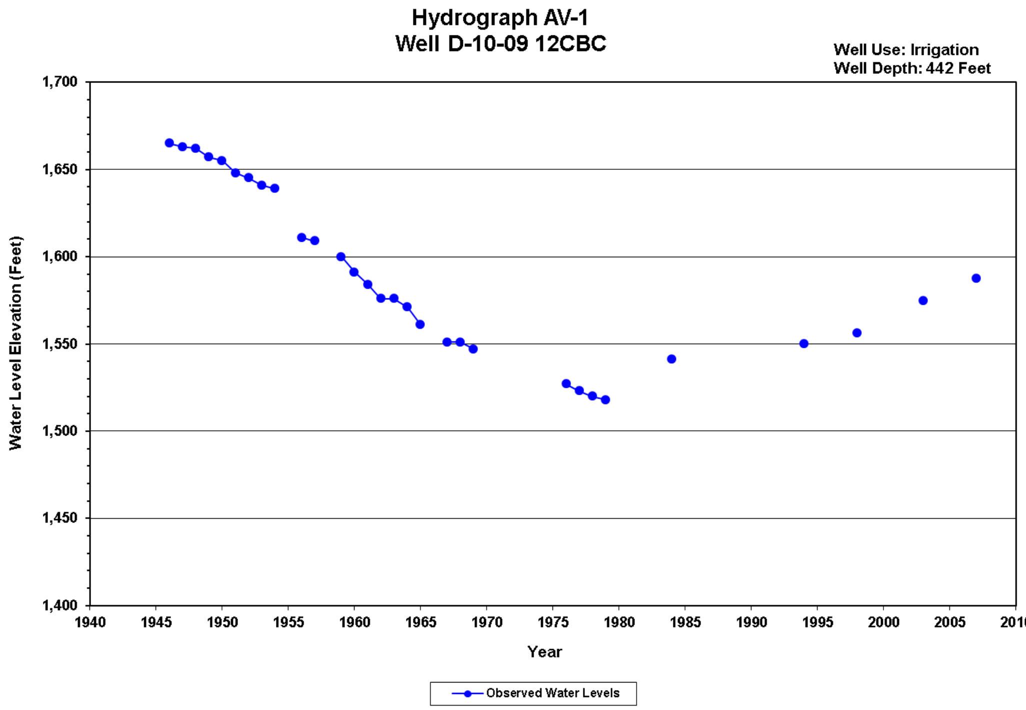


Figure 8. Hydrograph of northern Avra Valley boundary well, Tucson Model area.

2.4 Estimates of Groundwater in Storage

Previous estimates of groundwater in storage for the Tucson AMA regional aquifer have ranged from 68 million ac-ft to about 76 million ac-ft (Mason and Bota, 2006). Groundwater in storage in the USC sub-basin to 1,000 feet below land surface (bls) during pre-development time was estimated at about 52 million ac-ft (Davidson, 1973; Hanson and Benedict, 1994). For the Avra Valley sub-basin estimates of groundwater in storage to a depth of 1,000 feet range from about 16.5 to 24 million ac-ft (White and others, 1966; Hanson and others, 1990).

Since the 1940s consistent overdrafting of the Tucson AMA regional aquifer has resulted in the persistent, long-term loss of groundwater storage (Mason and Bota, 2006). A current estimate of groundwater in storage was calculated using the 2009-2010 water level surface, aquifer storage parameters from this model, and a limit of 1,000 feet bls. The groundwater in storage for the active model study area is estimated to be slightly over 50 million ac-ft, almost 33 million ac-ft in the USC sub-basin and a little over 16 million ac-ft in the Avra Valley sub-basin. Table 3 provides a breakdown of the calculated groundwater in storage by sub-basin (Figure 9).

Table 3. Estimated groundwater in storage, Tucson model area.

Sub-basin	Acre-Feet
Upper Santa Cruz	32,929,700
Avra Valley	16,330,800
Pinal AMA	787,100
Santa Cruz AMA	282,200
TOTAL	**50,329,800**

3.0 Simulation of Groundwater Flow

The Tucson AMA regional groundwater flow model study area is 3,250 mi^2 and includes portions of the Upper Santa Cruz and Avra Valley sub-basins in the TAMA, and small portions of the PAMA and the SCAMA (Figure 1). The model code selected to simulate groundwater flow in the TAMA study area was MODFLOW-NWT (NWT), developed by the U.S. Geological Survey (Niswonger and others, 2011). The MODFLOW code uses a finite-difference method to solve the groundwater flow equation in a three-dimension grid made up of rows, columns, and layers. NWT is very efficient at solving the groundwater flow equation where drying and rewetting of unconfined model layers creates nonlinearity in the groundwater flow equation. Due to the large water level declines and recoveries experienced in the TAMA, NWT was used to help provide a stable numerical solution when model layers convert from confined to unconfined conditions. For a detailed discussion of how NWT solves the problem of drying-rewetting nonlinearities see Niswonger and others (2011).

3.1 Model Design

The TAMA groundwater flow model simulates steady-state (predevelopment groundwater) conditions in 1940, and transient (developed groundwater) conditions from 1941 to 2010 using annualized stress periods. The model units of length and time are feet and days, respectively. The regional aquifer is divided into three model layers to enable the model to simulate three-dimensional groundwater flow. The general characteristics of the Tucson AMA regional groundwater flow model are presented in Table 4. The areal extents of the three layers used in the model are shown in Figure 10.

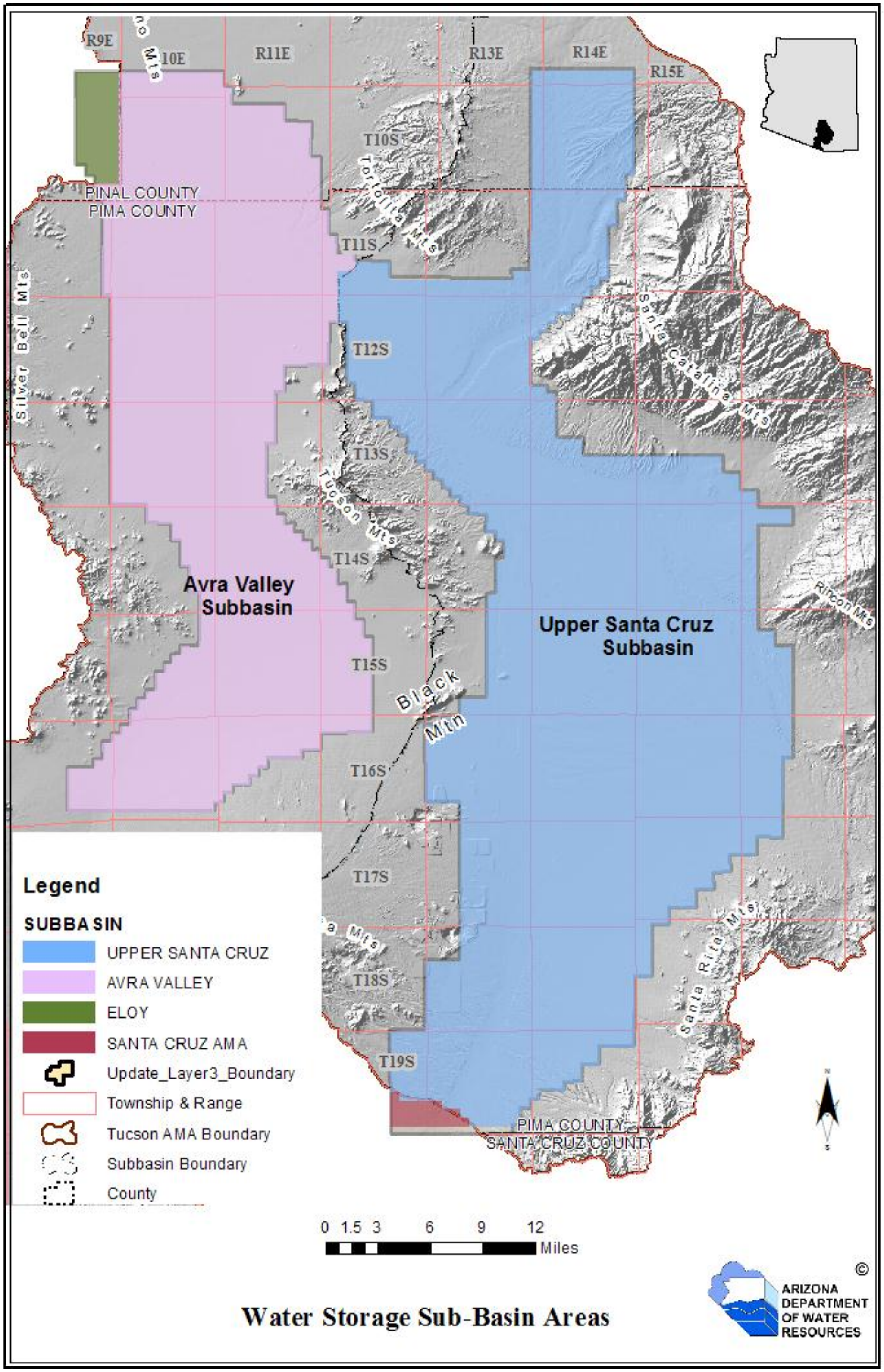


Figure 9. Water storage calculation areas, Tucson model area.

As with the previous ADWR model, no-flow cells delineate the active model domain by representing bedrock areas or areas where groundwater flow is parallel to a model boundary. Variable head cells define the active model area and represent the regional aquifer system in the study area. Constant head cells are located along some model boundaries in order to simulate groundwater underflow into or out of the study area (Figure 3). Utilizing constant head cells along these boundaries allows the groundwater flux across the boundaries to change in response to changing hydraulic gradients within the model. Specified fluxes were assigned along sections of the southern and northern boundaries to simulate underflow into the model from the Altar Valley and at the northern model boundary in Falcon Valley near the head of Big Wash (Figure 3).

3.1.1 MODFLOW Packages

The Tucson AMA groundwater flow model utilizes nine packages and one numerical solver that are offered in MODFLOW-NWT. The model parameter packages are: Basic (BAS), Upstream Weighting (UPW), and Discretization (DIS) Packages. Model stress packages are: Well (WEL), Recharge (RCH), and the Evapotranspiration (EVT). The Time-Variant Specified-Head (CHD) Packages is a head-dependent package used to control boundary flux into and out of the model. The Head Observation (HOB) and Hydrograph (HYD) Packages were used to help with model calibration, and the Generalized-Minimum-Residual (GMRES) Solver was used to solve the groundwater flow finite-difference equation. The brief discussion below describes how each package was used in modeling the TAMA regional aquifer:

1. The BASIC (**BAS**) package designated cells as no-flow, variable head, or constant head, and assigned the initial heads for each active cell.
2. The Upstream Weighting (**UPW**) package was used to define the cell-centered hydraulic parameters of the model. The hydraulic parameters defined in the UPW package include the cell-specific horizontal and vertical hydraulic conductivities and storage terms.
3. The Discretization (**DIS**) package established the physical layout of a model. The package assigned the number of model rows, columns, and layers, the physical dimensions of each cell, and the layer top and bottom elevations. The DIS package also assigned the model units of time and length, and the number and type of stress periods and their length.
4. The Well (**WEL**) package was used to simulate water that was withdrawn from or added to a model, usually by a well. Each well was assigned a specified rate of feet per day for a given stress period and was located within the model based on a layer, row, and column.
5. The Recharge (**RCH**) package was used to spatially distributed recharge to selected cells within a model. The recharge package is used to simulate precipitation that

percolates into the aquifer, mountain-front recharge, and various types of incidental recharge.

6. The Evapotranspiration (**ET**) package was used to simulate groundwater that was transpired by riparian vegetation or direct evaporation of groundwater at the land surface.
7. The Time-Variant Specified-Head (**CHD**) package was used to simulate groundwater flux into and out of certain model boundaries. The package simulates head-dependent boundaries by assigning variable head values at different times during the model simulation. This allowed boundary fluxes to vary with time based on the hydraulic gradient and conductance between the specified-heads and variable heads within the model.
8. The Head Observation **(HOB)** Package was used to compare observed heads to model simulated heads. The HOB package generated the difference between an observed and simulated head, the residual, which was used to assess how well the model simulated heads compared to field measured heads. The residuals were one measure of how well the model simulated the aquifer system through time.
9. The Hydrograph **(HYD)** Package allowed time-series simulated head data to be extracted from the model simulation. The time-series head data was used to create synthetic hydrographs that were compared to hydrographs of observed heads. The simulated hydrographs were another measure of how well the model simulated actual conditions through time.

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 Generalized-Minimum-Residual (GMRES) Solver was used in this study to solve the groundwater flow equation. For documentation describing the mathematical theory and application of MODFLOW, its associated packages and numerical solvers used in the TAMA model the reader is directed to McDonald and Harbaugh (1988), Hill (1990), McDonald and others (1992), Hanson and Leake (1999), Hill and others (2000), Wilson and Naff (2004), Harbaugh (2005), and Niswonger and others (2011).

3.1.2 Model Boundaries

The boundary conditions were not changed significantly from the previous ADWR TAMA groundwater flow model (Mason and Bota, 2006). Selection of appropriate boundary conditions is important to the modeling process and should reflect the hydrologic conditions along model boundaries. To simplify the modeling process, boundaries for the TAMA model were selected along mountain fronts and at points of underflow into or out of the regional aquifer (Figure 3). The inflow-outflow boundaries were selected at or as close as possible to the TAMA

Table 4. General Tucson model design components.

Model Component	Description	Units
Simulation: Combined Steady-State-Transient	1940-2010	Time = Days, Length = Feet
Model Grid	130 Rows x 100 Columns	Model Cells = 0.5 mi^2
Model Origin (Lower Left)	UTM, Zone 12, HARN 1983, Feet	X = 1488661.47638 Y = 11494611.8537
Model Cell Types	No Flow, Constant Head, Variable Head, Specified Flux	
Boundary Conditions	Constant Head and Specified Flux	
DIS Package	Specified aquifer tops and bottoms and time and length discretization	1 Steady-State and 70 Transient Stress Periods
BAS Package	Specified starting heads and active model domain	
UPW Package	Specified hydrologic and storage parameters and allows resaturation of cells that go dry	
Layer 1 – 3,105 active cells	Layer Type 1 – Unconfined Aquifer, T = K x Saturated Thickness	$K_x = K_y$ = Feet / Day
Layer 2 – 4,524 active cells	Layer Type 3 – Confined / Unconfined Aquifer, T = K x Saturated Thickness	$K_x = K_y$ = Feet / Day
Layer 3 – 4,954 active cells	Layer Type 3 – Confined / Unconfined Aquifer, T = K x Saturated Thickness	$K_x = K_y$ = Feet / Day
Vertical Conductivity	Assigned as a ratio between horizontal K and vertical K values	Dimensionless
Specific Yield	Volume of water yielded per unit area per unit change of water level in unconfined aquifer	Dimensionless
Specific Storage	Volume of water yielded per area per unit change in a confined aquifer's potentiometric surface	1/Length
Pumpage	Assigned to all simulated well locations	$Feet^3$ / Day
Recharge	Applied to uppermost active cells	Feet / Day
Evapotranspiration	Assigned rates per cell; Extinction Depth 30 ft	Feet / Day
Numerical Solver	Generalized-Minimum-Residual (GMRES)	Head Closure Criteria: 0.01 Feet, Budget Error 864 ft^3/day

political boundaries, and where possible, the inflow-outflow boundaries were selected to coincide with previous model boundaries so that current and previous model inflow and outflow fluxes could be compared.

Mountain-fronts were simulated as no-flow boundaries with specified flux cells representing mountain-front recharge. Underflow into and out of the model was simulated using constant head cells and specified fluxes. Simulated fluxes into or out of the model across the constant head boundaries were proportional to the hydraulic gradient and conductance between the constant head cells and adjacent variable head cells. Specified fluxes were assigned to selected cells along model boundaries to simulate groundwater underflow using the Well Package. A more detailed discussion of the model boundaries and how they are simulated can be found later in this report in Section 3.2.

3.1.3 Model Layers

For simulation purposes the TAMA regional aquifer was divided into three model layers. One of the planned updates to the model was to add a defined bottom to model layer 3, which previously was simulated as an assigned transmissivity layer that in essence made the layer bottomless. A bottom was added to layer 3 to improve the model's ability to simulate water level changes along the basin margins where the depth to bedrock is shallow. Cell-specific bottom elevations for layer 3 were initially assigned based on a depth to bedrock map developed by the Arizona Geological Survey (AZGS) (Richard and others, 2000). Along the model's margins the bottom elevation was modified from the AZGS depth to bedrock map where appropriate based on more recent well log data and modeling constraints. Figure 4 presents the ADWR modified depth to bedrock map for the TAMA. The bottom of layer 3 was truncated at 3,200 feet below land surface (bls) in areas where the basin-fill sediments extends below that depth. This generally occurs only in the center of the sub-basins (Figure 4). The bottom of the model was truncated for ease in modeling and because there are few water supply wells completed below about 2,500 feet below land surface.

The model layering structure was originally developed using the stratigraphic units suggested by Anderson (1987a, 1987b, 1988). Layer 1 consisted of upper basin-fill sediments that included the Younger Alluvium (steam channel deposits and flood plain alluvium) and the Fort Lowell Formation. Layer 2 was consisted of the upper Tinaja beds that formed the base of Anderson's upper basin-fill deposit. Model layer 3 includes the all of the lower basin-fill sediments, the Pantano Formation, and the Tertiary volcanic and sedimentary deposits. In the deepest sections of the model the maximum thickness of model layers 1 and 2, the upper basin-fill of Anderson (1987a, 1987b, 1988), is about 1,500 feet. The remaining model thickness to the maximum sedimentary thickness of 3,200 feet would be the lower basin-fill unit of Anderson (1987a, 1987b, 1988).

Applying the revised stratigraphy developed by Houser and others (2005) to the TAMA model alters the sedimentary units assigned to layers 1, 2, and 3 in many areas of the model. For example, the Exxon State 32-1 well is located in model cell 7477 (Figure 4). The cell column has a total thickness of 3,200 feet; layer 1 is 335 feet thick, layer 2 is 665 feet thick and layer 3 is truncated at 2,200 feet thick. Comparing the model layers to the Exxon State type section, layers 1 and 2 combined would be 1,000 feet thick and would be approximately equivalent to the 1,100 foot thick medial alluvial fan facies that forms the upper part of Unit A of Houser and others (2005) upper basin-fill. Model layer 3 would be the remaining 750 feet of Unit A and almost all of Unit B of the upper basin-fill. In contrast, layer 3 for cell 7477 would have been assigned to Anderson's lower basin-fill unit in the previous TAMA model by Mason and Bota (2006).

Based on the stratigraphy of Houser and others (2005) model layers 1, 2, and 3 mainly simulate the upper basin-fill sediments in areas of the model domain where the total sediment packet is deeper than 3,200 feet, (Figure 4). As the total sediment packet thins approaching the basin margins layer 3 would include increasingly thicker intervals of Units C and D of the lower basin-fill. On upthrown fault blocks located along the western edge of the USC sub-basin and north of Tanque Verde and Rillito Creeks there is essentially no change in the conceptual model layer assignments. In these areas model layers 1 and 2 consist of thin sequences of upper and lower basin-fill sediments and model layer 3 represent the Pantano Formation and the underlying Tertiary sedimentary rock sequences. The extent and thicknesses of the active model cells for layers 1, 2, and 3 are presented in Figures 11, 12, and 13. Layer 1 varies in thickness from 50 to just over 400 feet and has a limited saturated extent in the central and southern areas of the Avra Valley sub-basin and in the Canada del Oro drainage (Figure 11). The thickness of model layer 2 (Figure 12) varies from about 50 feet to about 1,200 feet, and the thickness of model layer 3 (Figure 13) ranges from 55 to almost 3,000 feet. Model layer elevations and aquifer parameters were augmented with recent data/information from driller's and geophysical logs, and from a variety of private and government sources.

3.1.4 Aquifer Parameters

Hydraulic conductivity, saturated thickness, and aquifer storage properties influence the groundwater flow system and its response to applied stresses. The initial hydraulic parameters for this report were based on the values from the previous ADWR TAMA groundwater flow model (Mason and Bota, 2006). Layers 1 and 2 horizontal hydraulic conductivities (K_x) were used as initial model values. Initial K_x values for Layer 3 were calculated by dividing the initial Layer 3 saturated thickness calculated using the assigned Layer 3 bottom elevation by the Layer 3 transmissivities used in the Mason and Bota (2006) model. The initial K_x values for layers 1 and 2 were not altered significantly except for areas along the Santa Cruz River, Pantano Wash, and near the model outflow point along the TAMA – PAMA boundary. Calibrated Layer 1 K_x values ranged from 0.5 ft. per day (ft/d) to 250 ft/d and averaged 35.3 ft/d. Layer 2 calibrated Kx values ranged from 0.4 to 110 ft/d and averaged 16.5 ft/d. The calibrated Layer 3 K_x values ranged from 0.1 to 55 ft/d and averaged 3.8 ft/d. Figures 14, 15, and 16 present the model

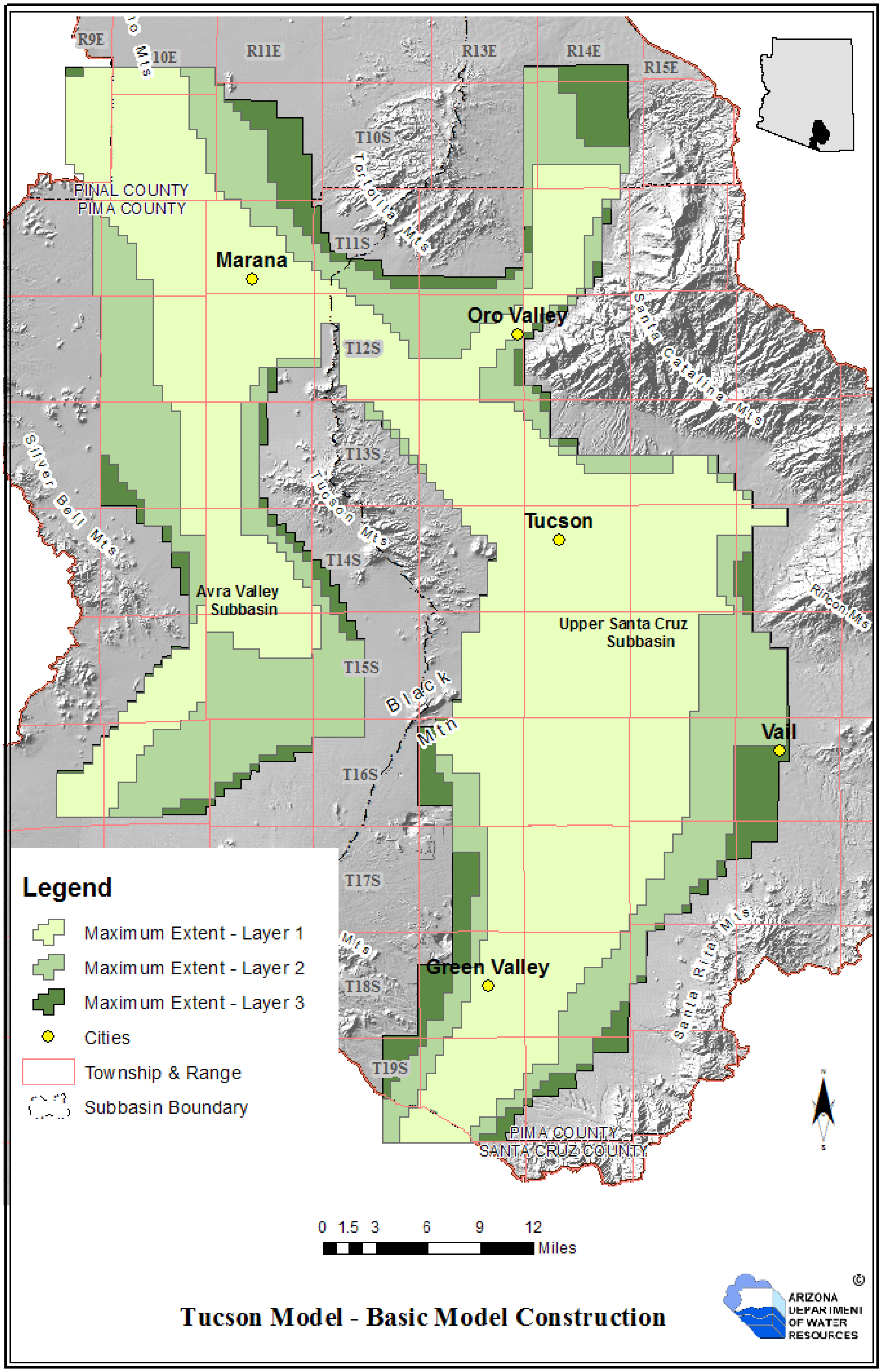


Figure 10. Extent of model layers, Tucson model area

calibrated K_x distribution for model Layers 1, 2, and 3, respectively. No horizontal anisotropy was simulated in the model.

The MODFLOW-NWT Upstream Weighting (UPW) Package allows some flexibility in simulating vertical anisotropy between model layers. The UPW package allows a cell's vertical conductivity (K_z) to be explicitly assigned or assigned as a ratio between a cell's K_x and K_z values (K_x/K_z). The option to assign the vertical anisotropy using a K_x/K_z ratio was used in this model simulation. Layer 1 was assigned a ratio of 10:1 (K_x to K_z), the Layer 2 vertical conductivity ratio ranged from 10:1 to 20:1, and the vertical conductivity ratio for Layer 3 ranged from 15:1 to 30:1.

The specific yield distribution per model layer was unchanged from the Mason and Bota (2006) model. Layer 1 specific yields range from 0.08 to 20 percent and averaged 0.13 percent. Specific yields for Layer 2 ranged from 0.05 to 0.18 percent and averaged 0.12 percent. Layer 3 specific yields ranged from 0.05 to 0.12 percent and averaged 0.07 percent. Specific storage was used in combination with a cell saturated thickness to calculate the storage coefficient. A specific storage value of 1.0×10^{-6} ft^{-1} was assigned to Layers 2 and 3. The assigned specific storage value used in this report simulated change in storage values that were comparable to the storage changes simulated by Mason and Bota (2006).

3.2 Simulated Inflows and Outflows

The model simulated inflow and outflow budget components developed for this report relied primarily on the previous ADWR Tucson model datasets developed by Mason and Bota (2006). The existing model budget components were supplemented with updated reported pumpage from the RoGR database and artificial recharge volumes reported to the ADWR from the period 2000 to 2010. A discussion of sources of data used to develop groundwater withdrawals and recharge used for this report is presented below.

3.2.1 Stream Flow Recharge

Stream flows in the Tucson AMA are extremely variable, so much so that the mean annual flow in a stream often has little relationship to the flow that can be expected for any given year (Condes de la Torre, 1970). The stream flow recorded at Continental, Arizona (USGS Gage 09782000) is an example of the annual flow variability. The gage has 58 years of annual flow data from 1940 to 2012 and a mean annual flow past the gage of 15,765 ac-ft (Table 2). However, the mean flow has only been exceeded during 12 of the 58 years of record, and the mean annual flow is about 2.5 times greater than the median annual flow of 5,945 ac-ft. This relationship is typical of the highly variable nature of stream flow data in the TAMA.

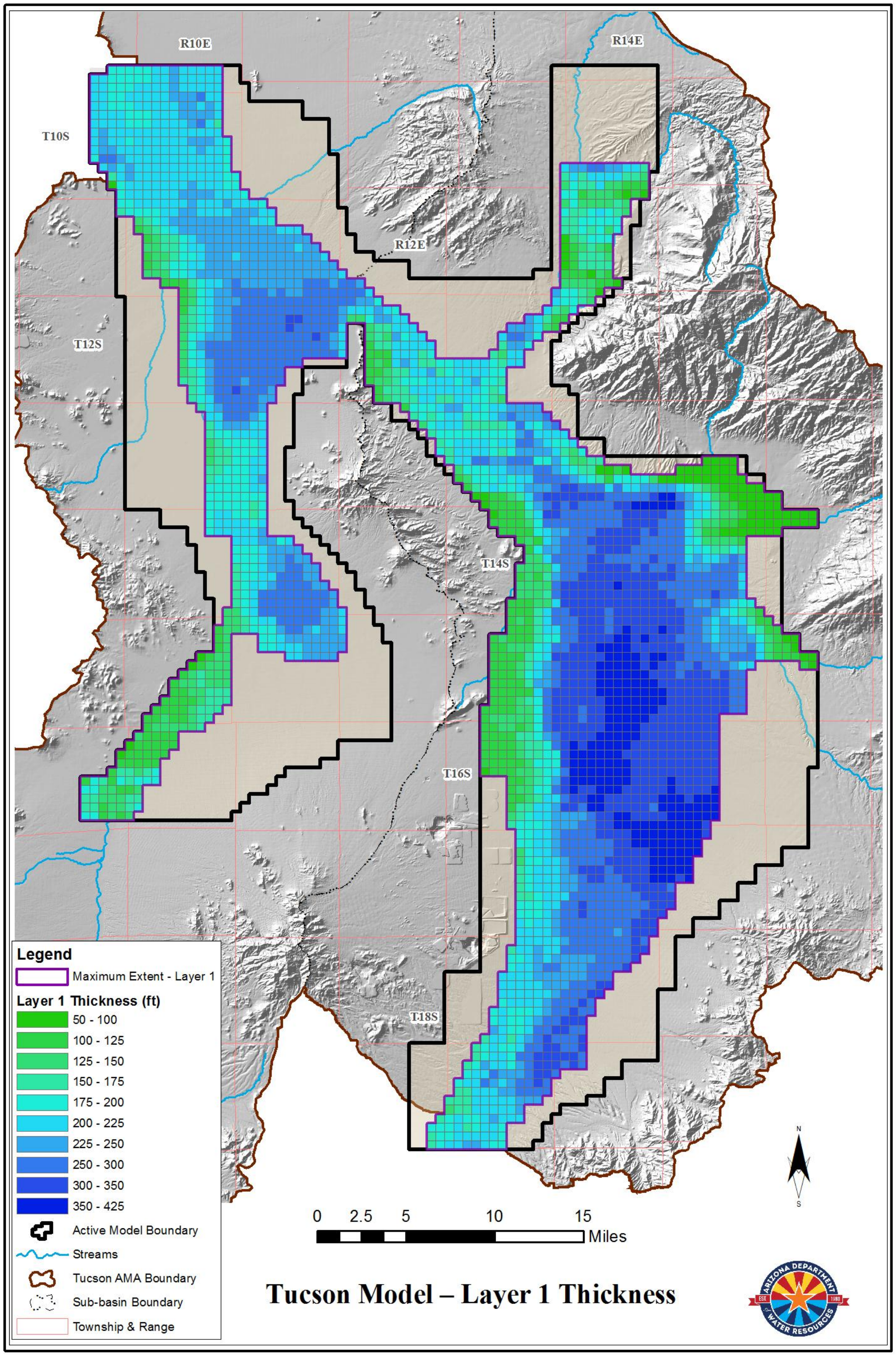


Figure 11. Active extent and thickness of model layer 1, Tucson model area.

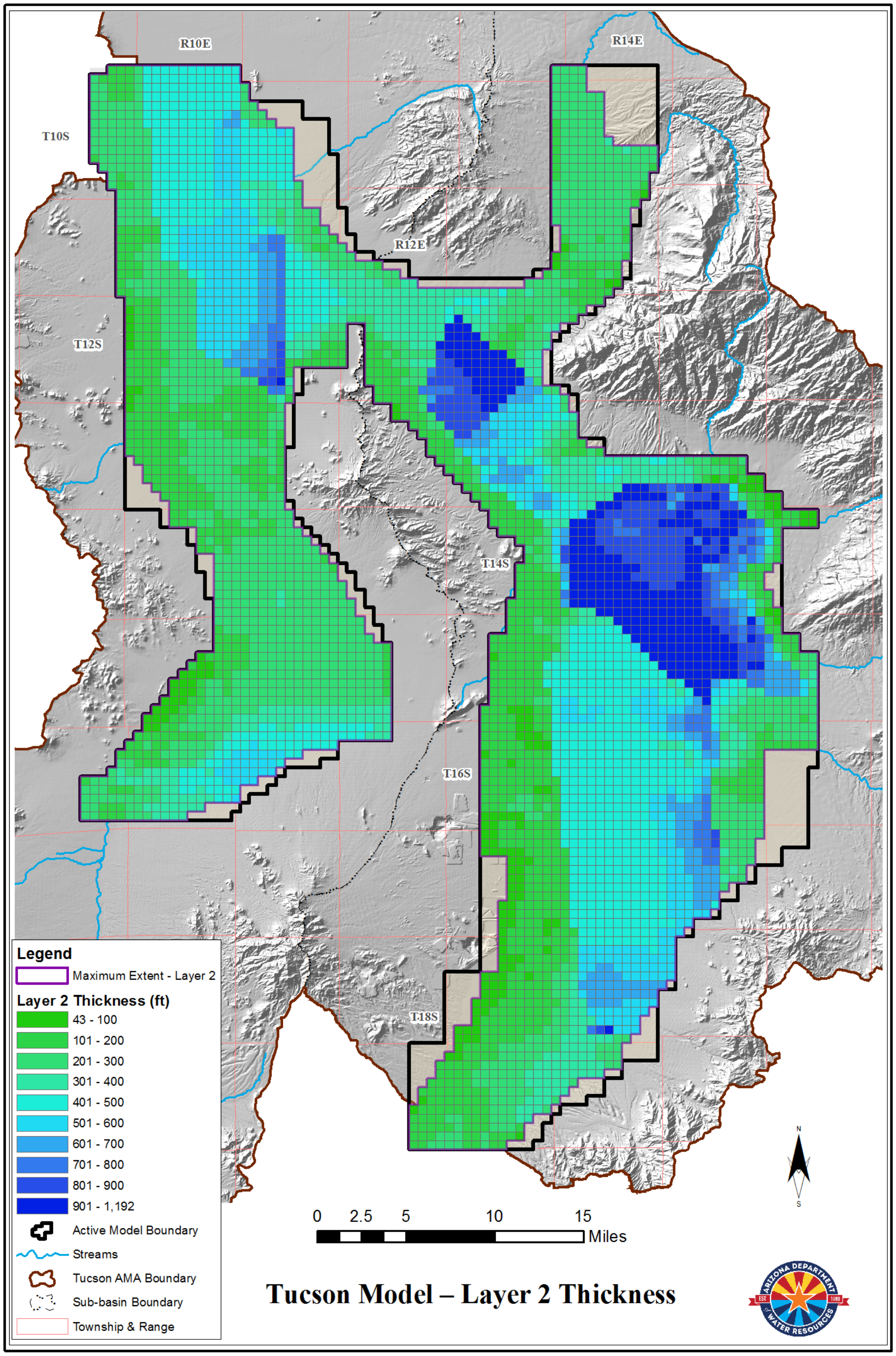


Figure 12. Active extent and thickness of model layer 2, Tucson model area.

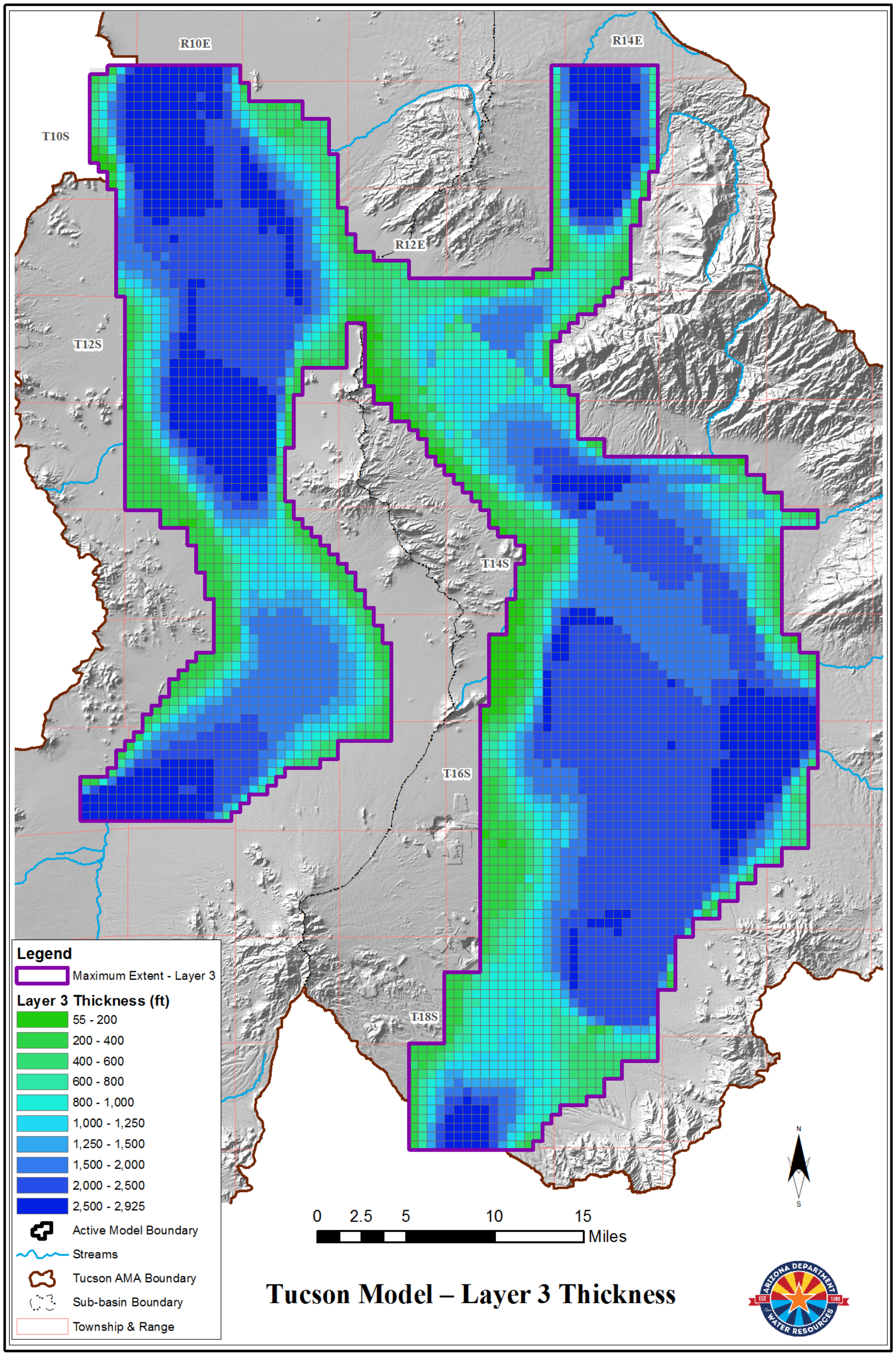


Figure 13. Active extent and thickness of model layer 3, Tucson model area.

The annual variability in stream flow is due to a combination of climatic events that can occur in Arizona. Intense, short-duration summer monsoonal storms, early fall cyclonic storms that bring wide-spread, high intensity precipitation events, winter frontal storms with lower intensity, long-duration precipitation events, and winter snow melt combine to create a highly variable regime of flow events. Research by numerous investigators indicates that infiltration of water from flow events is also extremely variable and depends on both flow duration and flow volume (Burkham, 1970, Keith, 1981, Stonestrom, and others, 2007).

Schwalen and Shaw (1957), Matlock and Davis (1972) and Keith (1981) concluded that winter flow events are more effective than summer flow events at supplying recharge to the TAMA regional aquifer. Winter-spring flow events generally are long-duration, low intensity flow events as opposed to the summer flows, which are usually flashy short-duration, high intensity flow events. An additional assumption by Keith (1981) is that extremely high flow events, whether during the winter or summer, may lose a smaller percentage of flow to infiltration than lower, more "normal" flow events. Keith (1981) examined stream flow losses along Rillito Creek from 1961 to 1974 in an attempt to determine patterns of stream recharge for the Rillito Creek watershed. Based on an analysis of inflow-outflow losses, Keith (1981) estimated that on average about 90 percent of the winter flows and about 80 percent of summer flows were lost to the streambed. However, only about 45 percent of the flow in what were deemed "extreme" flow events was lost to infiltration along the streambeds. Keith (1901) believed that the short duration and high intensity of the extreme flows precluded the infiltration of a larger volume of water.

The previous ADWR model of the TAMA by Mason and Bota (2006) used long-term average infiltration estimates to simulate the stream recharge. For this update a detailed analysis of the available flow data from the U.S. Geological Survey (USGS) stream gage network was undertaken to determine the historical flow of major streams/tributaries on an annual basis (Figure 6). Both daily and peak flow data were used when and where it was available (Table 2). Precipitation data was used to estimate annual stream flows at some gages with long gaps in the flow record. The median annual flow value was substituted for recorded flows during short gaps at some gages with an otherwise long flow record.

The general empirical relationship between stream inflow rates and infiltration rates for selected stream reaches within the Tucson Basin developed by Burkham (1970) was used to estimate an initial annual stream infiltration. The relationship developed by Burkham is:

$$\text{Infiltration Rate} = \mathbf{C} * (\text{Inflow Rate})^{0.8}, \quad \text{(Equation 1)}$$

where **C** is a variable coefficient that is a combination of a number of parameters. Burkham assigned average coefficient values to each stream reach based on their physical attributes. Using the relationships developed by Burkham and the average monthly flow data, the annual recharge from stream channel infiltration was calculated for the Santa Cruz River, Brawley-Los

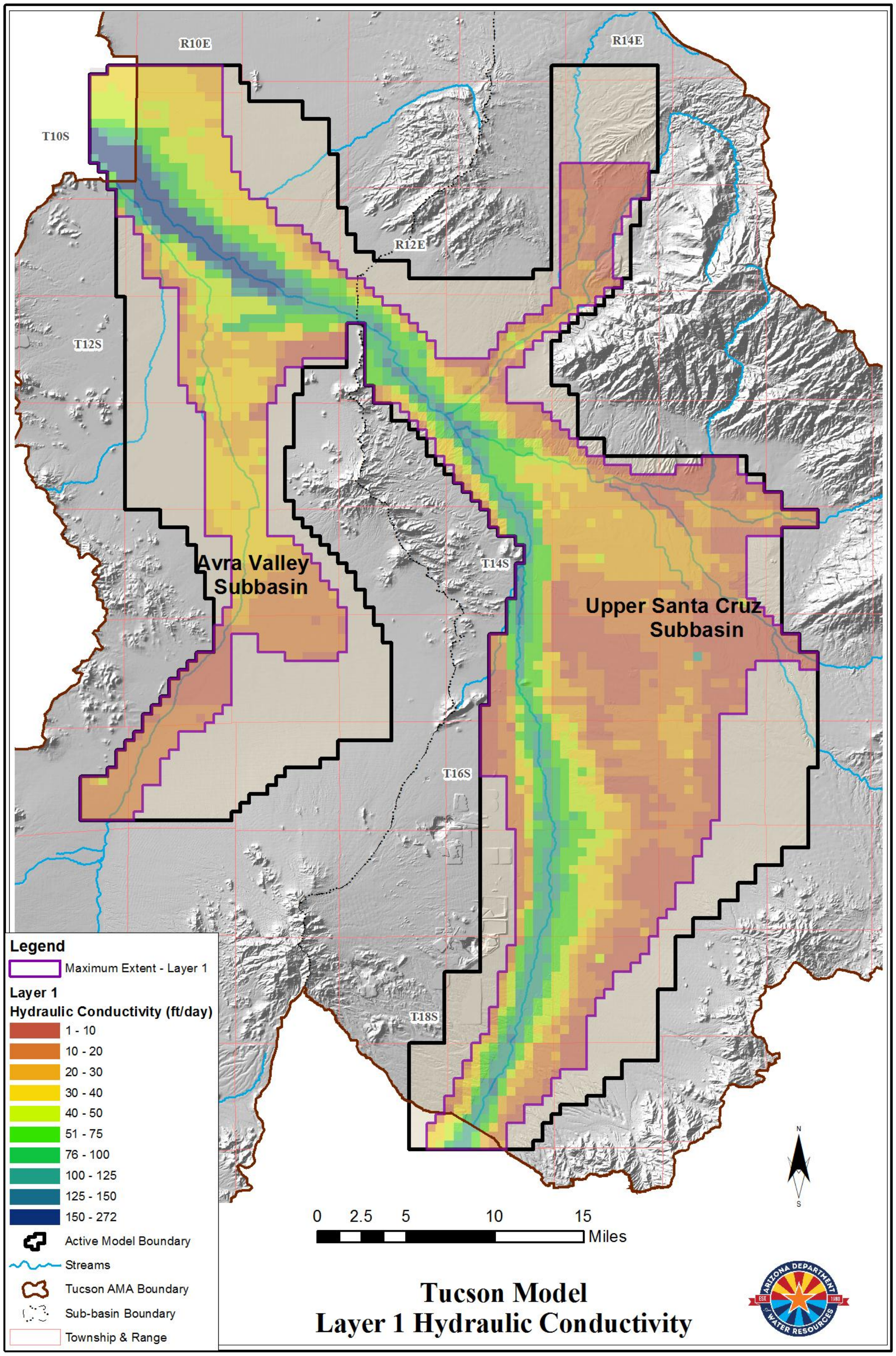


Figure 14. Hydraulic conductivity distribution of model layer 1, Tucson model area.

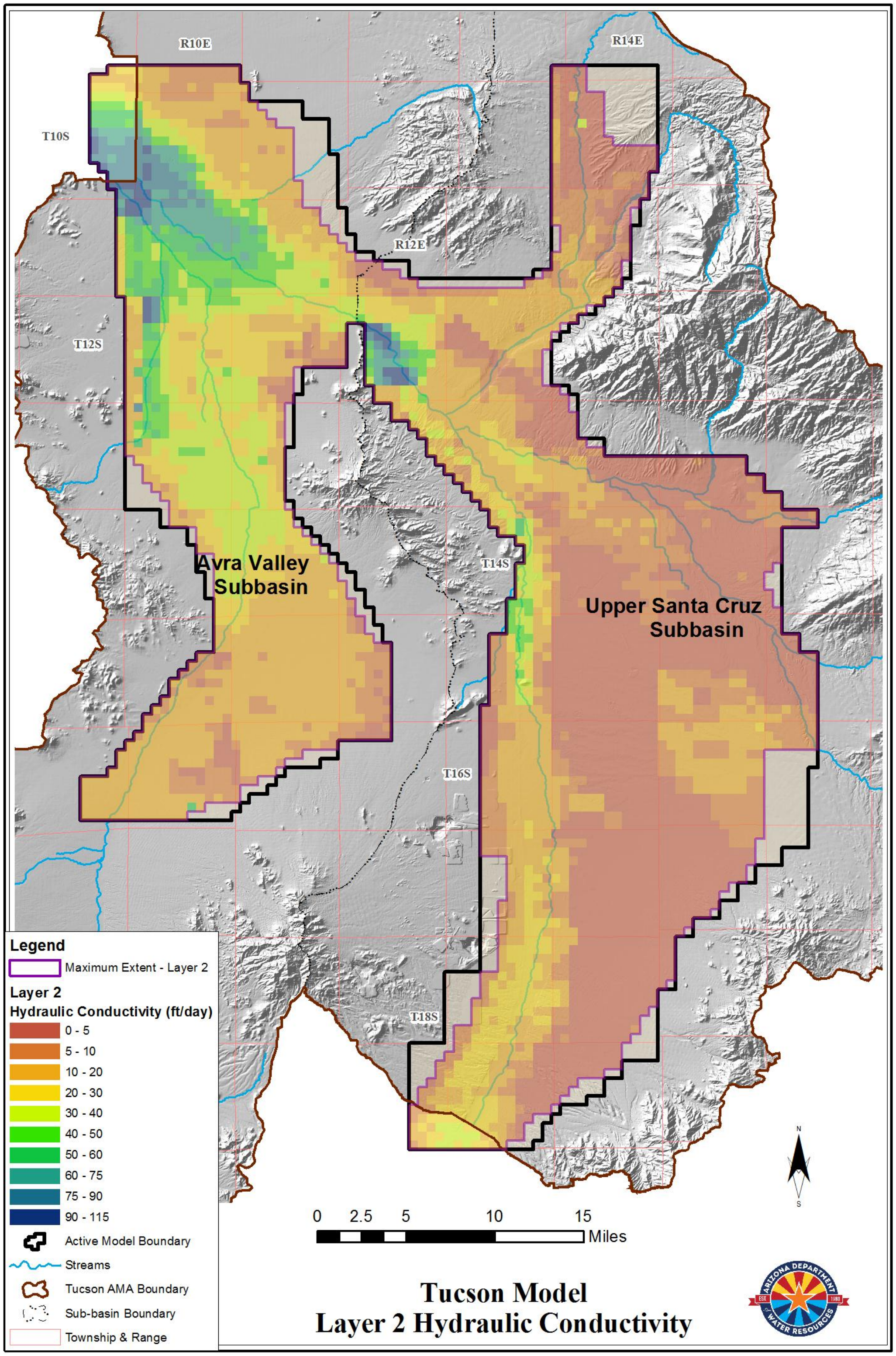


Figure 15. Hydraulic conductivity distribution of model layer 2, Tucson model area.

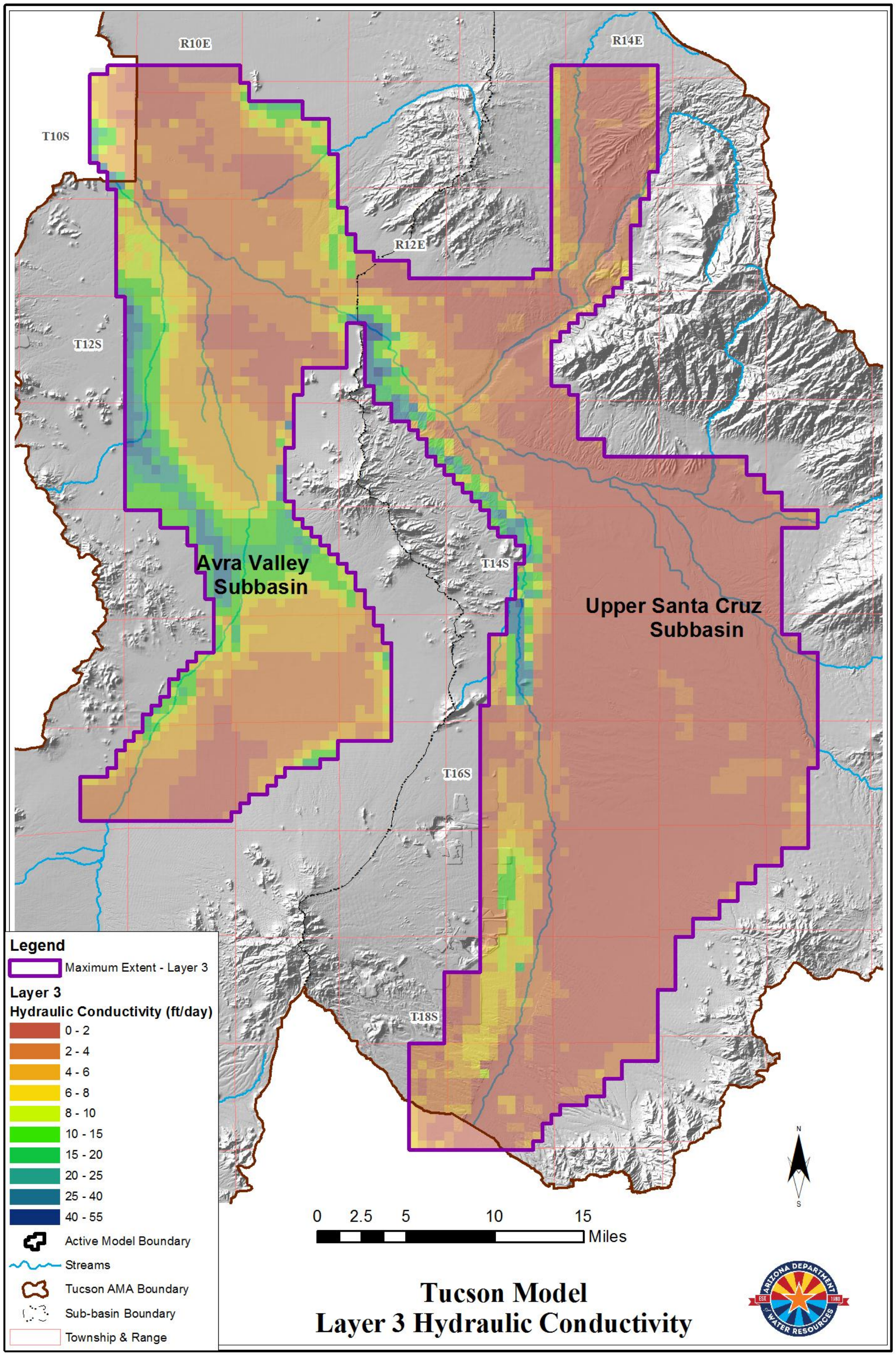


Figure 16. Hydraulic conductivity distribution of model layer 3, Tucson model area.

Robles Wash, Rillito Creek, Tanque Verde Creek, Canada del Oro and Big Wash, Sabino Creek, Agua Caliente Wash, Rincon Creek and Pantano Wash. The annualized recharge was applied to model cells along stream segments located between USGS stream gages using the recharge (RCH) package (Figure 6).

Avra Valley Sub-basin Stream Recharge

The main drainage system for the Avra Valley sub-basin consists of Avra, Brawley, and Los Robles Washes (Figure 6A). The stream channel is called Altar Wash south of Township 15 South, and between there and about Township 11 South the channel is called Brawley Wash. North from Township 11 South to its confluence with the Santa Cruz River the channel is referred to as Los Robles Wash.

Stream flow gauging data for the Brawley Wash system only partially covers the model time period of 1940-2010. The Altar Wash gage (09486800) is located outside the model, approximately 10.8 miles south of the model boundary, and the Brawley Wash near Three Points, Arizona gage (09487000) is located about 6.3 miles north of the model's southern boundary (Figure 6A). The Altar Wash gage has daily flow records from 1967 to 1975 and from 1992 to 2010, the Brawley Wash gage has a shorter record of daily flows dating from 1992 to 2010 (Appendix A).

The available flow data indicates that the Brawley Wash system is dominated by localized, short-duration, summer monsoon flows occurring mostly in July, August, and September. Occasional long duration flows from cyclonic events or winter frontal storms create the longest flows, usually from September to March. There are numerous years with either no significant flows or only small, local flows of very short duration in the flow record.

The initial annual stream infiltration values were calculated using a combination of existing flow data and precipitation data from the Desert Research Institute's (DRI) Western Regional Climate Center (Desert Research Institute, 2010). Precipitation data were used to estimate potential flows into the model along Brawley Wash for 1940 to 1965 and from 1976 to 1993, flow data at the Altar Wash gage were used to estimate potential flows for 1966 to 1975, and measured flow data from Brawley Wash were used from to estimate flows 1993 to 2010.

The DRI precipitation station at Anvil Ranch, located about 1 mile south of the model boundary, has a precipitation record that runs from 1943 to the present (Figure 6A). Regression analysis was used that compared annual precipitation at Anvil Ranch with measured flows at the Brawley Wash gage from 1993 to 2010. The results of the regression analysis were used to construct estimated annual synthetic flow values for 1940 to 1965 and from 1976 to 1993, time periods when there are no flow records for either the Altar or Brawley Wash gages. Regression analysis was also used to compare the flow records at the Brawley Wash and Altar Wash gages from 1993 to 2010, times when both gages had flow records. The results of the regression analysis were used to estimate flow volumes entering the model for the period from 1966 to

1975, a period when the Altar gage was active, but before the Brawley Wash gage was operational. Measured flow data from the Brawley Wash gage were used to estimate stream infiltration values for 1993 to 2010. Several extreme flow events that are not included in the measured flow record were identifiable in the precipitation record. The dates of these events correlate with information that identified major flood events related to tropical cyclones in a report by Roeske and others (1989).

Analysis of peak flow data for the Altar, Brawley, and Los Robles gages suggest that flows at the Brawley Wash gage rarely, if ever, pass completely through to the confluence of Los Robles Wash and the Santa Cruz River, and that only the very largest flow events pass through the system. The estimated annual cell-specific infiltration volumes for Brawley Wash were assigned in a linear decreasing rate based on the length of streambed in each cell. The result of this method is that only the largest flow events supplied recharge to the aquifer from the model boundary to the confluence with the Santa Cruz River.

Upper Santa Cruz sub-basin Stream Recharge

The Santa Cruz River and Rillito-Tanque Verde Creeks are the major drainages in the Upper Santa Cruz sub-basin (Figure 6A). The Santa Cruz River and its tributary washes drain most of the central and southern areas of the sub-basin. The Rillito-Tanque Verde Creek system drains the eastern part of Upper Santa Cruz sub-basin, including the Santa Catalina, Tanque Verde, and Rincon Mountains (Figure 6B). Tributaries to this system include Agua Caliente Wash, Sabino Creek, Ventana Canyon Wash, Pantano Wash and Rincon Creek. The Big Wash-Canada del Oro (CDO) system drains the northern part of the model and enters the Santa Cruz River near Marana (Figure 6A).

The annual cell-specific stream recharge values were calculated for each segment using Burkham’s formula, the coefficient value for the segment, and the measured or synthetic flow past the gage. Finally, cell-specific recharge was calculated based on the length of streambed in each cell and the segment’s total estimated recharge volume.

The Santa Cruz River has 5 stream gage sites within the model area (Figure 6A). As shown in Table 2 three of the gages along the Santa Cruz River have long periods of record. The stream gage data from all the gages show that the Santa Cruz River has a very strong summer monsoonal flow signature with about 70 percent of annual flows occurring during July, August and September (Appendix A). The Santa Cruz River was divided into four segments in order to distribute stream infiltration along its length. From the southern model boundary to the gage at Continental (09482000), Continental gage to the Tucson gage (09482500), Tucson gage to the Cortaro gage (09486500), and Cortaro gage to the northern model boundary.

The estimated stream recharge for the first Santa Cruz River segment, from the southern model boundary to Continental, was calculated using a per mile version of Burkham’s infiltration relationship for the segment from the Continental gage to the Tucson gage and annual flow data at the Continental gage (see discussion below). This method was deemed appropriate because the streambed material between the model boundary and the Continental gage is generally similar to the material downstream from the Continental gage.

The second segment, Continental gage to the Tucson gage, corresponded to Burkham's Reach 1. The annual stream recharge for this segment was calculated using equation 1 with a coefficient variable (**C**) of 1.6. The Continental gage is missing 10 years of flow data during the model calibration period; 1947 - 1950 and 1985 - 1990. For these years the median of the annual median flow, 8.2 cubic feet per second (cfs), was used to estimate the annual infiltration.

The third Santa Cruz River segment, from the Tucson gage to the Cortaro gage, corresponded to Burkham's Reach 7 and was assigned a **C** value of 1.4. The annual cell-specific infiltration was calculated using equation 1 with 1.4 for the coefficient (**C**) value. To estimate flows for periods when there was no gage data, a relationship between flow at the Tucson and Continental gages was developed. The relationship was used to estimate flows at the Tucson gage for years when Continental had flow data and Tucson had no flow data. For those years when there were no flow data at either the Continental or Tucson gages, the long-term median of the annual flow for Tucson, 14 cfs, was used to estimate the annual infiltration. Since 1970, effluent releases from the Ina Road and Rogers Road WWTPs have affected flow in this segment downstream from the discharge points (Figure 6A). Infiltration of effluent was assigned to cells between the WWTP outfalls and the Cortaro gage as described below in the section on incidental recharge

The fourth Santa Cruz River segment, from the Cortaro gage to the northwestern model boundary has been impacted by effluent releases from the WWTPs (Figure 6A). Prior to the early 1970s, stream flows past the Cortaro gage was flashy with many periods of no flow. The mean monthly flows from 1939 to 1969 peaked in the summer and were generally 10 cfs or less the rest of the year (Appendix A). Mean monthly flows from 1970 to 2010 still peak in the summer, but all the non-summer monthly means are greater than 40 cfs (Appendix A). This illustrates the impact of the WWTP releases on the flow regime past the gage. Effluent below the Cortaro gage was not simulated separately, but included as the total flow past the gage. Annual infiltration from the Cortaro gage to the model's northwestern boundary was calculated using equation 1 with a **C** value of 1.4.

The Rillito-Tanque Verde Creek system has nine stream gages that were evaluated to determine simulated flows (Figure 6B). Tanque Verde Creek and Rillito Creek have five gages, Pantano Wash has three gages, and Rincon Creek one gage. The system has a biannual flow distribution, with a dominate winter flow regime from December to March, and a fairly well defined summer monsoon flow signature. The one exception to this biannual distribution is Pantano Wash, which has a strong summer flow regime and a very weak winter flow signature (Appendix A).

The Rincon Creek stream gage is located outside the model area and only about 3.5 miles of the streambed is in the model domain. The stream gage data begins in 1952 and runs to 2010, with a 14 year break from 1974 to 1988. Precipitation data from the DRI precipitation station located at Lazy H Ranch, along Rincon Creek, was used to generate estimated stream flow for years when there were no measured flow data (Figure 6B). Annual infiltration for the Rincon Creek gage was calculated using equation 1 with a **C** value of 2.5, reflecting a high amount of infiltration along the upper part of the creek where it enters the model domain. Recharge was applied to cells in the 3.5 miles along Rincon Creek above its confluence with Pantano Wash (Figure 6b).

Pantano Wash has three stream gage stations along its length (Figure 6B). Only the Vail gage (09484600) has a long record; 1959 to 1974 and 1989 to 2010. The Pantano Wash near Tucson gage (09485500) has a very fragmentary record, and the Pantano Wash at Broadway Boulevard gage (09485450) has data from 1998 to 2012. Pantano was divided into two segments, from the Vail gage (09484600) to the confluence with Rincon Creek and from the Pantano Wash-Rincon Creek confluence to the confluence of Pantano Wash with Tanque Verde Creek (Figure 6B). The daily flows at the Vail gage and precipitation data from a DRI precipitation station near Vail, Arizona were used to calculate the annual infiltration for the first section (Figure 6B). The second section, from the Pantano-Rincon confluence to Rillito Creek, used flow data from the Pantano Wash at Broadway Boulevard (09485450) to calculate recharge from 1998 to 2010. Flows from 1940 to 1997 were assigned based on a regression relationship between flows at Vail (09484600) and at Pantano Wash at Broadway Boulevard (09485450). Annual infiltration for the two segments of Pantano Wash was calculated with a **C** value of 2.4. During calibration more recharge was applied to the upper section of segment 1, generally above its confluence with Rincon Creek. This was done to reflect high infiltration rates along the upper part of the creek where it enters the model domain (Burkham, 1970).

Tanque Verde and Rillito Creeks were treated as one system and divided into three segments (Figure 6B). The first segment was from the Tanque Verde near Tucson gage (09483100), located outside the model, to the Tanque Verde at Tucson gage (09484500). The second segment was from the Tanque Verde at Tucson gage to the Rillito Creek near Tucson gage (09485850). The last segment ran from the Rillito Creek near Tucson gage to the confluence of Rillito Creek with the Santa Cruz River. The Rillito Creek near Tucson gage (09485850) has the longest continuous record; 1914 to 1983. The other Rillito Creek gages have only been active since 1988. The Tanque Verde Creek gages have mixed records, with Tanque Verde at Tucson gage (09484500) having the longest record. The daily flow records for the gages and precipitation data from DRI precipitation stations for the University of Arizona, the Tucson Magnetic Observatory, and Sabino Creek, Arizona were used to calculate the synthetic annual recharge values for the three segments (Figure 6B). Annual infiltration for the first segment was calculated on a per mile basis within the model area using a **C** value of 1.8 per length of channel. The second segment used a **C** value of 1.7 and the third segment a **C** value of 1.4.

The Big Wash-Canada del Oro (CDO) system drains the northern part of the model and enters the Santa Cruz River near Marana (Figure 6B). The CDO system has a summer dominant flow regime, but mean monthly flow rates recorded at gages are low indicating that very few flows make it through the system to the gauging sites, which are located close to the CDOs confluence with the Santa Cruz River (Figure 6B). Due to the spotty record of gage data Big Wash and the Canada del Oro were treated as two separate segments. The long-term average recharge from the previous model was used as the initial recharge values for both segments. Precipitation data from DRI the precipitation stations for the University of Arizona and Sabino Creek were used to either increase or decrease the annual values depending on whether the annual precipitation was above or below the long-term average. During calibration more recharge was applied to the upper section of CDO to reflect high infiltration rates along the upper part of the creek near the mountain fronts. Local water levels and hydrograph data along both Big Wash and the CDO were also used to guide how much recharge was applied along the Big Wash and the CDO segment.

3.2.2 Incidental Recharge

Incidental recharge was simulated through the MODFLOW recharge package. Incidental recharge is water that recharges the TAMA regional aquifer during the course of human use. Sources of incidental recharge include agricultural, industrial, and municipal sources. Currently the largest source of incidental recharge is from CAP surface water recharged at artificial recharge facilities. Other sources include recharge from excess water applied to agricultural fields, water from seepage through mine tailing ponds, effluent released into the Santa Cruz River, and effluent used to irrigate parks, cemeteries, and golf courses. The locations of incidental recharge simulated in this report are shown in Figure 17.

<u>*Agricultural Recharge*</u>

Agricultural (Ag) recharge is the result of the excess water that is applied to crops that is not used by the crop, or evaporated. The difficultly in modeling agricultural recharge is three fold, estimating the volume of water that is recharged, the distribution of the recharge, and how long it takes water to reach the water table, the lag time. ADWR Modeling Report No. 13 (Mason and Bota, 2006) provided a detailed account of the data and methodology used to determine the initial agricultural recharge simulated in the model.

Besides being updated through 2010, the method of lagging the agricultural recharge was modified to reflect the change in water level elevations beneath Ag lands through time. The new method calculated the time lag per cell, the time it would take for the recharge water to travel to the water table, every five years starting in 1940. For each succeeding five years, a new lag time was calculated based on the corresponding depth to water and assigned to cells with Ag recharge for the next five stress periods. The lag was calculated and assigned in two steps. First, the depth to water for cells in the Ag areas was determined using measured water levels and a lag

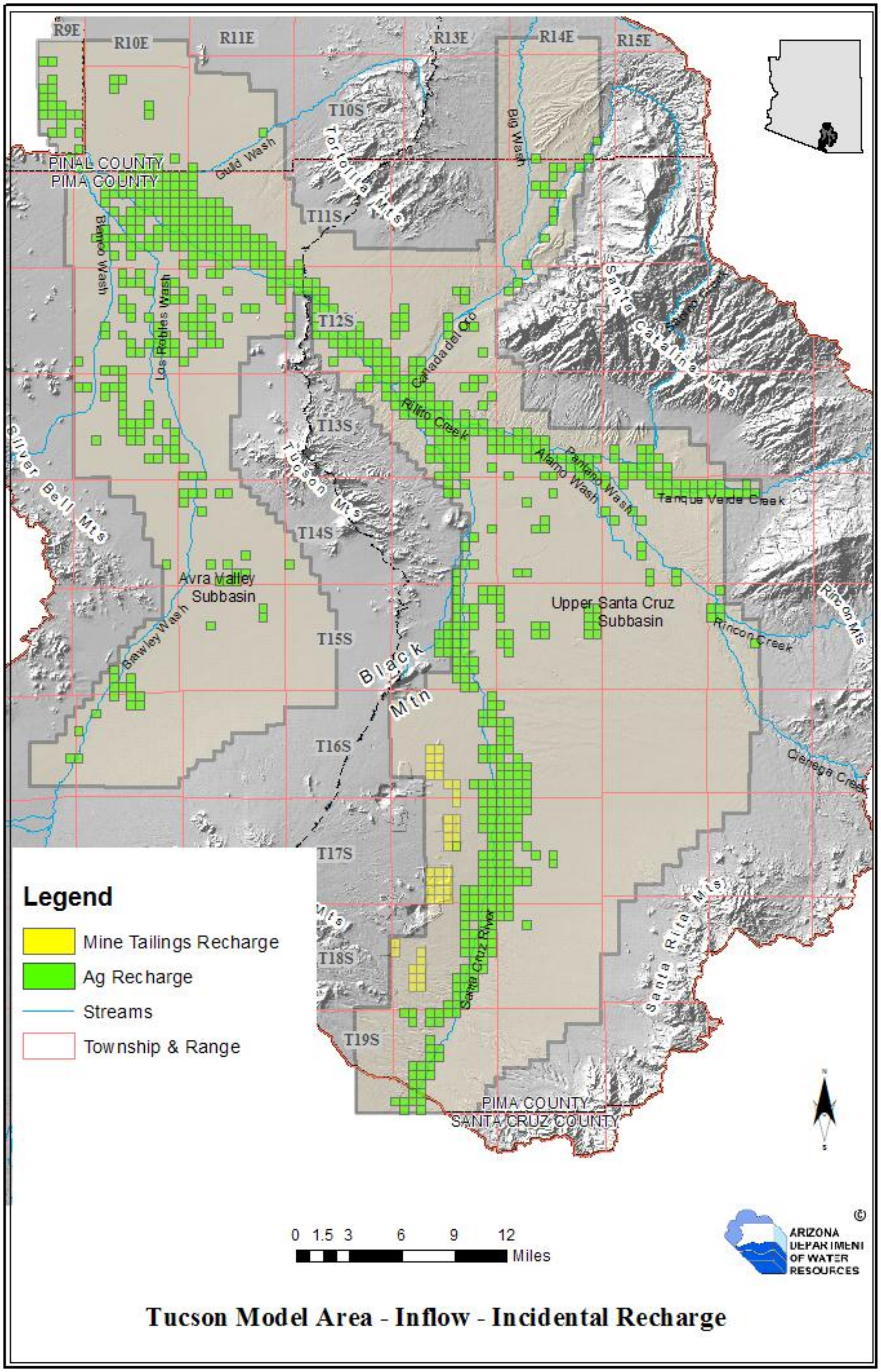


Figure 17. Incidental recharge locations, Tucson model area.

time was calculated for each cell based on an assumed travel rate. In the second step, the lag time was added to the pumping year and the maximum calculated recharge was added to the recharge database for the updated year. The volume and timing of irrigation recharge were model components adjusted during the model calibration process.

The agricultural recharge locations depicted in Figure 17 indicate where Ag recharge has occurred during the period 1940 to 2010. Some of the areas might not currently be receiving Ag recharge because they are out of production or urbanized. However, at some point between the years 1940 to 2010 there was agriculture in the model cell.

Effluent Recharge

Effluent has been released into the Santa Cruz River in large quantities from WWTPs since 1969. The total infiltration along the Santa Cruz River below the WWTPs comes from a combination of both natural flows and flows from effluent releases. As discussed in earlier in this section, effluent releases have influenced the flow past the Cortaro gage (09486500) since 1970. Effluent released into the Santa Cruz River was distributed into cells with stream segments located downstream from the WWTPs and above the Cortaro gage (09486500) (Figure 6B). Initial estimates of effluent infiltration were based on values developed from an effluent infiltration study by Galyean (1996). Downstream from the Cortaro gage effluent infiltration is not specifically simulated, but is included as part of the total flow past the gage (see Section 3.2.1 Stream Flow Recharge). Prior to about 1978, most of the effluent released into the river is believed to have infiltrated inside the Tucson AMA. After 1978, a percentage of the effluent is believed to exit the model area as surface water flows. Figure 18 shows the annual effluent released to the river for 1950 to 2010. Combined effluent releases from the Ina and Rogers Road Wastewater Treatment Plants have averaged 53,600 ac-ft. per year during the model update period of 2000-2010.

Artificial Recharge

Recharge at USFs started in the TAMA in 1989 with the recharge of effluent at several facilities. The volume of effluent recharged at USFs has grown in the recent years; but as shown in comparing Figure 19 and Figure 20, the amount of effluent recharge is small compared to the amount of CAP surface water that is recharged. Artificial recharge of CAP surface water at USFs began in the TAMA in 1996, and between 1996 and 1999 about 64,525 ac-ft. of CAP was stored (Figure 19). During update period for this report, from 2000-2010, CAP surface water storage increased dramatically and about 1.39 million ac-ft. of water has been recharged at USFs (Figure 19). An additional 141,200 ac-ft. of CAP surface water has been supplied to GSFs for direct use in lieu of groundwater withdrawals (Figure 20). Tables 3 and 4 list the currently permitted USFs and GSFs and the type of water they recharge. The location of the USF and GSF facilities are shown in Figure 7.

Artificial recharge at USF's was simulated in the model using the Recharge Package. A relatively quick response of local water level elevation to the recharged water has been observed at the constructed USF facilities. To match this response the artificial recharge was lagged over a three year period with 30 percent applied the first year, 40 percent the second year, and 30 percent the third year. This lagging scenario generally produced simulated water levels that matched observed water levels in observation wells near the USFs (see Hydrographs AV-15, AV-16, and AV-17 in Appendix E).

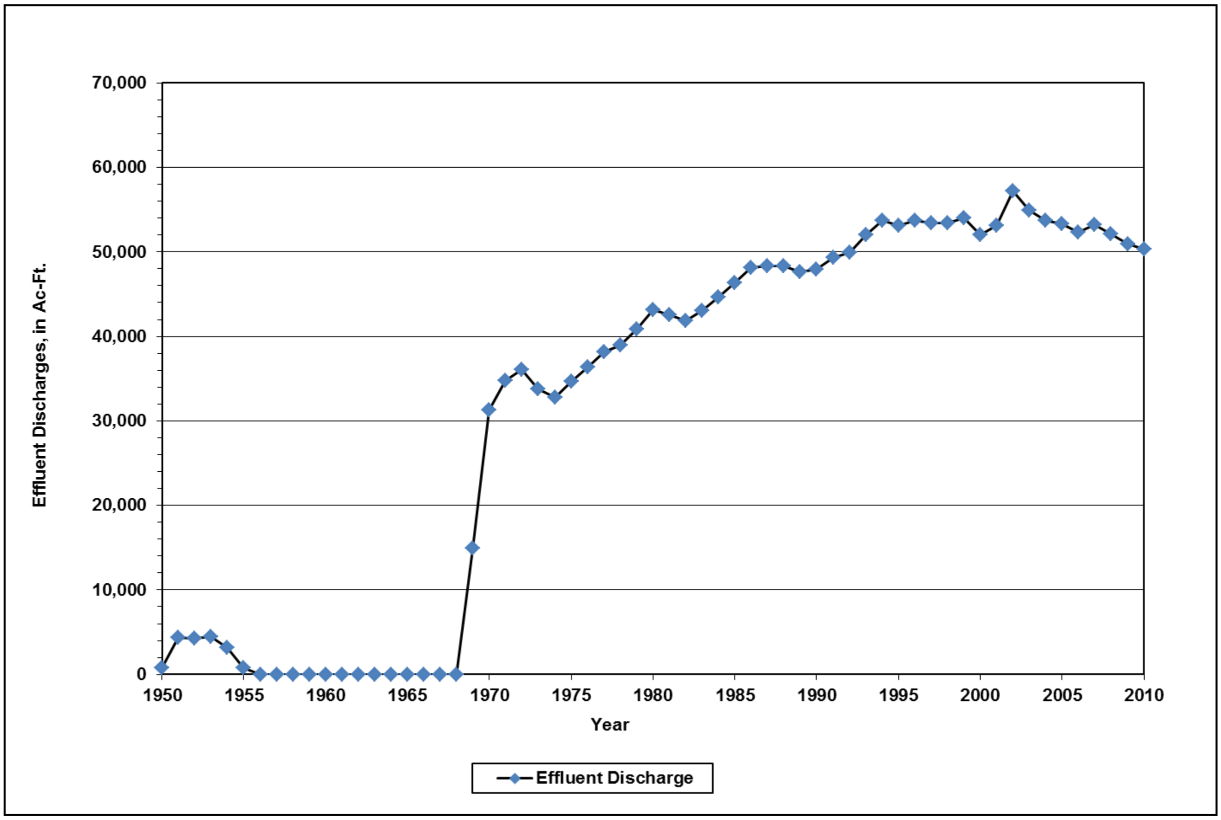


Figure 18. Annual effluent releases into the Santa Cruz River: 1950-2010.

Mine Tailings Pond Recharge

Seepage from tailing ponds for Freeport-McMoran's (formerly Phelps-Dodge) Sierrita and Esperanza mines, the Park Corporation's (formerly ANAMAX) Twin Buttes mine, and Asarco Groupo Mexico's Mission mine is simulated in the model. Estimates of tailings pond recharge locations and volumes for the Sierrita, Esperanza, and Twin Buttes mine were obtained from reports provided by Montgomery and Associates (Montgomery and Associates, 2009). Seepage for the Mission mine was estimated based on reported annual pumping volumes and the reported water applied to the tailings ponds for the other mine operations. Appendix B contains the estimated annual recharge from the tailings ponds from Montgomery report and Associates

(1999) that were used in this report; and the location of the tailing pond recharge is presented in Figure 17. The tailings pond recharge was lagged over a three year period with 30 percent applied the first year, 40 percent the second year, and 30 percent the third year. This lagging scenario generally produced simulated water levels that were comparable to observed water levels.

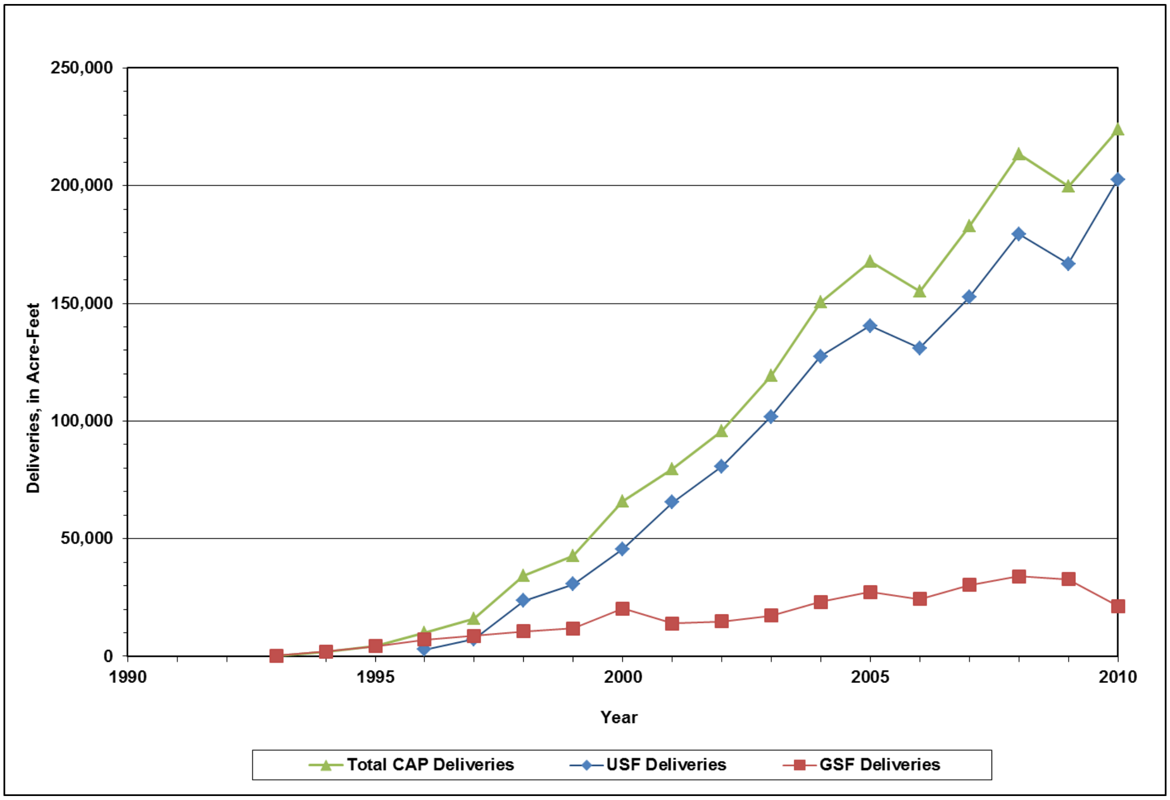


Figure 19. CAP surface water deliveries to the Tucson AMA: 1990-2010.

3.2.3 Mountain Front Recharge

The initial mountain-front recharge distribution was simulated along seven separate mountain fronts (Table 7). The cell-specific distribution was similar to the distribution developed by Mason and Bota (2006) and was adjusted slightly in several areas to match changes to the active model domain (Figure 21). The annual volume of mountain-front recharge held constant during both the steady-state and transient periods and totaled 27,775 ac-ft/yr.

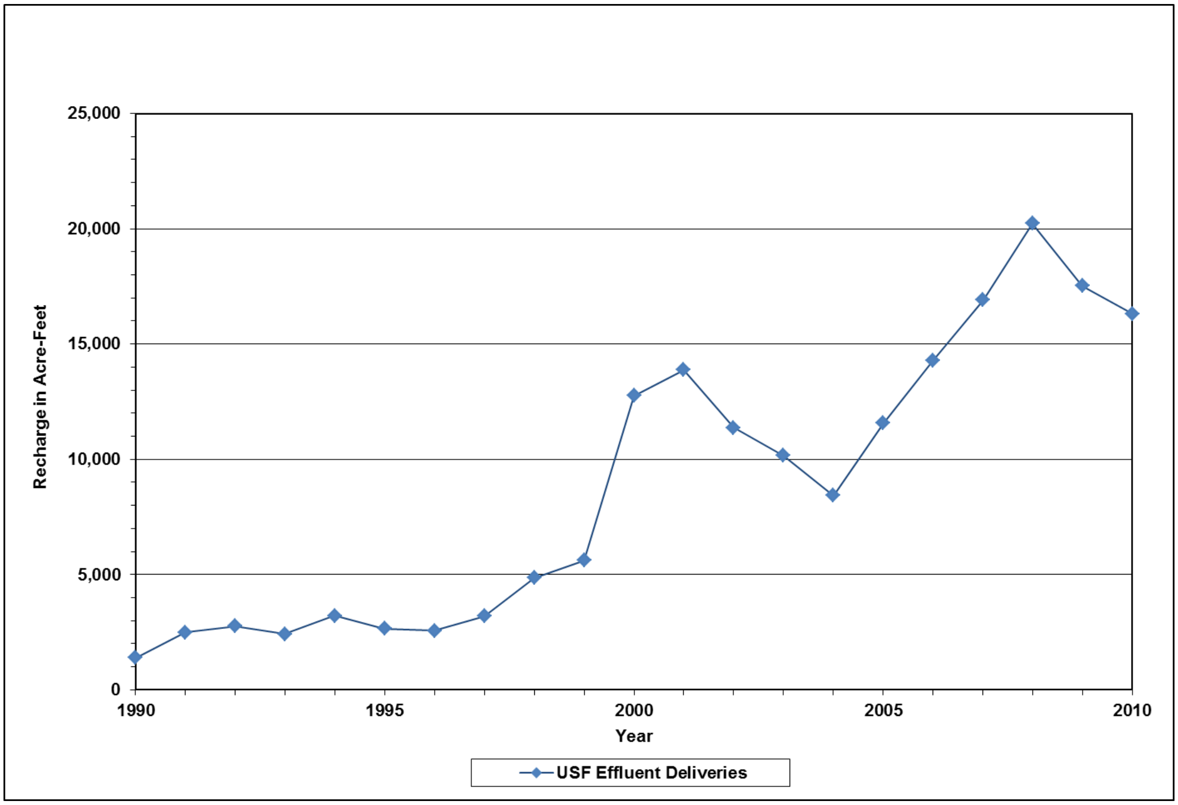


Figure 20. Effluent recharge at USFs in the Tucson Model Area.

3.2.4 Groundwater Underflow

As previously discussed, groundwater underflow both enters and exits the TAMA regional aquifer (Figure 21). Water levels in wells near the Altar Valley – Avra Valley model boundary were generally stable during the model simulation period; therefore, the flux across this boundary was held constant for the entire model simulation using specified fluxes in the well package (Figure 21). Groundwater flux into the model from Falcon Valley, at the northern head of the Big Wash drainage, was also simulated as a long-time constant during the model simulation. The calibrated groundwater flux into the model for Altar Valley – Avra Valley and Falcon Valley was 10,200 and 70 ac-ft/yr, respectively.

Groundwater underflow across the SCAMA – TAMA and TAMA – PAMA boundaries was simulated using the Time-Variant Specified-Head (CHD) Package. The CHD package allows the flux across a boundary to change based on an assigned head, the cell conductance and the simulated heads of variable-head cells near the boundary. This allows the flux across a boundary to change over the transient period as heads change within the model. The specified heads in the CHD package were assigned based on hand-contoured water levels and examination of hydrographs from wells near the model boundary.

Table 5. Underground Storage Facilities in (USFs) the Tucson Model Study Area.

USF Right Number	USF Permittee	USF Name	USF Type	Type of Water Recharged
71-564896	CAWCD	Avra Valley Airport USF	Constructed	CAP
71-578806	Tucson Water	Clearwater (CAVSRP)	Constructed	CAP
71-561366	Pima County FCD / CAWCD	LSCRP-Constructed	Constructed	CAP
71-211276	Tucson Water	SAVSARP	Constructed	CAP
71-577501	CAWCD	Pima Mine Rd	Constructed	CAP
*	BOR	Arroyos	Managed	CAP
71-563876	Pima County FCD / Town of Marana	Marana High Plains	Constructed	Surface water & Effluent
71-211284	Pima County RWRD	Corona De Tucson	Constructed	Effluent
71-581379	Robson Ranch Quail Creek, LLC	Quail Creek-Robson Ranch	Constructed	Effluent
71-595209	Town of Sahuarita	Sahuarita WWTP	Constructed	Effluent
71-520083	Tucson Water	Santa Cruz-Sweetwater	Constructed	Effluent
71-591928	City of Tucson, Marana, CMID, AVIDD, Pima County, et al	Lower Santa Cruz Managed	Managed	Effluent

* The Arroyos Recharge and Recovery is a Bureau of Reclamation project on The San Xavier Indian District and is not permitted through ADWR.

Table 6. Groundwater Saving Facilities (GFSs) in the Tucson Model Study Area.

GSF Right Number	GSF Permittee	GSF Name	Type of Water Recharged
72-5831332	BK Farms - CAWCD	BKW- Tucson	CAP
72-563502	BKW Farms	BKW-Milewide	CAP
72-538100	Cortaro Marana Irrigation District	Cortaro Marana Irrigation District	CAP
72-558092*	Kai Farms	Kai Farms Red Rocks	CAP

* The Kai Farms Red Rocks GSF is just outside of the present model boundaries.

Table 7. Mountain Front Recharge Summary – Tucson Model

Location	Recharge Flux (ac-ft/yr)
Tortollita Mountains	3,700
Santa Catalina Mountains	7,960
Tanque Verde Mountains	1,720
Rincon Mountains	1,400
Santa Rita Mountains	7,290
Sierrita Mountains	4,060
Tucson Mountains	458
Silver Bell Mountains	575
Roskruge Mountains	612
Total	27,775

The flux into the TAMA from the Santa Cruz AMA is believed to have increased since the 1940s (Nelson, 2007). The increasing inflows reflect an increasing water table gradient along the boundary caused by generally stable water levels in the northern part of the SCAMA and declining water levels due to groundwater withdrawals in the southern area of the TAMA. Water levels have remained generally stable in the northern part of the SCAMA due, in part, to regular releases of effluent into the Santa Cruz River. Treated effluent has been released into the Santa Cruz River or its tributaries by the Nogales International Wastewater Treatment Plant (NIWWTP). Nogales, Arizona and Nogales, Sonora, Mexico released sewage effluent into the Santa Cruz River or its tributaries beginning in the early 1950s (ADWR, 1999b). The NIWWTP has been treating sewage from the twin cities of Nogales, Arizona and Nogales, Sonora and releasing it into the Santa Cruz River since 1972 (ADWR, 1999b). This steady source of water has generally stabilized water levels in the area between the NIWWTP and the SCAMA – TAMA boundary since the mid-1970s (Nelson and Erwin, 2001).

Mason and Bota (2006) simulated the expected increase in underflow into the TAMA, increasing from about 11,000 ac-ft/yr in 1940 to almost 25,000 ac-ft/yr in 1999. The 1999, inflow value is very similar to the outflow from a groundwater flow model developed for the northern portion of the SCAMA by the Nelson (2006). Results from that model indicate a groundwater flux across the SCAMA – TAMA boundary for the quasi-steady-state period for 1997 to 2002 of approximately 22,000 ac-ft/yr (Nelson, 2006).

Groundwater flux out of the model across the TAMA – PAMA boundary was also simulated using the CHD Package (Figure 22). Groundwater flux out of the model across this boundary was estimated to decline during the 1950s, 1960s, and 1970s, during a time of wide-spread water level declines in the northern Avra Valley. Figure 8 shows the water level decline and recovery of a well located adjacent to the TAMA – PAMA boundary. As water levels began

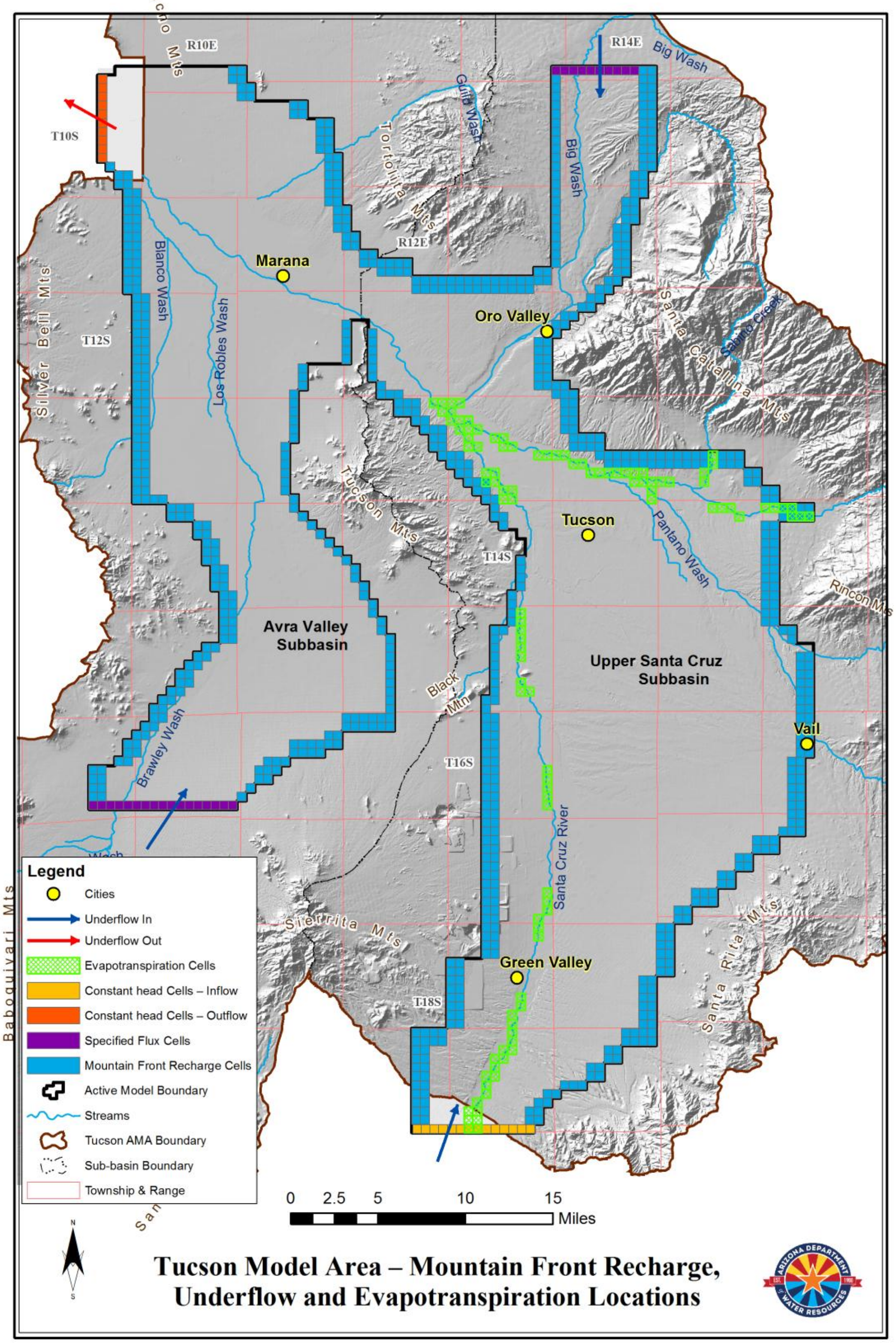


Figure 21. Underflow, ET, and Natural Recharge Locations in the Tucson Model Area.

recovering in the mid-1970s, groundwater underflow was expected to begin increasing as the saturated thickness of the aquifer at the model boundary increased.

3.2.5 Groundwater Withdrawals

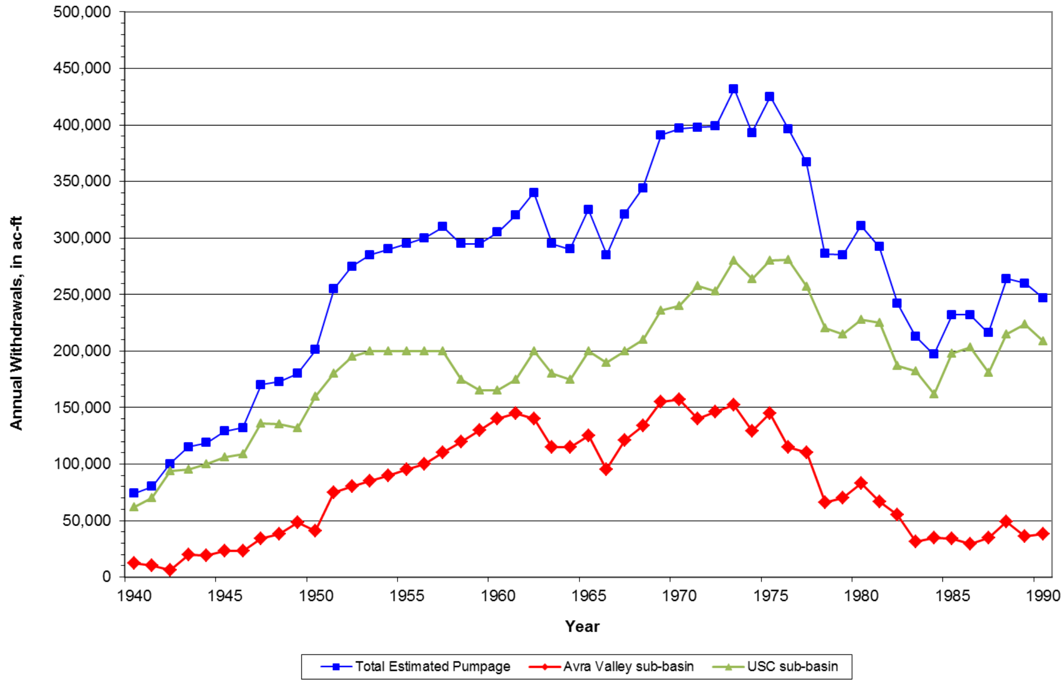
Groundwater withdrawals were not well known prior to about 1960. From about 1960 to 1983, the amount and location of groundwater withdrawals are better known due to better record keeping by many of the large municipal and agricultural entities. The adoption of the GMA in 1980 and its' requirement for reporting well-specific pumpage to the ADWR's Registry of Groundwater Right (ROGR) data base provides withdrawal volumes and locations for the last 26 years of the model simulation period (1984-2010).

Estimates of groundwater withdrawals in the TAMA increased steadily from the 1940s and peaked in the mid-1970s at almost 435,000 ac-ft/yr (Figure 21: Anning and Duet, 1994). Overall withdrawals generally decreased from the late-1970s through the mid-1990s. Since 1990 the average annual withdrawals in the Tucson AMA has been slightly more than 300,000 ac-ft/yr (ADWR, 2010).

Mason and Bota (2006) developed estimates of withdrawal volumes and locations for the TAMA area from 1940 to 1983. These volumes and distribution were used as initial values for this report. Groundwater withdrawals for this report were updated for 2000 to 2010 from the ADWR ROGR database. Some 1984 to 2000 withdrawals were altered to reflect revised withdrawal reports filed with the ADWR. Groundwater withdrawals prior to 1984 were also updated with additional historic water company data obtained from the Arizona Corporation Commission, crop census data from the University of Arizona, and a detailed analysis of historical well construction records from the ADWR Well Registry and the State Land Department's old well registry file, referred to as the 35 File. This additional research resulted in an improved distribution of historic water company and agricultural withdrawals.

The vertical distribution of the pumpage was assigned using one of the following three methods: 1) based on the transmissivity of the layer if well depth and well perforated interval data was available, 2) based on transmissivity and well depth if perforation data was not available and finally 3) based on average well depth in the area if the specific well depth was not known. The WEL package was used to simulate pumpage from each well per model layer based on the methods cited above. When necessary to maintain simulated withdrawal volumes, model pumpage wwas reset to deeper model layers when cells went dry. The distribution of pumping in 1940 (Figure 23) compared to the 2010 distribution (Figure 24) provides a visual representation of how the groundwater withdrawals have increased with time both in volume and spatially.

The model layer definitions were designed to place the most productive sedimentary units in the TAMA regional aquifer system into model layers 1 and 2. Most of the high-capacity production wells are less than 1,000 feet deep, and based on known well depths and model layer geometry most model simulated pumpage was assigned to layers 1 and 2. Layer 1 has been



1) Source: Anning and Duet, 1994

Figure 22. Estimated withdrawals in the Upper Santa Cruz and Avra Valley sub-basins.

dewatered in many areas of the TAMA due to historic groundwater development. As a result, layer 2 has become a more important source of groundwater in these areas. In the southern portions of Avra Valley sub-basin groundwater has been withdrawn from layer 2 because the regional water table lies below the bottom of layer 1. Pumpage from layer 3 generally produces small to moderate amounts of water; however, along the basin margins where layers 1 and 2 have small saturated thicknesses or are unsaturated layer 3 is an important source of groundwater.

3.2.6 Evapotranspiration

The location and rate of ET simulated for the USC sub-basin remained the same in this report as in Mason and Bota (2006). As with the previous model, water levels in the Avra Valley sub-basin are generally too deep to support riparian vegetation so all ET was assigned to the USC sub-basin (Figure 21).

The ET input estimates, both the spatial locations and rates, were held constant for both the steady-state and the transient model simulation. Simulated ET was estimated to decline through the transient simulation, reflecting both the long-term water-level declines experienced in the USC sub-basin and urbanization activities along the Santa Cruz River and its tributaries.

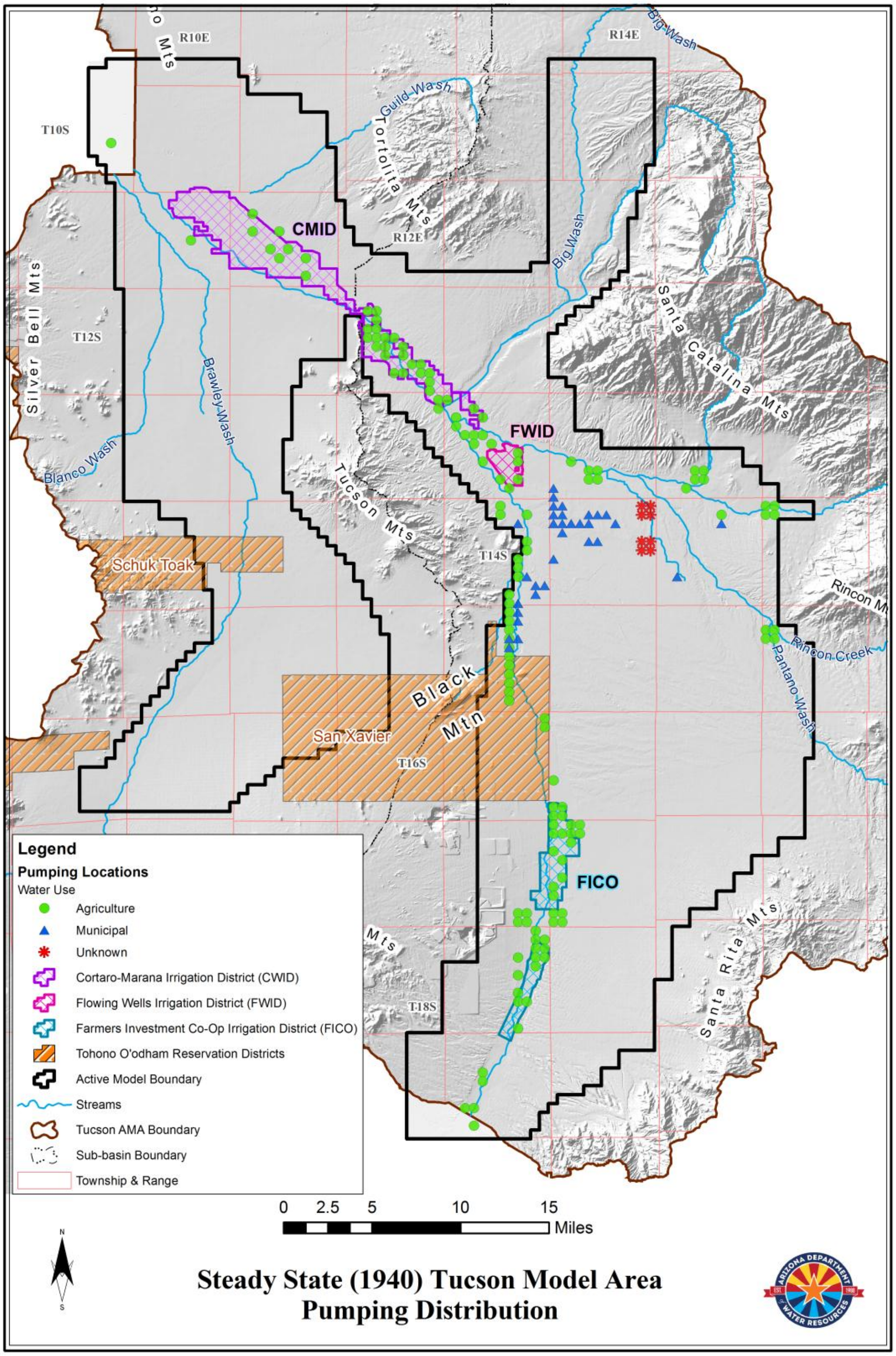


Figure 23. Steady-State Pumping Distribution - Tucson Model Area

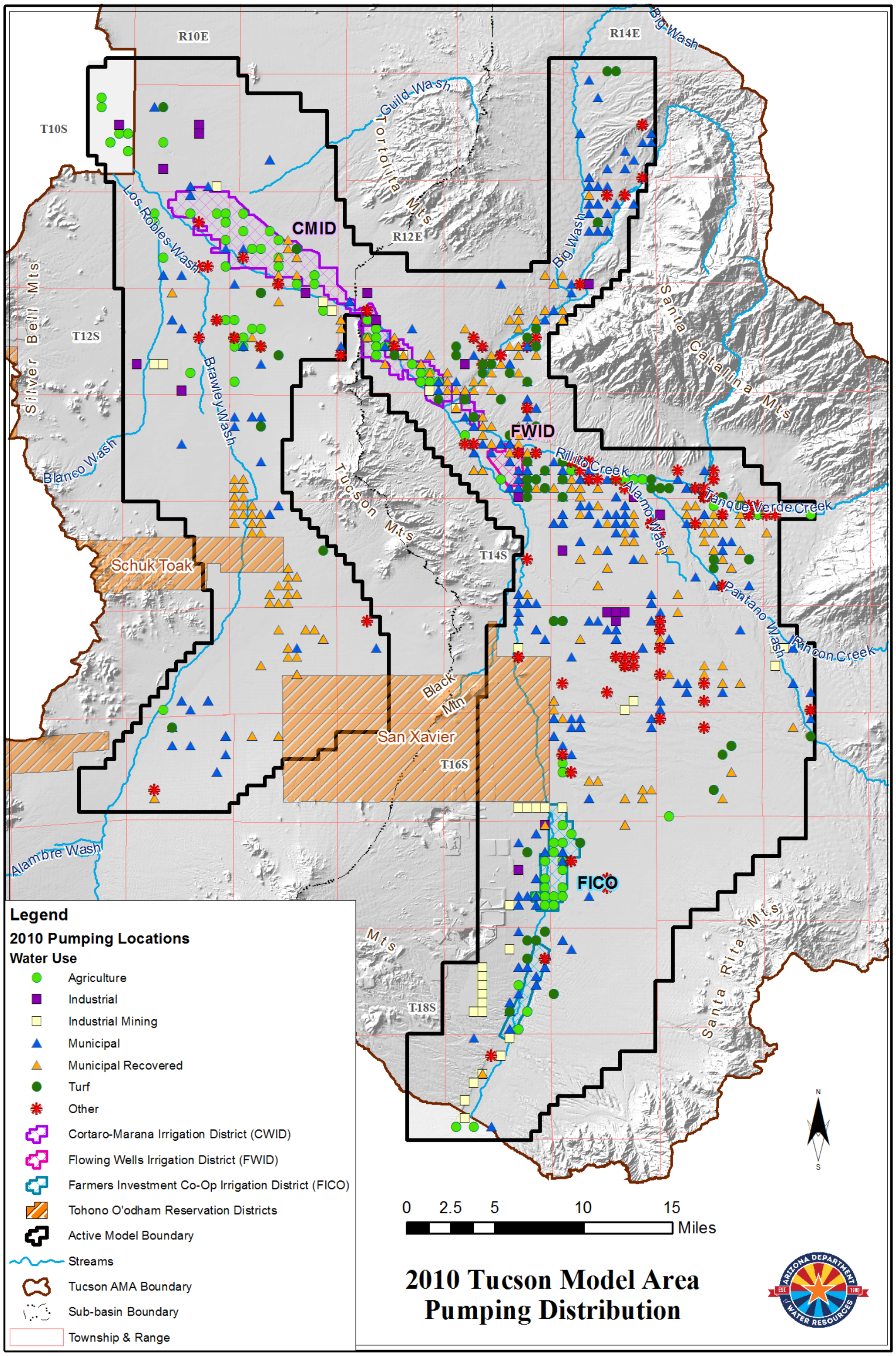


Figure 24. Pumping Distribution - 2010 in the Tucson Model area.

In the previous model simulated ET declined from over 13,000 ac-ft/yr to slightly less than 3,000 ac-ft/yr by 1999. Given the ongoing water level declines, simulated ET is expected to continue to decline through 2010. The location of ET simulated in the model is shown in Figure 21.

4.0 Model Calibration

Model calibration generally involves varying model inputs within established ranges to obtain an acceptable 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 values and observed data. A number of initial model input parameter estimates were adjusted, within a range of observed values, to obtain a "best-fit" to measured data. The final adjustments were compared as a whole to ensure that the conceptual model estimates were honored.

Given the significant updates to the previous model all of the model parameters were examined in the calibration process. Significant changes were made in the following areas:

- Model stresses such as pumping and recharge volumes and distributions
- Horizontal hydraulic conductivity values in all layers
- Layer 3 thickness i e., via adjustment of model bottom elevation
- Assigning annual stream flows/infiltration volumes

4.1 Calibration Criteria and Model Error

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 can include individual calibration targets as well as more generalized systemic targets. Individual calibration targets can include water levels or estimated fluxes that have a measured or estimated value that falls within an 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 errors 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. A more detailed discussion concerning the background of ADWR's calibration criteria and use of model error can be found in Chapter 5 of Mason and Bota (2006).

The water level data used to create target water-level maps and observation heads for the previous ADWR steady-state and transient model simulations were used for this report. Additional water level data collected from 2000 to 2010 were used to create updated water level elevation maps and to expand the MODFLOW Head Observation Package (HOB). The 1940 water level elevation map was constructed using 237 water level measurements from ADWR's

GWSI database and various other historical sources (Figure 3). A water-level contour map for the final year of the transient period, 2010, was developed from water-level data points collected during the fall of 2010 and early spring of 2011 and is presented in Figure 5.

The HOB Package compares observed heads to model simulated heads and calculates the difference between them. This allows the HOB Package to aid in model calibration by calculating the difference, or residual, between a simulated head and an observed head. The HOB package contained observed water level data at five year interval from 1940 until 1975, after 1975 the HOB file water level data is from years when major basin sweeps were done by either the ADWR or the USGS. The major sweep years are 1981-82, 1987-88, 1994-95, 1999-2000 and 2004-05. The 2010-2011 water level elevations incorporated in the HOB file were collected by both the ADWR and Tucson Water. Table 8 lists the HOB time periods and the number of water level observations that were used to evaluate the model simulation. The HOB file contained a total of 8,395 selected water levels from 1935 to 2011. The residuals created by the HOB were used to statistically analyze the model calibration. An explanation of the HOB package and how it is applied can be found in Hill and others (2000).

Table 8. Head Observation Periods

Observation Period	Measurement Years	Number of Observations [1]
1	1939-1942	237
2	1944-1946	169
3	1949-1951	297
4	1954-1956	366
5	1959-1961	370
6	1964-1966	266
7	1969-1971	275
8	1974-1975	332
9	1981-1983	658
10	1987-1988	763
11	1994-1995	1,020
12	1999-2000	768
13	2004-2005	962
14	2010-2011	733
	Total	7,216

1). The HOB Package contained a total of 8,395 head observations.

The head residuals generated from the HOB Package were one of the main calibration bench marks. The residuals were calculated using the formula:

$R = H_s - H_o$

Where:

R = the residual in feet

H_s = the interpolated simulated head elevation in feet

H_o = the observed head elevation in feet

If the simulated head is higher than the observed head, then residual is positive, and if the simulated head is lower than the observed head, then the residual is negative.

Hill (1998) discussed issues relating to weighting of observed data so that models may be more effectively calibration. This report employed the method utilized by Mason and Bota (2006) of weighting observed data based on the accuracy of the well head altitude. This method of weighting head observation data allows wells with more accurately assigned well head elevations to have more influence on the residual analysis. See Mason and Bota (2006) Chapter 5 and Appendix B for a more detailed explanation of the residual weighting process.

4.2 Calibration Targets

Water level data and the water-budget components were used to establish calibration targets for this study. Based on previous modeling experience and suggested model error criteria from Anderson and Woessner (1992) the following calibration criteria were developed for the Tucson model:

- The total head change across the Tucson model is approximately 1,350 feet. The maximum absolute value of any weighted model residuals will be less than or equal to 10 percent of the total head change, or 135 feet.
- The mean of the absolute value of the weighted head residuals (MAE) will be less than 2 percent of the total head change, or 27 feet.
- 90 percent of the absolute value of the weighted head residuals (MAE) will be less than or equal to 5 percent of the total head change, or 50 feet.
- The RMSE (Standard Deviation) of the weighted head residuals (ME) will be less than or equal to 2 percent of the total head change, or 27 feet.
- The ratio of the head change to the RMSE will be less than 10 percent.
- The percent error in the MODFLOW water budget is less than or equal to 0.1 percent.
- A reasonable match between hydrographs of selected wells and simulated heads.
- The simulated heads produce a water-level elevation contour map that reasonable replicates hand contoured water-level elevation map based on 2010-2011 measured water levels.

The last two calibration criteria listed above are subjective measures and can be included in the more generalized model calibration criteria that include water budget data and regional water levels trends. These calibration criteria are subjective measures of model validity because of the uncertainty involved in how they were determined or how the results can be interpreted.

4.3 Steady-State Calibration

The TAMA steady-state model was calibrated to the aquifer conditions as they existed in 1940. There were no major changes to the basic conceptual model developed by Mason and Bota (2006). Very little adjustment was done to the distribution of layer specific hydraulic conductivity (K_x) values for layers 1 and 2. Layer 3 cell-specific K_x values were calculated based on the new model bottom and the previous assigned transmissivity. Most of the calibration for the steady-state model involved adjusting the initial layer 3 hydraulic conductivity values. In some areas layer 3 bottom elevations along the model margins were modified to keep cells along the edges saturated. Some minor adjustments to pumpage and natural recharge volumes and locations were done, and pre-1940 agricultural recharge was added to the model.

4.3.1 Steady-State Results

The steady-state model calibration simulation was analyzed both quantitatively and qualitatively to determine the acceptability of the simulation to the established calibration criteria. The steady-state generally met the selected calibration criteria outlined in Section 4.2.

<u>Water Levels</u>

The water level contour map of 1940 simulated water levels was superimposed over the hand-contoured 1940 water level map (Figure 25) to qualitatively evaluate model simulated heads. The comparison of simulated to observed water level contours reveals a generally acceptable match of water levels at a regional scale. The 1940 observed and simulated head contours have a good match with both the simulated and observed head gradient and flow directions almost identical to each other (Figure 25).

As discussed previously, slightly more than 8,395 water level measurements were used to aid in model calibration. The water-level observation points were assigned using wells that had well depth or well perforation information and fell within the active model domain. The head observations for each well were assigned to either a single layer or multiple layers based on the well's perforation intervals or well depth. If only a well's depth was known, the observation head was assigned to the lowest layer that the well penetrated. Head observations for wells lacking perforations or well depth information were not used in the analysis.

Head Residuals

The steady-state calibration analysis is based on 237 water levels and includes a statistical analysis of the weighted heads residuals (Table 9) and a map (Figure 26) with the spatial distribution of the residuals. Table 9 presents basic statistics for the 1940 weighted head residuals and a frequency distribution of the absolute value of the weighted residuals. The frequency distribution of the weighted residuals was calculated using intervals of 10 feet to match the calibration level intervals. Appendix C contains more detailed steady-state residual statistics and the frequency distributions data.

The steady-state calibration is very good with about 90% of the weighted residuals within ± 10 feet (Table 9B). The overall mean error (ME) is only –0.1 feet and the mean of the absolute value of error (MAE) is 4.6 feet (Table 9A). The ME for the Avra Valley and the USC sub-basins are 2.4 and -0.9 feet, respectively. The weighted residuals ranged from +34 feet to –96 feet and have a RMSE of 9.9 feet. The ratio of RMSE to the total head change in the model is 0.0072 or 0.73 percent. In the USC sub-basin there is an almost even split of residuals between positive and negative values, 91 positive to 94 negative. In the Avra Valley sub-basin about twice as many residuals are negative (37) as are positive (15) (Appendix C).

The overall slight negative ME for the steady-state heads is due to the influence of one high negative value (-96 feet) in the USC sub-basin (Table 9A). The absolute value of all the weighted residuals is less than 50 feet except for that one value (Table 9B). The data point is an outlier that has an effect on the relatively small steady-state head residual data set. If the data point were ignored the steady-state ME would be 0.3 feet for all residuals, and an ME for the USC sub-basin would drop from -0.9 feet to -0.3 feet.

The steady-state simulated and observed heads were examined for correlation using a scatter plot and by calculating Pearson's correlation coefficient (Figure 27). Hill (1998) suggests that when observed heads are plotted against simulated heads they should fall close to a line with a slope of 1.0 and the correlation between them should be greater than 0.90. The steady-state weighted simulated and observed heads were closely grouped along a one-to-one line and had a correlation coefficient of 0.9999 (Figure 27).

One way to check for bias in a groundwater flow model is to plot weighted residuals against hydraulic head (Hill, 1998). Ideally the residuals should not be consistently higher or lower in areas of high hydraulic head than they are in areas of lower hydraulic head. Examination of Figure 28, which plots steady-state weighted head residuals against the unweighted observed heads, indicates that there are several areas of potential bias present. One is between 1,600 and 1,800 feet in elevation where residuals are consistently positive, another is between 1,800 and 2,000 feet in elevation here the residuals are consistently negative, and a third above 2,600 feet in elevation where the residuals are generally positive. These areas can also be observed by examining the spatial distribution of the weighted residuals in Figure 26.

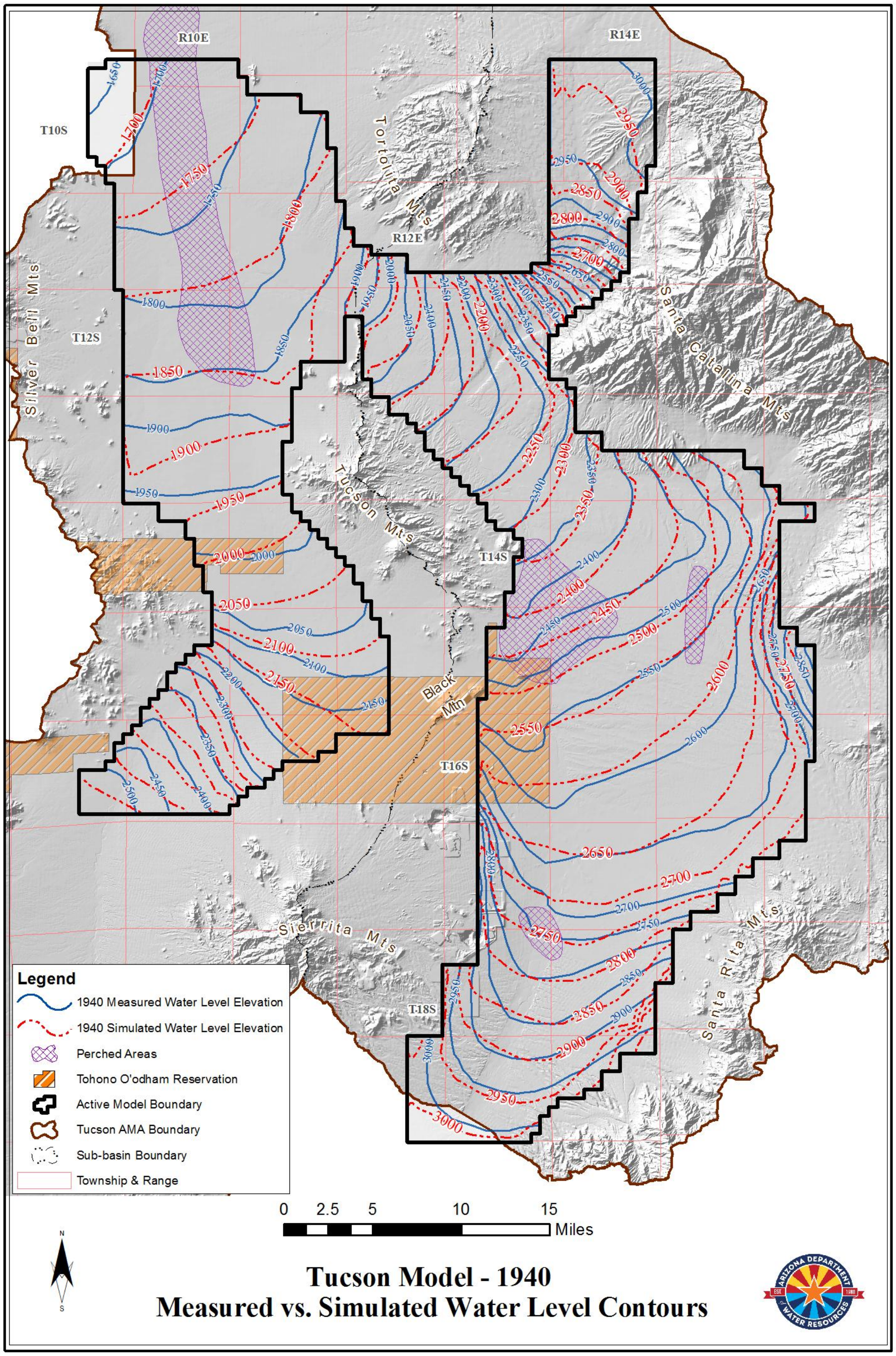


Figure 25. 1940 Measured vs. Simulated Water Level Contours.

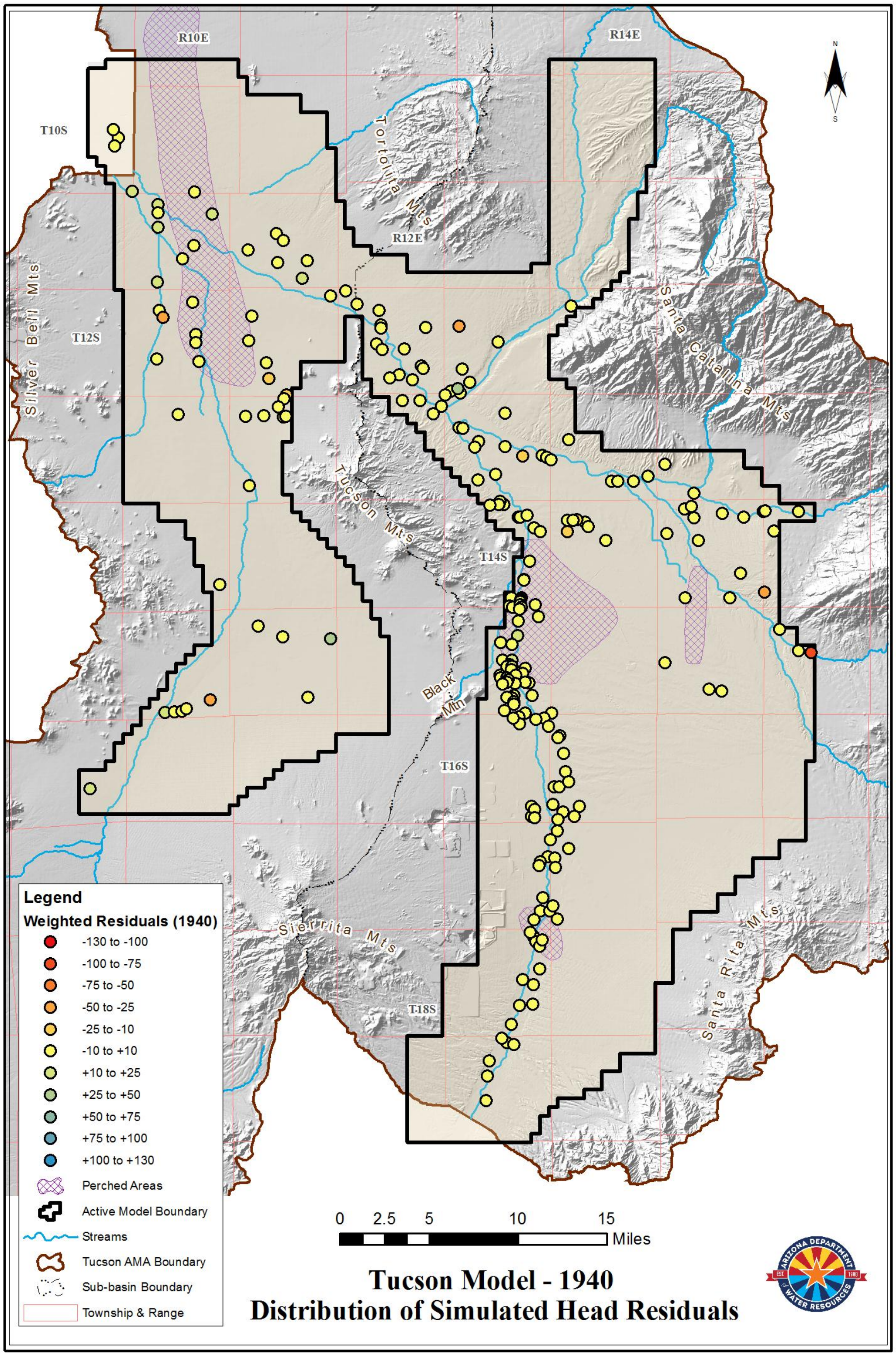


Figure 26. Distribution of Simulated 1940 Head Residuals - Tucson Model.

Table 9. Tucson Model 1940 Weighted Head Residual Summary

A). Weighted Residual Statistics: 1940 (all values are in feet)

	Model-Wide	Avra	USC
ME	-0.1	2.4	-0.9
RMSE	9.9	11.3	9.4
MAE	4.6	7.7	3.7
Median	0.2	1.4	0.0
Max	34	34	34
Min	-96	-35	-96
Count	237	52	185

B). Distribution of Absolute Value of Weighted Residual: 1940

Calibration Level	*Absolute Range (Ft)*	*Frequency*	*Cumulative Percent*
Level 1	0 to 10	213	90%
Level 2	10 to 20	14	96.2%
Level 3	20 to 30	4	97.9%
Level 4	30 to 40	4	99.6%
Level 5	40 to 50	1	99.6%
Level 6	50 to 60	0	99.6%
Level 7	60 to 70	0	99.6%
Level 8	70 to 80	0	99.6%
Level 9	80 to 90	0	99.6%
Level 10	90 to 100	1	100%
Level 11 or more	> 100	0	100%
	Count	237	

<u>Water Budget</u>

The steady-state model water budget is presented in Appendix E. Most simulated water budget components were similar to conceptual estimates. Simulated recharge was 83,500 ac-ft that included 41,700 ac-ft of stream recharge, 27,800 ac-ft of mountain-front recharge, and 14,000 of incidental recharge. Underflow into the model totaled 20,900 ac-ft, 10,600 through the constant head boundary between TAMA and SCAMA and 10,270 as specified flux from Altar and Falcon Valleys. Total steady-state simulated flux into the model was 104,400 ac-ft, slightly more than the conceptual total inflows of 102,900 ac-ft (Table 1). Simulated flux components out of the steady-state model were 70,500 ac-ft in pumpage, 9,300 ac-ft of ET, and 24,700 ac-ft of underflow out to the PAMA (Appendix E). The steady-state water budget had an error of -6 ac-ft, or 0.01 percent of the total simulated flux into and out of the model.

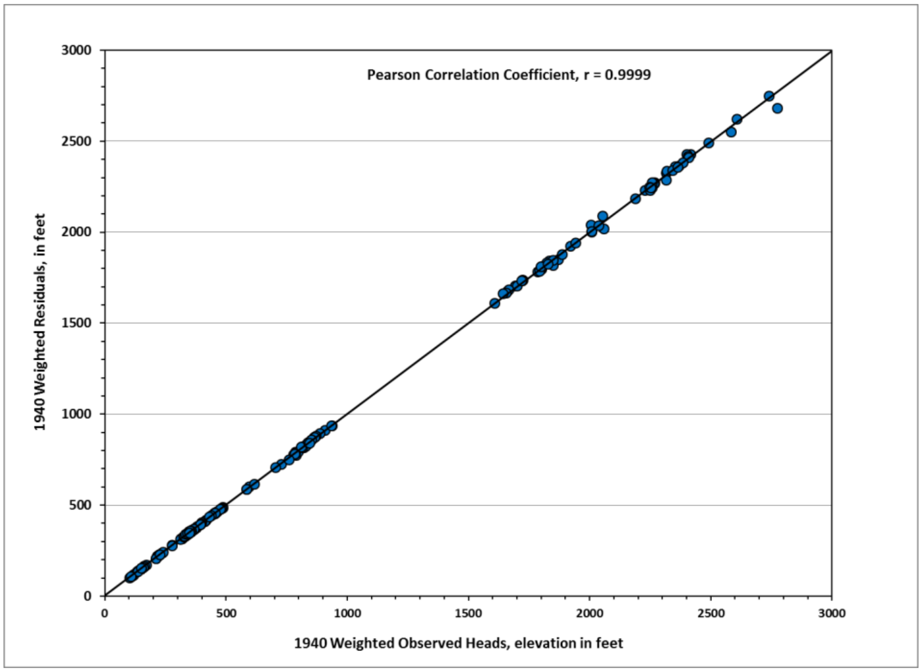


Figure 27. 1940 Weighted Observed Heads vs. 1940 Weighted Simulated heads.

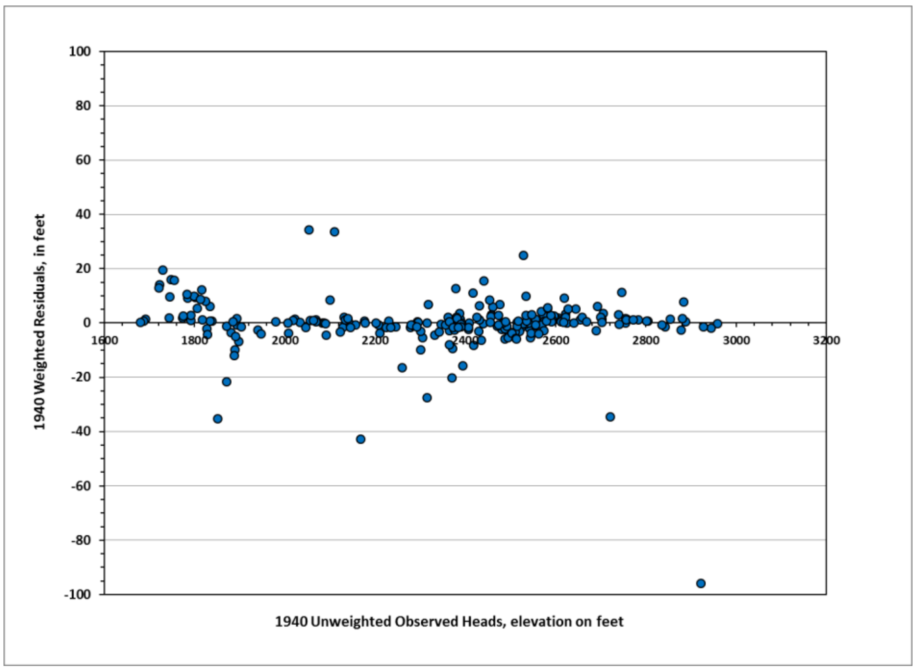


Figure 28. 1940 Weighted Residuals vs. 1940 Unweighted Observed Heads

4.4 Transient Calibration

The transient model simulated the response of the regional aquifer system to changing stress conditions that existed for the period of groundwater development from 1941 to 2010. The transient model calibration involved making adjustments to model stresses (pumping and recharge) and hydrological parameters (hydraulic conductivity). Recharge components that were adjusted included agricultural recharge, annual stream infiltration, and mine tailings pond recharge. Pre-1984 pumping was adjusted to improve the calibration between 1940 and 1983. After 1984, pumping totals reported through the ROGR database were incorporated directly into the model pumping data sets. The adjustments to the recharge values for the transient period involved modifying annual stream infiltration values to reflect the estimated annual variation in stream flows and distribution of recharge within a reach of the stream between stream gage points. Agricultural recharge was adjusted based on the distribution and amount of annual pumpage.

Because the previous model's distribution of total transmissivity was generally believed to be reasonable, the majority of changes to model inputs during the transient calibration involved researching and adjusting stream infiltration values, pre-ROGR pumping volumes and locations. Model hydraulic conductivity values were modified in several specific areas and these changes are detailed in Section 4.4.3. The specific yield distributions developed by Mason and Bota (2006) was not modified during the calibration.

Stream Infiltration Modifications

One significant change incorporated into this report is simulating stream infiltration on a yearly basis. Initial annual stream infiltration values for stream segments between the various stream gage sites were developed based on measured and synthetically generated stream flows (see Section 3). During calibration the infiltration in the various stream segments was adjusted in an attempt to match observed water levels from hydrographs located in close proximity to the streambeds. In addition, the distribution of the recharge along a stream segment was adjusted to reflect a decrease in flows downstream along the stream segment. This allowed for the effect of lower flows not traveling along the entire length of a stream segment to be simulated.

Pumping and Recharge Modifications

By the mid-1970s, model cell dewatering in layers 1 and 2 made it necessary to reassign some withdrawals to either layers 2 or 3. The need to assign most pumping to layers 2 and 3 reflects the loss of saturated thickness in the upper model layers due to overdrafting of the regional aquifer. Agricultural withdrawals and the associated lagged incidental recharge volumes were increased and decreased in tandem so that incidental recharge volumes were consistent with pumping volumes. The agricultural efficiency factors used to estimate the volume of agricultural recharge and the lag factor used to time the application of the incidental recharge were also adjusted during the calibration process. The final calibrated agricultural efficiency values are 33 percent for the period 1941 to 1970, 28 percent for 1971 to 1980, and 25 percent for 1984 to 2009. The final lag time for all incidental recharge is based on a deep percolation rate of 20 feet per year.

Cell-specific lag times were calculated using the deep percolation rate and time-variant depth to water for cells receiving agricultural and some classes of effluent recharge as described in Section 3.2.2. The cell-specific lag times yielded agricultural lag times that ranged from 1 to 30 years and averaged 6 years. Lag times in the Avra Valley sub-basin ranged from 6 to 25 years and averaged 10 years. In the USC sub-basin lag times ranged from 1 to 20 years, but averaged only 5 years. Lag times for recharge from artificial recharge projects were spread out over three years. The annual recharge was assigned to the three years at 30 percent for the first year, 40 percent for the second year, and 30 percent in the final year.

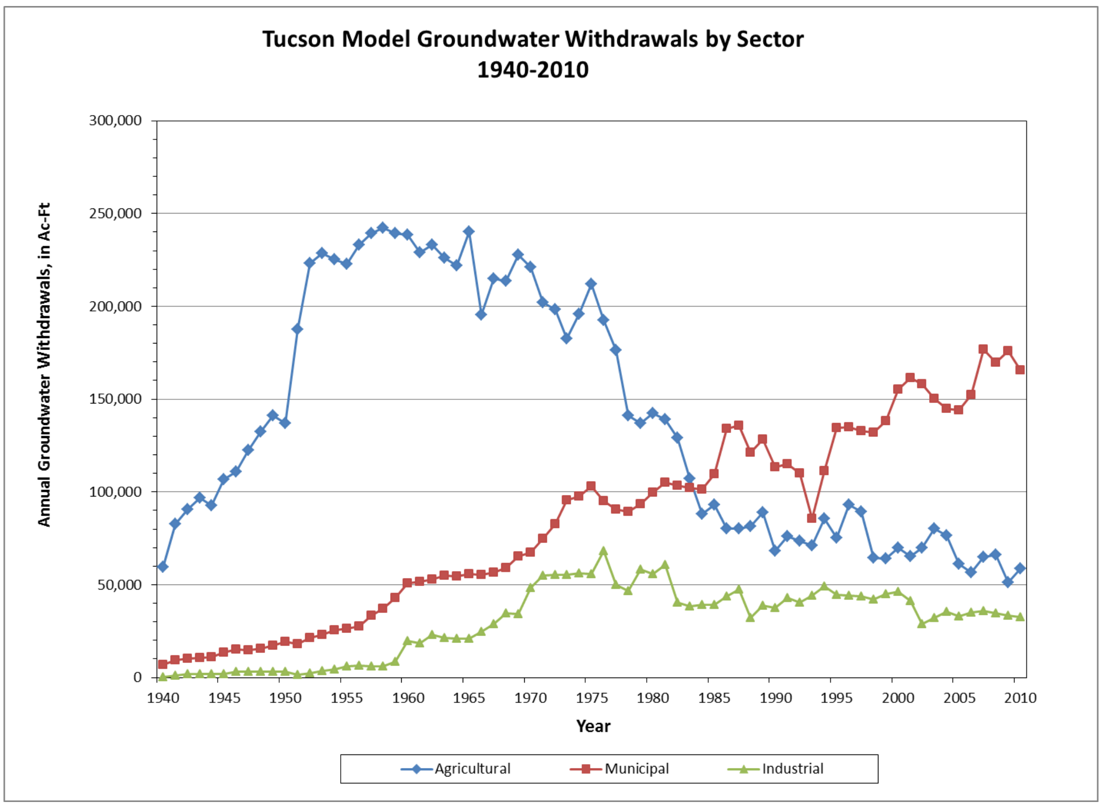


Figure 29. Simulated Groundwater withdrawals by Sector, Tucson AMA Model

The relative change in the distribution of groundwater withdrawals can be seen by comparing the 1940 to the 2010 pumpage distributions presented in figures 23 and 24, respectively. Figure 29 shows the model simulated groundwater withdrawals broken out by the three main categories; agricultural, municipal, and industrial. Figure 30 shows the model simulated groundwater withdrawals by sub-basin. A detailed history of pumping for the Avra valley and the Upper Santa Cruz sub-basins can be found in Mason and Bota (2006).

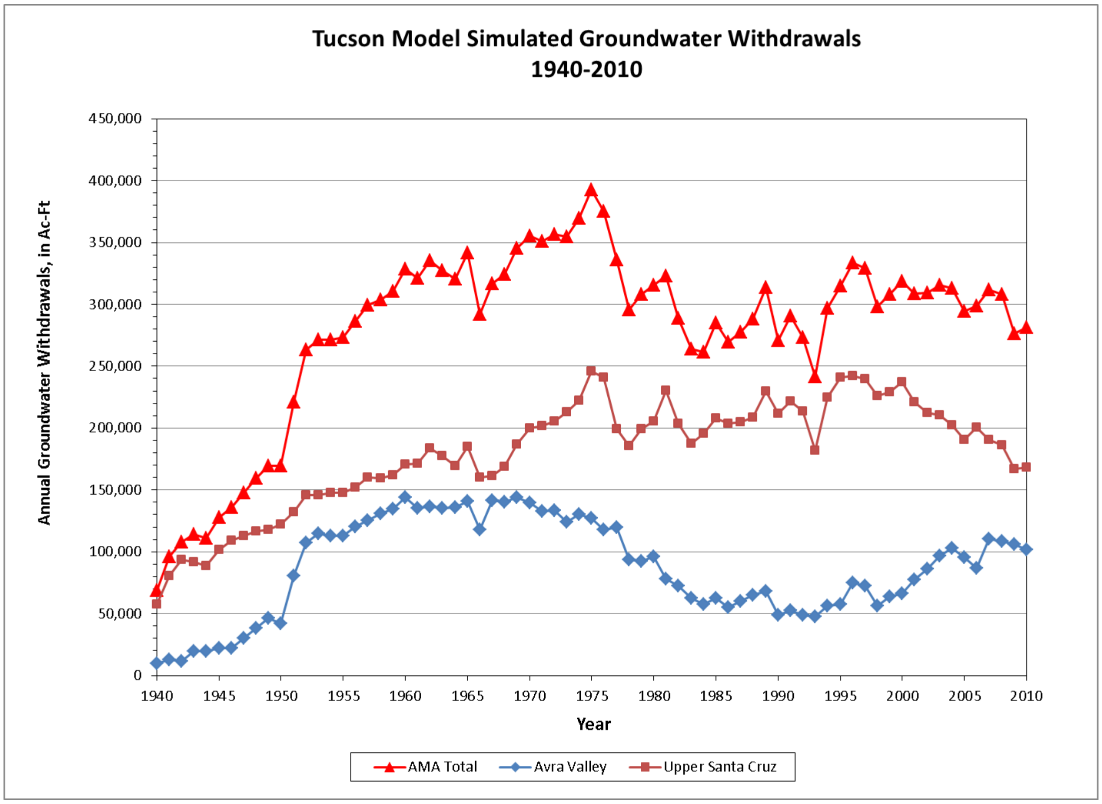


Figure 30. Simulated annual groundwater withdrawals - Tucson AMA Model

<u>Hydraulic Conductivity Modifications</u>

Other than calculating Layer 3 hydraulic conductivity values based on the new model bottom and the previous assigned transmissivity, very little calibration work was done on the distribution of layer specific hydraulic conductivity values. However, the model transmissivity distribution was adjusted in the following areas in an effort to improve the overall model calibration:

- The Upper Santa Cruz sub-basin in Township 14 S, Range 15 East.
- The southern section of the Avra Valley sub-basin.
- Along the model margins where the addition of a model bottom necessitated adjustment of the model transmissivity and layer thickness.
- The northwestern section of Avra Valley sub-basin near the TAMA-PAMA boundary.
- Along the Santa Cruz River to accommodate the larger annual stream recharge volumes.

4.4.1 Transient Calibration Results

Water Levels

The final model stress period (2010) was analyzed both quantitatively and qualitatively to determine the acceptability of the simulation to the established calibration criteria. Water level contour maps were used to qualitatively evaluate the final model simulated heads. Water level contour of 2010 simulated water levels were superimposed over the hand-contoured 2010-2011 observed water level contours (Figure 31). The comparison of simulated to observed water level contours reveals a generally acceptable match of water levels at a regional scale. The 2010 simulated and observed contours have a general correspondence between simulated and observed head gradient and flow directions (Figure 31). The model simulated contours reproduce several localized features seen in the observed water level elevation contours. The localized features include the groundwater mounds that are developing in central Avra Valley under the two USFs operated by the City of Tucson. In the USC sub-basin the developing groundwater mound under the Pima Mine Road USF in the southwest corner of T16S, R14E is also simulated. Although the small closed simulated contour that represents an elevation of 2,550 feet amsl isn't as large as the observed mound, the growth of the simulated mound can be seen in the developing budge of the 2,500 foot simulated contours to the northwest of the Pima Mine Road USF (Figure 31).

Some localized discrepancies exist between simulated and observed contours. One example is located in the USC sub-basin in Township 13 South, Range 15 East and Township 14 South, Range 15 East where the model can't simulate the very tight observed water level contours that parallel to Pantano Wash (Figure 31). The very steep water level gradient in this area has water levels changing as much as 200 feet or more within a mile. A second area is located in the USC sub-basin in Township 15 South, Range 13 East and Township 15 South, Range 14 East where a large perched water table area exists (Figure 31). The model is unable to reproduce the steep observed water level gradients at the southern end of the mapped perched area. The inability of the model to simulate the observed steep gradients may be caused by 1) localized variability in hydraulic parameters that the model data set can't capture due to the model grid size, and 2) MODFLOWs inability to accurately simulate areas of high hydraulic gradients due to the model's cell size.

Model Residuals

A statistical analysis of the weighted head residuals for the final transient stress period (2010) is presented in Table 10, and the spatial distribution of the residuals is shown on Figure 32. The 2010 model results had 708 observation water levels available for statistical analysis (Table 10A). The ME of the 2010 weighted head residuals was 2.5 feet and the MAE of the weighted residuals was 19.3 feet, or a little less than 1.5 percent of the head loss across the study area (Table 10A). The weighted residuals ranged from +120 feet to –123 feet and had a RMSE of

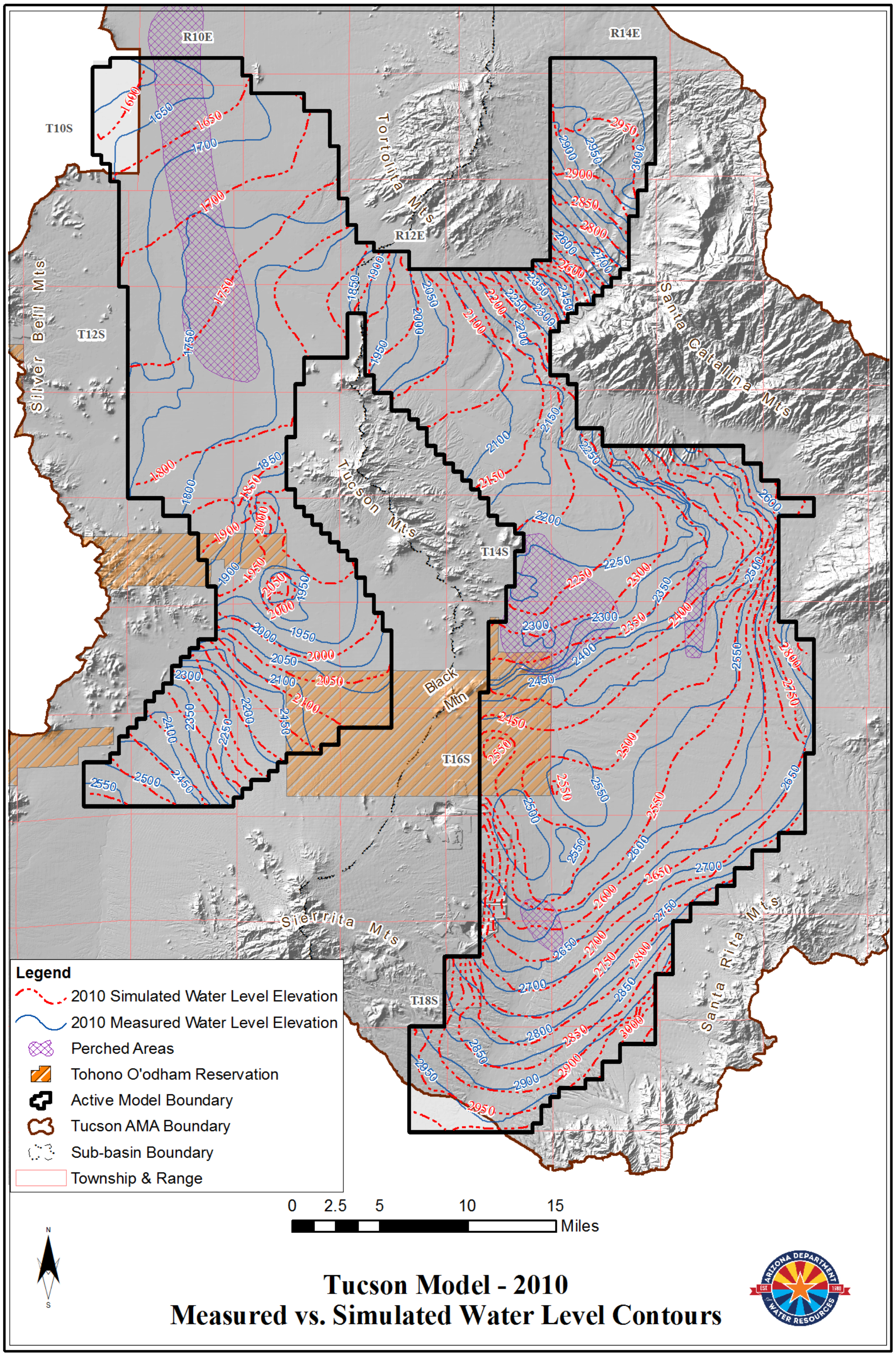


Figure 31. 2010 Measured vs. Simulated Water Level Contours

27.6 feet. The ratio of RMSE to the total head change in the model was 0.02096 or about 2.1 percent of the total head change across the model. The ME for residuals in the Avra Valley and the USC sub-basins are –4.7 and 5.1 feet, respectively. For the 2010 calibration about 42 percent of the residuals were ± 10 feet and 92 percent were ± 50 feet (Table 10B).

Table 10. Tucson Model 2010 Weighted Head Residual Summary

A). Weighted Residual Statistics: 2010 (all values are in feet)

	Model-Wide	Avra	USC
ME	2.5	-4.7	5.1
RMSE	28.3	14.3	30.7
MAE	19.3	10.9	22.4
Median	1.0	-3.2	3.9
Max	120	31	120
Min	-123	-48	-123
Count	708	190	518

B). Distribution of Absolute Value of Weighted Residual: 2010

Calibration Level	*Absolute Range (Ft)*	*Frequency*	*Cumulative Percent*
Level 1	0 to 10	297	42%
Level 2	10 to 20	153	64%
Level 3	20 to 30	83	75%
Level 4	30 to 40	62	84%
Level 5	40 to 50	53	92%
Level 6	50 to 60	25	95%
Level 7	60 to 70	19	97.7%
Level 8	70 to 80	4	98.3%
Level 9	80 to 90	5	99.0%
Level 10	90 to 100	1	99.2%
Level 11 or more	> 100	6	100%
	Count	708	

The overall positive ME for 2010 weighted residuals is unduly influenced by the fact that the USC sub-basin has more than twice as many head observations than the Avra Valley sub-basin. The skewing of model-wide residual data due to over-representation of residuals in the USC sub-basin is a problem throughout the model calibration period. In 2010, the ME for the USC sub-basin was 6.5 feet and the MAE was 23.5 feet, and almost 60 percent of residuals in the USC sub-basin were positive (Appendix C). In the Avra Valley sub-basin the ME and the MAE were -4.7 feet and 10.9 feet, respectively. In the Avra Valley sub-basin about 67 percent of the weighted residuals were negative (Appendix C).

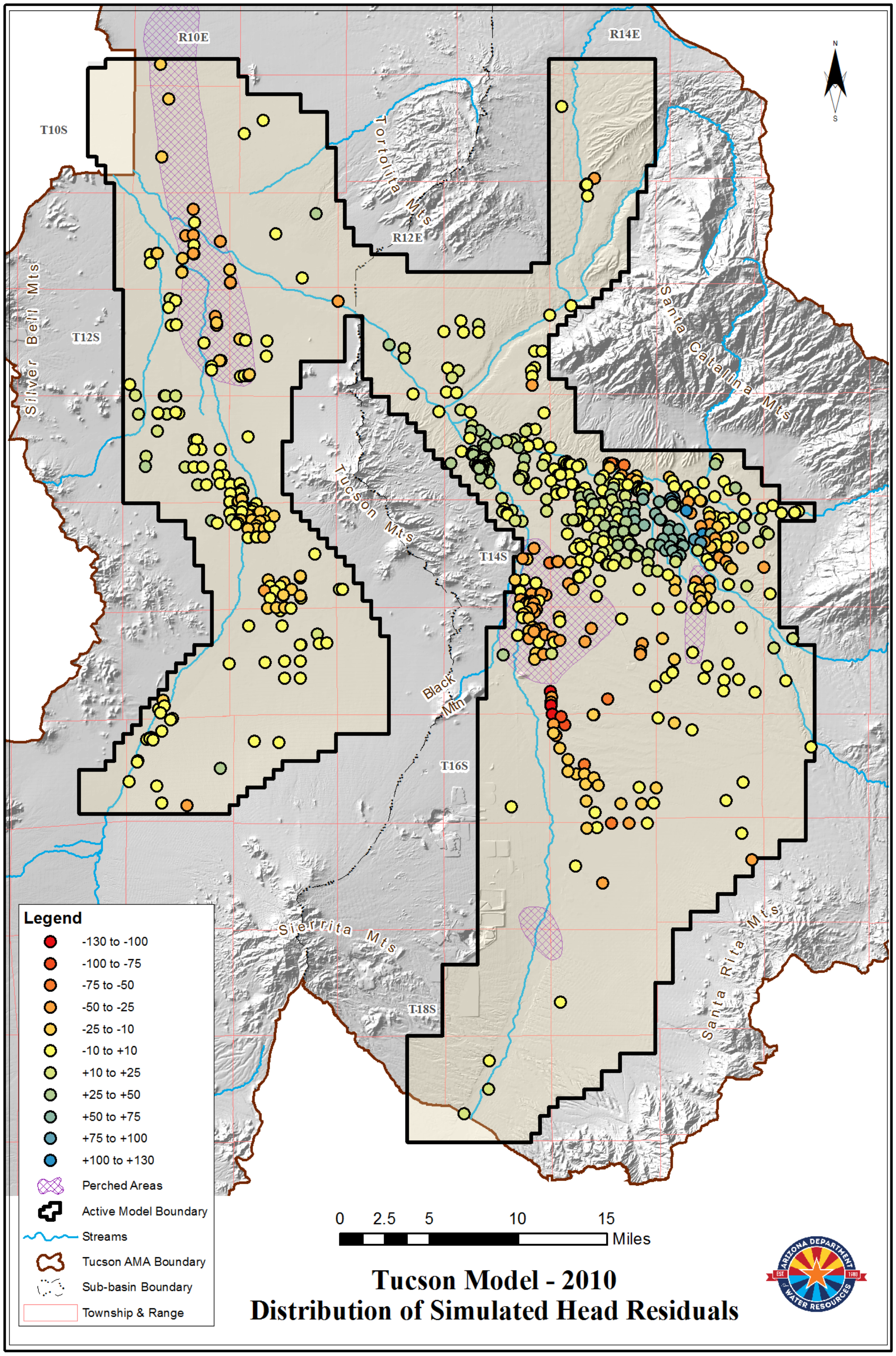


Figure 32. Distribution of simulated 2010 head residuals - Tucson Model.

The 2010 weighted simulated and observed heads were examined for correlation and general bias using scatter plots (Figure 33 and 34). The 2010 weighted simulated and observed heads were closely grouped along a one-to-one line and had a correlation coefficient of 0.9995 (Figure 33). Figure 34, which plots 2010 weighted head residuals against the unweighted observed heads, indicates that there are several areas of residual bias present. One area is between 1,600 and about 2,100 feet in elevation where residuals tend to be negative. The negative trend is most noticeable about 2,000 feet in elevation. This area is roughly the northern and central sections of the Avra Valley sub-basin and the northwestern section of the USC sub-basin where it opens into the Avra Valley sub-basin.

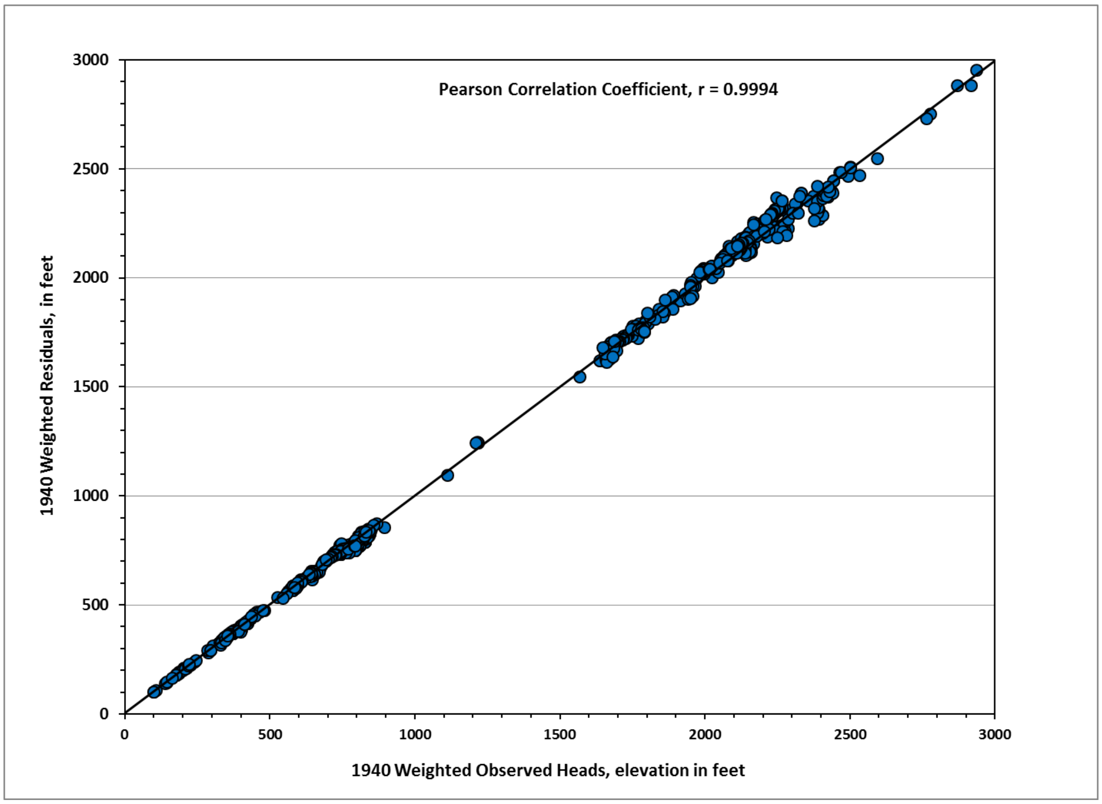


Figure 33. 2010 Weighted Observed Heads vs. 2010 Weighted Simulated Heads

Examination of the 2010 weighted residual map (Figure 32) reveals several groups of negative residuals that overlie the groundwater mounds that have developed under the Clearwater and SAVSARP USFs in the Avra Valley sub-basin (Figure 7). The model generally under-simulates water levels in the area of the mounds. A second area of bias is from about 2,100 feet in elevation to about 2,300 feet where the residuals are consistently positive. The source of the bias in this area is probably located in the USC sub-basin where the Santa Cruz River and Rillito Creek converge. The confluence of the two drainages, the Sweetwater effluent recharge facility and the discharge point for the Ina and Rogers Roads WWTP are all located in fairly close proximity to each other at about this elevation (Figures 6B and 7).

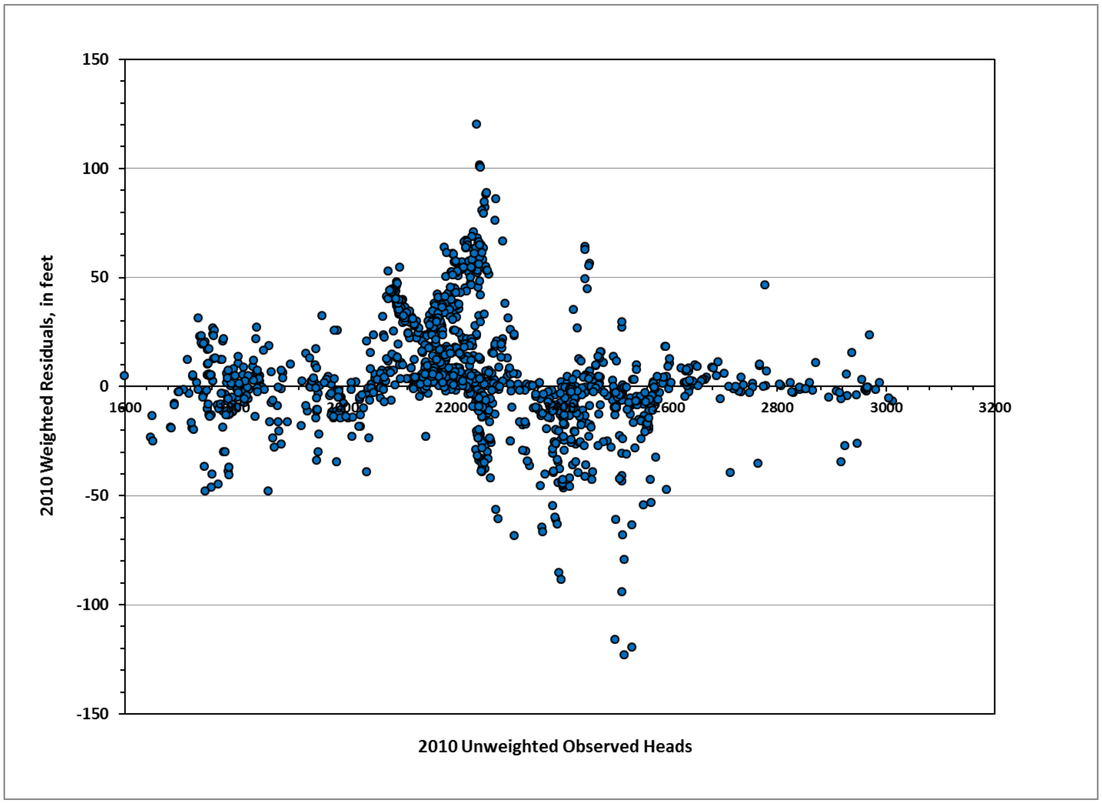


Figure 34. 2010 weighted Residuals vs. 2010 Unweighted Observed Heads.

The third area of bias is from about 2,300 to about 2,600 in elevation where residuals are predominately negative. This area is probably caused by residuals in the perched groundwater area in the USC sub-basin located in Townships 14 and 15 South, Ranges 13 and 14 East. These areas of bias can also be observed by examining the spatial distribution of the weighted residuals in Figure 32. The effect on the head residual distribution of the very steep water level gradient in Township 13 South, Range 15 East and Township 14 South, Range 15 East can be observed in Figure 32. Up gradient of the tight contours head residuals are generally negative and down gradient they are positive. This illustrates the inability of the model to slow groundwater flow through the high gradient zone, resulting in lower simulated water level elevations up-gradient and higher simulated water level elevations down-gradient.

Model Residuals: 1040-2010

An analysis of all head observations from 1940 to 2010 is presented in Table 11. The ME of all 8,382 weighted head residuals was 3.7 feet and the MAE was 11.3 feet, or about 0.85 percent of the head loss across the study area. The weighted residuals ranged from +137 feet to

–141 feet and had a RMSE of 18.3 feet. The ratio of RMSE to the total head change in the model for all observation residuals is 0.0132 or 1.32 percent (Appendix C). The model weighted residuals (1940-2010) were slightly skewed towards the positive with 60 percent positive and 40 percent negative (Appendix C). The ME for the Avra Valley and the USC sub-basins are 1.6 and 4.2 feet, respectively. For the entire model simulation 82 percent of weighted residuals fell within calibration level 1 and 2, within 0 to ± 20 feet of an observed head, and 97 percent were within ± 50 feet of an observed head, or a level 5 calibration (Table 11B). A more detailed analysis of all the residuals, both weighted and unweighted, is presented in Appendix C, Tables C-1, C-2, and C-3.

The ME of the weighted residuals varied during the model calibration period of 1940 to 2010, ranging from zero in 1940 to a high of 4.7 feet for the 1987-1988 calibration period (Appendix C; Table C-1). Both the MAE and the RMSE (Standard Deviation) increased during the calibration period. The MAE increased about 15 feet, from 4.6 feet to 19.3 feet, and the RMSE increased over 17 feet from about 10 feet to 27.6 feet (Appendix C; Table C-1).

The increasing RMSE, or variability of the model error, through time is probably the cumulative effect of multiple sources that influence the model simulated heads. One source of error is the initial steady-state conditions; hydraulic parameters, model stresses, and boundary conditions, are confined to a relatively small area of the model. During the transient period the model parameters in the areas outside of the initial calibration area have an increasing influence on the model solution, which tends to magnify the legacy effect of the initial head bias. Another sourceof error is the inherent inability of the model to simulate the natural heterogeneity of the hydraulic properties of the regional aquifer. As the stresses applied to the model impact progressively larger areas of the model the heterogeneity of the regional aquifer increases the potential for model error. This in turn, may produce more variability in the head residual data.

Hydrograph Analysis

The calibration of the model was also evaluated by examining its ability to replicate the regional aquifer's response to stresses by comparing hydrographs of observed water levels versus simulated water levels (Figure 35). Hydrographs of 95 wells with long-term observed water level records compared to simulated model heads are presented in Appendix E. The observed water level elevations in the hydrographs were constructed using water level data from the ADWR's GWSI database. The observed water levels are from the fall and winter months of October through March. Winter water levels are used because they reflect a period of lowest stress on the regional aquifer. Model simulated heads were generated by the MODFLOW HYD package and were the average of the fall-winter simulated heads. The hydrographs are organized by region for ease of analysis.

Table 11. Tucson Model 1940-2010 Weighted Head Residual Summary

A).Weighted Residual: 1940-2010 (all values are in feet)

	Model-Wide	Avra	USC
ME	3.7	1.6	4.2
RMSE	18.3	14.6	19.2
MAE	11.3	10.1	11.6
Median	1.3	1.5	1.3
Max	137	62	137
Min	-141	-73	-141
Count	8382	1757	6625

B). Distribution of Absolute Value of Weighted Residual: 1940-2010

Calibration Level	*Absolute Range (Ft)*	*Frequency*	*Cumulative Percent*
Level 1	0 to 10	5552	66%
Level 2	10 to 20	1341	82%
Level 3	20 to 30	659	90%
Level 4	30 to 40	398	95%
Level 5	40 to 50	160	97%
Level 6	50 to 60	118	98%
Level 7	60 to 70	87	99.2%
Level 8	70 to 80	17	99.4%
Level 9	80 to 90	18	99.6%
Level 10	90 to 100	9	99.7%
Level 11 or more	> 100	23	100%
	Count	8382	

In general, the hydrographs show that the model was able to duplicate the observed water level trends between 1940 and 2010 at many of the hydrograph sites. The best match between observed and simulated heads occurred in the northern and central sections of the Avra Valley sub-basin, the central well field area (T 14 S, R 14 E) of the USC sub-basin, and in the southern portions of the USC sub-basin (Figure 35). Hydrographs AV-1 through AV-12 and CMID 1 through 5 represent wells in the agricultural areas of northern Avra Valley (Figure 35). Hydrographs for wells in this area generally had long-term water-level declines from the 1940s into the early 1970s, and then water level recoveries through the 1980s to the present. The model was generally able to simulate the long-term water-level declines and the recoveries that began in the late 1970s. Even in wells where the observed and simulated water levels differed by 15 to 20 feet, the slopes of the simulated water levels generally parallel the observed water levels, and the break in slope that marks the late 1970s recovery period also was generally simulated. Hydrographs AV-13 through AV-19 are located in central Avra Valley and include wells adjacent to the Clearwater and SAVSARP USFs (Figures 7 and 35). The model was able to simulate the rapid water level rises observed near the Avra Valley USFs. Hydrographs of AV-15, AV-16, and AV-17 are all near the USFs and all three show simulated model head increases that mirror observed water level rises from the mounding of groundwater near the USFs (Appendix E).

Hydrographs of simulated heads vs. observed heads from wells in the USC sub-basin also exhibited a generally good matched. However, hydrographs USC-2 to USC-6, located in T 13 S, R 13 E, the area of consistently large positive residuals near the convergence of the Santa Cruz River and Rillito Creek, all show the simulated heads higher than the observed heads. Interestingly, the simulated hydrographs in CMID 6 through CMID12, located in the Rillito narrows area that is down-gradient from the USC-2 to USC-6 hydrographs, closely match observed water levels. Hydrographs in the central well field area, Township 14 South, Range 14 East (Figure 35), displayed a generally good matched between simulated and observed heads indicating that the model was able to accurately simulate the historic aquifer response in that area (USC-15 to USC-20).

Hydrograph of wells located close to the Santa Cruz River and Rillito and Tanque Verde Creeks show that the model was able to match the general long-term downward trend of water levels in the USC sub-basin and the response of the aquifer to natural flood flow events simulated by the recharge package. Hydrographs USC 4 to USC6, USC-26 to USC-30, USC-32, USC-35, USC-41, and USC-47, and USC-49 to USC-57 are located close to the Santa Cruz River (Figure 35). Hydrographs USC-8 to USC-14 are located along Rillito and Tanque Verde Creeks (Figure 35). Several hydrographs located in the zone of perched water levels illustrate the models inability to simulate the localized water level elevations observed in that area (Figure 35). The observed and simulated water levels in hydrographs USC-31 and USC-33 show some general agreement in the overall trend before the 1980s, but have sharply divergent trends after the mid-1980s (Figure 35; Appendix E).

Water Budget

The annual simulated water budget is presented in Table D-1 of Appendix D. During the calibration process some of the ADWR’s model water budget components were compared to components of previously published models of the Tucson area as a means of checking if the volumes simulated were reasonable. Hanson and Benedict (1994) simulated groundwater flow the Tucson basin, which includes a large part of the ADWR’s USC sub-basin, from 1940 to 1986. The northern extent of Hanson and Benedict’s (1994) model domain is almost identical to

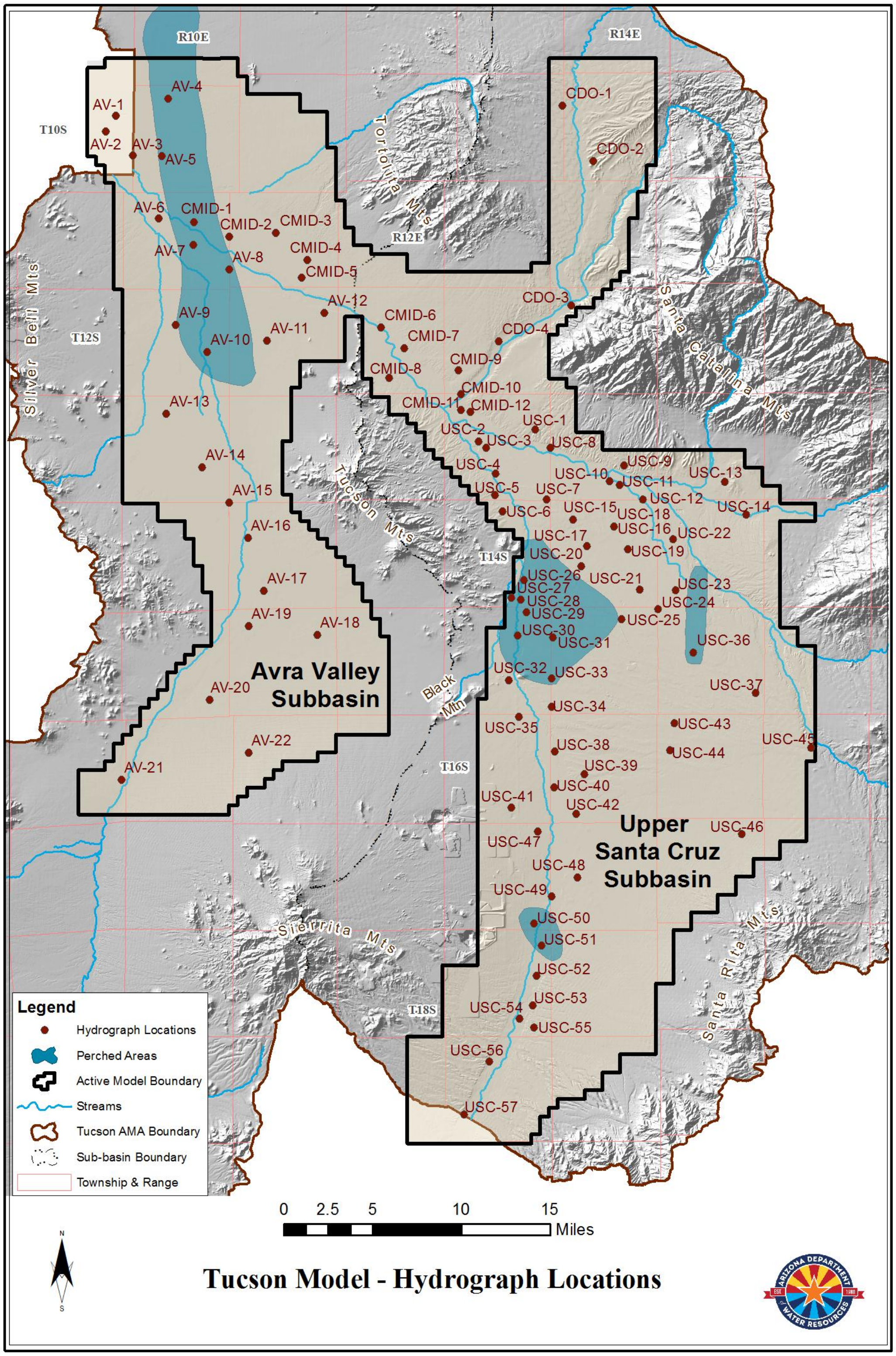


Figure 35. Maps showing well hydrograph locations, Tucson AMA model

the ADWR's USC sub-basin. However, Hanson and Benedict's (1994) model domain extended about 16 miles further south into Santa Cruz County than the ADWR model. Pool and others (1990) simulated groundwater flow in Avra Valley from 1940 to 1984. Pool's (1990) model domain is almost identical to the area in the Avra Valley sub-basin modeled by the ADWR.

It is difficult to compare model simulated recharge, both natural and incidental, between the Hanson and Benedict's (1994) and Pool and others (1990) models and this report. The previous models recharge was conceptualized differently and no attempt was made to add lag time to the recharge components, as was done in this report. Groundwater withdrawals between the models can be compared; understanding that the Hanson and Benedict (1994) model encompassed a larger area than the ADWR's USC sub-basin and therefore, should contain more withdrawals. Figure 36A contains a comparison of the Hanson and Benedict (1994) simulated withdrawals, the USGS estimated withdrawals (Anning and Duet, 1994), and the final ADWR simulated withdrawals assigned to the USC sub-basin. Figure 36B contains a similar comparison of the Pool and others (1990) simulated withdrawals, the USGS estimated withdrawals (Anning and Duet, 1994), and the final ADWR simulated withdrawals from the Avra Valley sub-basin. Figure 36C contains the combined withdrawals for the two USGS models, the USGS estimated withdrawals for the Upper Santa Cruz area, and the total withdrawals simulated in this report.

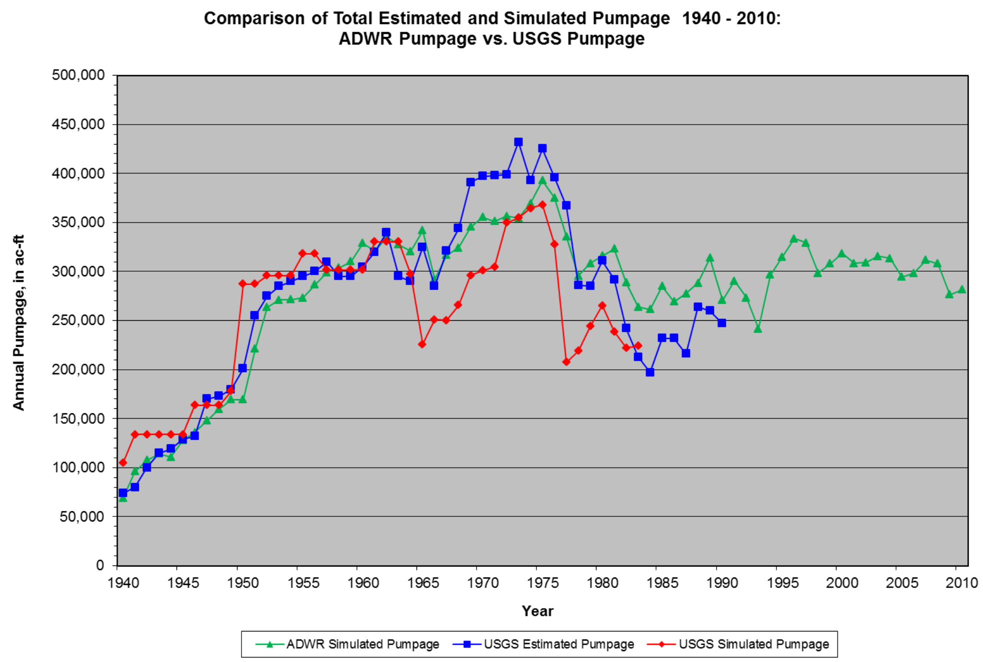
Groundwater withdrawals for the model period 1940 to 2010 totaled slightly more than 20 million acre-feet (Appendix D: Table D-1). In the USC sub-basin groundwater withdrawals simulated in this report were generally less than the initial USGS withdrawal estimates and less than withdrawals simulated by Hanson and Benedict (1994) from 1941 through the mid-1960s. From the mid-1960s to 1986, the end of the Hanson and Benedict (1994) model simulation period, the simulated withdrawals for the two models were similar and generally tracked each other well (Figure 36A)

Groundwater withdrawals simulated in this report for the Avra Valley sub-basin were generally equal to the initial USGS withdrawal estimates, but less than withdrawals simulated by Pool and others (1990) from 1941 through the mid-1960s. From the mid-1960s to 1985, Pool and others (1990) simulated withdrawals were generally less than the USGS estimated withdrawals and the withdrawals simulated in this report (Figure 36B). Total withdrawals peaked in the mid-1970s at over 400,000 ac-ft, and then began declining (Appendix D: Table 1 and Figure 36C). From 1990 to 2010 the simulated groundwater withdrawals have averaged about 300,000 ac-ft/yr (Appendix D: Table 1).

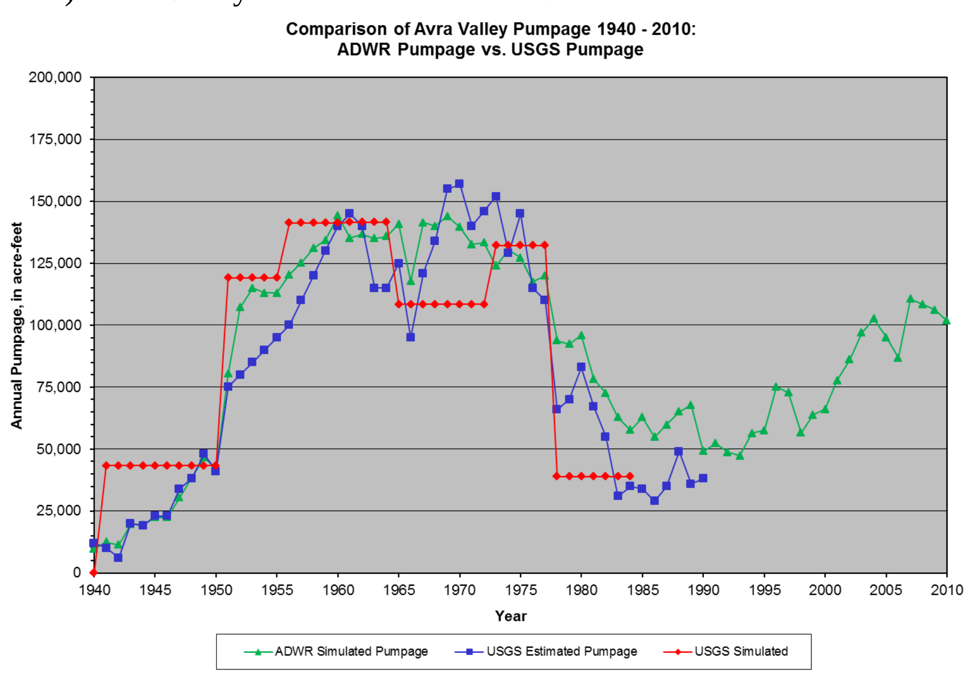
Simulated groundwater underflow into the Tucson AMA across the model's southern boundary was simulated using constant heads (Figure 22). Simulated groundwater inflows remained relatively consistent until the early 1960s, averaging about 11,400 ac-ft/yr (Appendix D, Table 1). Inflows gradually increased through the 1960s, 1970s, and 1980s; average inflows were 12,200 ac-ft/yr during the 1960s, 17,600 ac-ft/yr during the 1970s, and 18,700 ac-ft/yr for the 1980s. From 1990 to 2010, the model simulated a fairly consistent inflow of about 21,000 ac-ft/yr (Appendix D: Table D-1). As discussed earlier, the simulated groundwater flux into the

Figure 36 Comparison of ADWR and USGS model simulated pumpage.

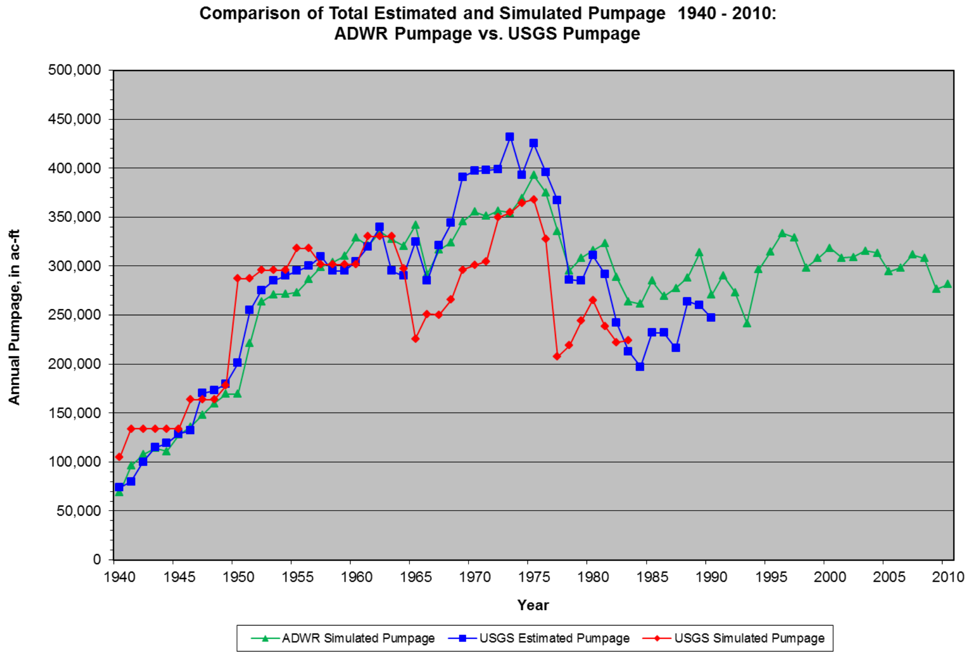
A) Upper Santa Cruz sub-basin withdrawals.



B) Avra Valley sub-basin withdrawals.



C) Total Tucson AMA withdrawals.



model after 1990 is similar to the outflow from Nelson's (2006) northern SCAMA model of 22,000 ac-ft/yr.

The simulated groundwater outflow across the model northern boundary into the Pinal AMA boundary was also simulated using constant heads (Figure 22). The simulated groundwater flux out remained relatively stable during the 1940s, averaging about 26,500 ac-ft/yr (Appendix D: Table D-1). However, the flux increased during the 1950s and 1960s. This is probably due to model simulating higher water levels than were assigned to the constant heads package during this time. The flux out of the model began to decline in the 1970s and 1980s, as the model error in the outflow area became smaller and the simulated heads more closely simulated observed heads. By 2000, the simulated groundwater flux out of the model was close to the flux simulated in the final stress period by Mason and Bota (2006).

The groundwater budgets for the sub-basins within the TAMA model area were analyzed using the Zone Budget (ZONEBUD) 3.0 program (Harbaugh, 2008). MODFLOW calculates flow between adjacent cells within the model domain, but only prints out cumulative water budget data that tabulates flow into and out of the entire model domain. The zone budget program is used to examine model simulated cell-by-cell flux between or within different sub-regions of a model domain. The Tucson model domain was divided into three separate zones or sub-regions. The USC and Avra Valley sub-basins were divided along the designated sub-basin boundaries (Figure 1). The third zone was the Canada del Oro (CDO) drainage area above Township 12 South (Figure 1). This zone was created so that the groundwater flux out the CDO area could be compared to the flux simulated by Benedict and Hanson (1994). The CDO area was included in the USC sub-basin for the sub-basin analysis.

Based on the flow zones described above, the simulated groundwater flow from the USC sub-basin to the Avra Valley sub-basin for the steady-state of 14,800 ac-ft was very close to the 1940 flow simulated by Hanson and Benedict (1994) of 15,300 ac-ft. The groundwater flow from the USC sub-basin into Avra Valley decreased through the 1940s, and then began to increase starting in the early 1950s leveling off at about 16,000 ac-ft/yr by the early 1960s. The groundwater flux into the Avra Valley sub-basin from the USC sub-basin peaked at about 17,000 ac-ft/yr in the mid-1970s. The groundwater flow into Avra Valley started a long, slow declining in the 1980s, and in 2010 was only about 11,000 ac-ft. The simulated groundwater flow out of the CDO area by Hanson and Benedict (1994) was also controlled by constant heads and in 1940 was 5,430 ac-ft. The 1940 flow out of the CDO in this report was 5,520 ac-ft. and has increased to about 7,000 ac-ft/yr. Overall, the inflow and outflow components of the groundwater budget for this report are similar to estimates from previous reports and other models.

Appendix D, Tables D-1 and D-2 presents the simulated annual and cumulative change in storage for the TAMA model. The total simulated change in storage at the end of the model simulation totaled -6.6 million ac-ft (Table D-1). The total cumulative change in storage peaked in 2004 at about -6.8 million ac-ft (Table D-1). During most of the transient period annual change in storage values were negative, indicating long-term overdraft conditions within the TAMA. However, during years when large flood flow events provided significant recharge pulses to the aquifer the change in storage values were close to zero or, in the case of several extreme flood events, positive (Table D-1). The annual simulated change in storage values range from -222,800 ac-ft to +272,500 ac-ft (Table D-1). The impact of large flood recharge pulses on the annual change in storage values can be seen in Figure 37A, 38A and 39A. During the last 6 years of the model simulation (2005-10) the annual change in storage values were mostly positive (Table D-1 and Figure 37A and 37B). This period coincides with the recharge of large volumes of Central Arizona Project (CAP) surface water at underground storage projects (USFs) in the Avra Valley sub-basin.

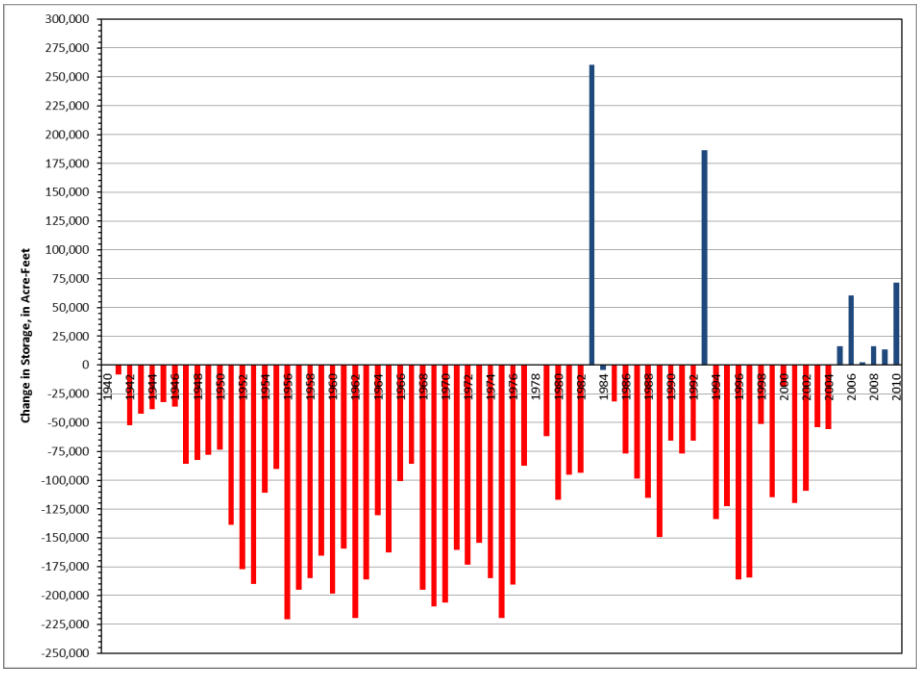
The total simulated change in storage from 1941 to 2010 in the Avra Valley and USC sub-basins was about -2.2 million ac-ft and -4.3 million ac-ft, respectively (Table D-2). Simulated annual storage depletion in the Avra Valley sub-basin is presented in Table D-2 and in Figures 38A and 38B. The change in storage in Avra Valley followed the general pattern of historic water level decline and recovery (Appendix E: Hydrographs AV-1 to AV-22). Simulated annual storage depletions steadily increased after 1941, peaking in the late 1950s at more than 130,000 ac-ft/yr, and then remained between 80,000 and 100,000 ac-ft/yr throughout the 1960s (Table D-2 and Figure 38A). Observed water-level declines through this period reflected the large annual storage depletion. The large annual storage depletions began decreasing in 1970, and by the early 1980s, the net cumulative change in storage peaked at -2.95 million ac-ft and storage depletions in the Avra Valley sub-basin reversed and the aquifer began recording net annual surpluses (Figure Table D-2, 38A and 38B). The trend of increasing aquifer storage in the sub-basin continued until the end of the model simulation in 2010 (Table D-2, Figure 38A and 38B). Since the late 1990s, when the first large-scale recharge projects came on-line the Avra Valley sub-basin has recorded large positive annual change in storage volumes (Figure 38A). The transition from large annual storage depletions to surplus conditions in Avra Valley is also reflected in well hydrographs (Appendix E). It should be noted that the change from aquifer depletion to gain is due to a combination of CAP surface water recharged at the USFs, lagged agricultural recharge, and reduced pumping stresses.

The USC sub-basin has experienced continual overdraft conditions throughout the period of groundwater development (Table D-2 and Figure 39B). Annual overdrafts varied through the development period, peaking in the early 1970s, then declined as agricultural development declined. The overdrafts increased again in the 1980s and 1990s as municipal demands increased (Figure 39A). Starting in about 2000 the groundwater overdraft in the USC sub-basin has decreased due to the City of Tucson shifting a large portion of its groundwater withdrawals to wells located in Avra Valley. Over the last eight years of the model simulation, 2003-2010, the overdraft in the USC sub-basin has averaged only 47,400 ac-ft/yr (Table D-2).

The long-term overdrafts in the USC sub-basin have resulted in long-term drawdowns in most wells in the sub-basin, as can be observed in most hydrograph in the basin (Appendix E). The only exceptions are wells located in the floodplain of the Santa Cruz River and its major tributaries. As previously discussed, hydrographs of wells located on the upper reaches of Tanque Verde Creek and along the Santa Cruz River in the USC sub-basin reflect the impacts of major flood events (Appendix E).

Figure 37. Simulated change in storage: Tucson AMA: 1940-2010.

A) Annual change in storage: 1940 – 2010



B) Cumulative change in storage: 1940 - 2010.

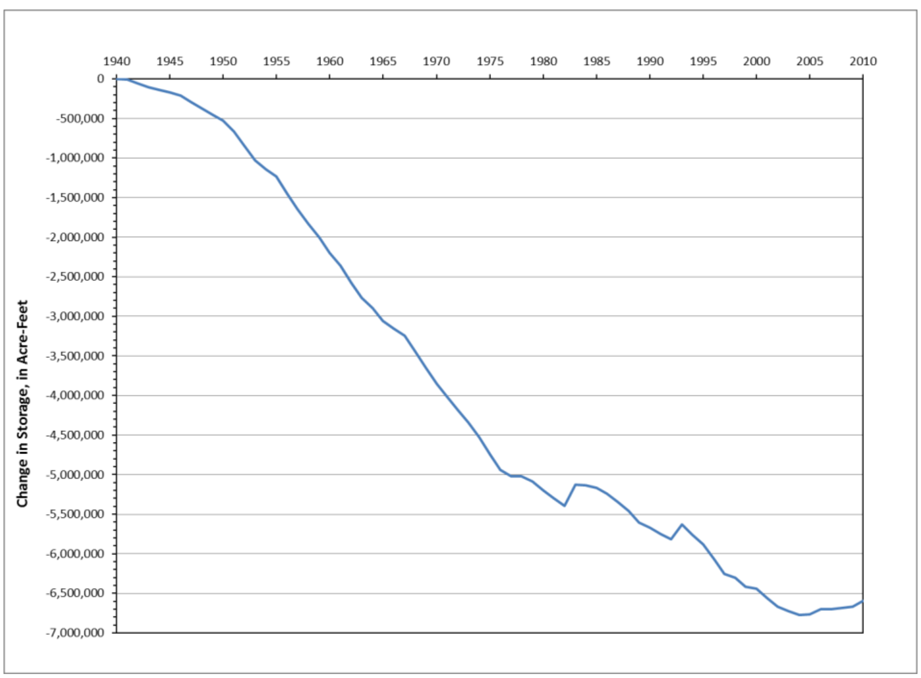
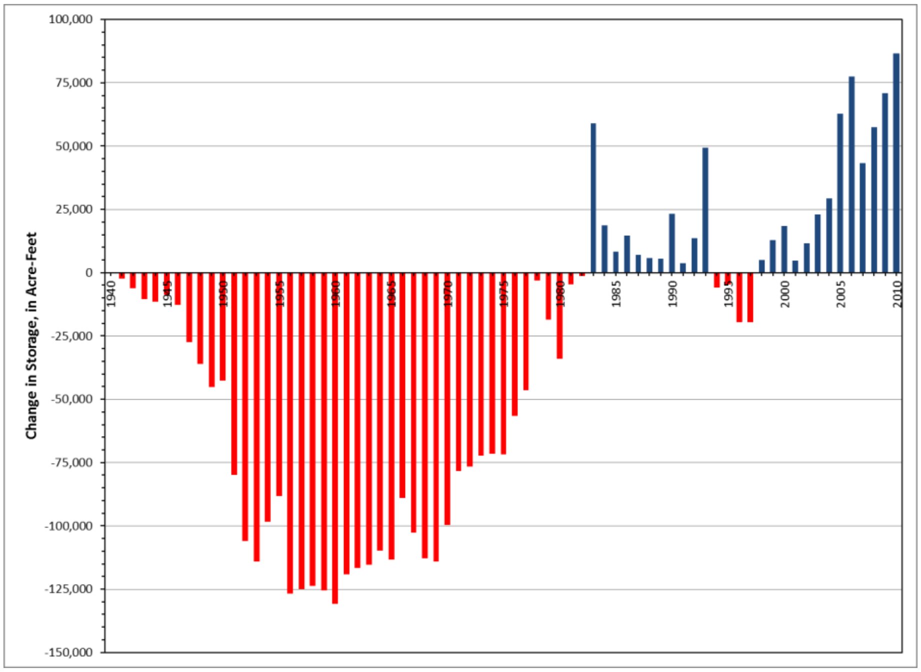


Figure 38. Simulated change in storage: Avra Valley sub-basin: 1940-2010.

A) Annual change in storage: 1940 – 2010



B) Cumulative change in storage: 1940 – 2010

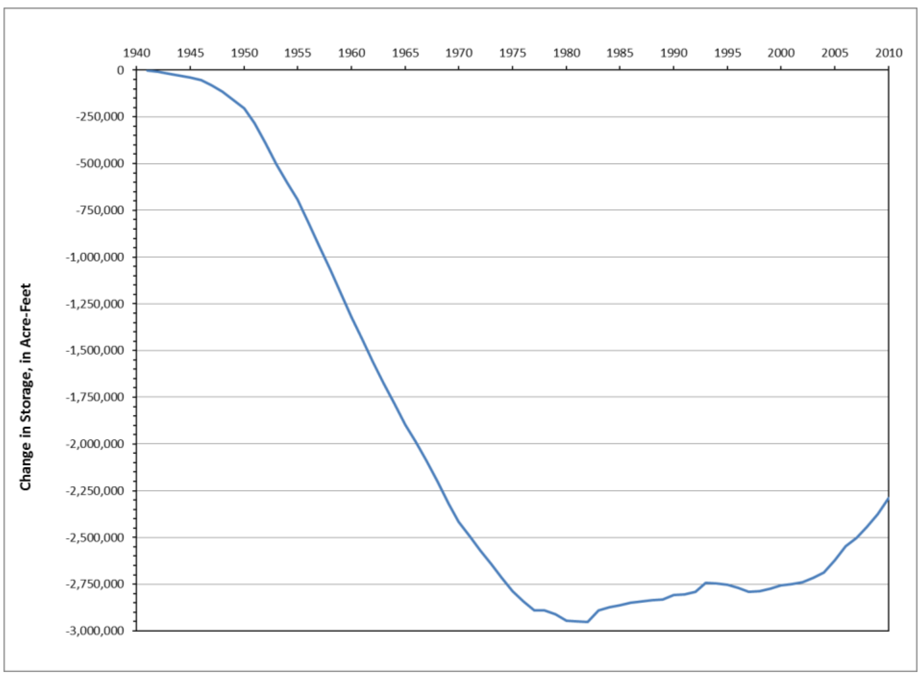
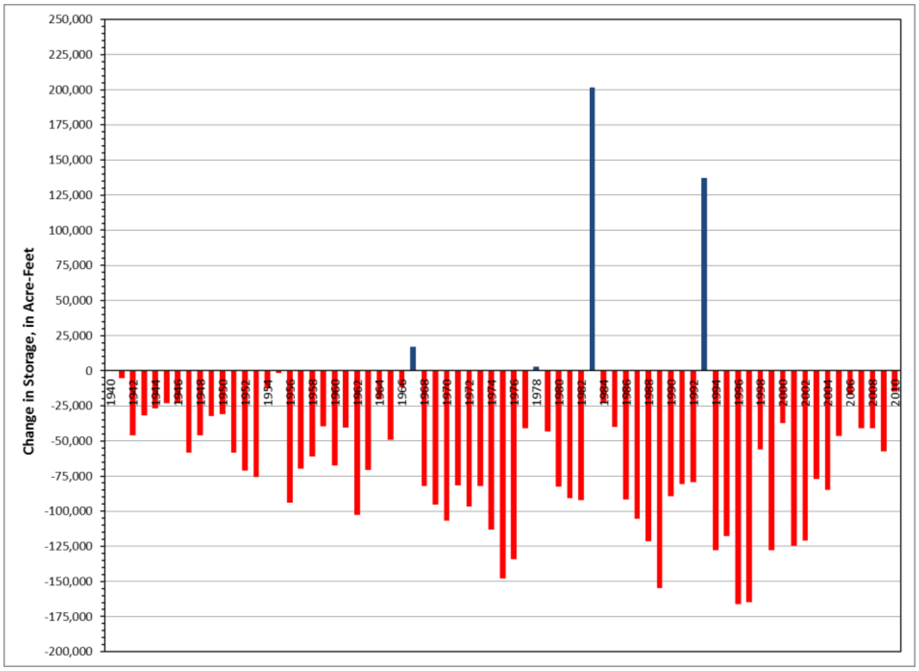
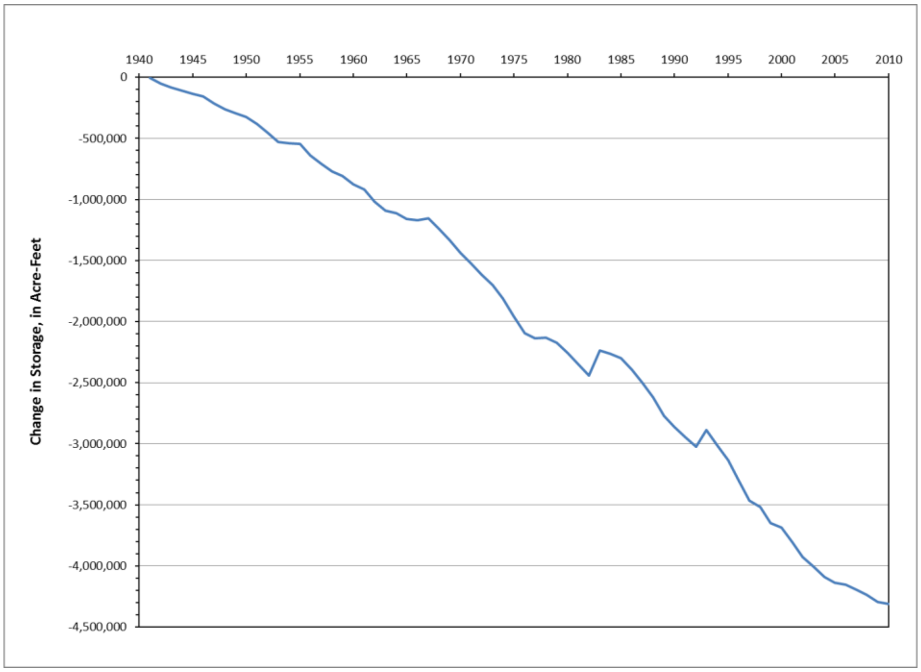


Figure 39. Simulated change in storage: Upper Santa Cruz sub-basin: 1940-2010

A) Annual change in storage: 1940 – 2010.



B) Cumulative change in storage: 1940 – 2010.



5.0 Model Summary and Recommendations

Model Results

The results of the transient model calibrations indicate that the updated Tucson AMA model reasonably simulates the regional groundwater flow system. The model is able to generally simulate the observed historic changes in water levels in both sub-basins. The transient model has very low overall average model error. The mean value for all head residuals is 3.2 feet and the mean of absolute value of all head residuals is 11.3 feet. The ratio of the RMSE to head loss across the model is 1.32 percent, which indicates that the model error represents a very small part of the overall model response. The transient model water budget very closely matches conceptual estimates, and the simulated change in aquifer storage is similar to previously published estimates of change in storage for the TAMA.

Model accuracy is related to the amount, accuracy, and distribution of the data used to develop the model. Model error is evaluated by comparing measured heads to simulated heads and usually reveals small-scale heterogeneities within an aquifer that are difficult for a model to simulate due to cell-size or data limitations. Model error is usually greatest in areas with sparse data or high hydraulic gradients and smallest in areas with large amounts of data or areas with small hydraulic gradients. Better estimates of model input data and/or more data points usually result in a smaller model error and greater confidence in the model results.

Model Limitations and Application

The primary objective of the Tucson 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. This regional groundwater flow model provides a tool for the ADWR and local stakeholders to develop and evaluate long-term management plans for the Tucson AMA. The geodatabase accompanying this report contains the data used to create the model datasets and documents the results from this simulation that will assist future model users.

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 TAMA 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 available data. Large-scale regional models may not be suitable for site-specific locations. This is especially true for model areas that relied on sparse data or are along the model edges where boundary conditions can impact the model results. Cell-size limitation, the lack of localized data, and the regional scale of the analysis can add a higher degree of uncertainty to the simulation of localized conditions. The trial-and-error method of model calibration is somewhat subjective and does not produce a unique solution. Trial-and-error model solutions are subject to uncertainty due to the need to estimate many model input parameters and boundary conditions.

Each ADWR regional model has limitations and it should not be assumed that the models can be used, as is, without first reviewing the various aspects of the model, such as calibration, cell size and boundary conditions, to determine if it is an appropriate tool for a specific task. In many cases, the ADWR models may be sufficient to use, as is; however, it is contingent on the user to review the model for their specific purpose and address any issues before the model can be used to conduct hydrologic analysis required in support of applications submitted to the ADWR recharge program, AAWS program, or well impact analysis requirements. If an ADWR model is used in conjunction with an application, it should be reviewed for suitability before proceeding with the analyses.

Model Recommendations

The update of the Tucson 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 future Tucson model updates.

1. Aquifer test data and well logs need to be collected on a continuing basis. These data need to be complied and maintained at a central location for easy access and inclusion in future model updates to help refine the model layer geometry and aquifer parameters.
2. Water-level monitoring needs to be expanded, especially in areas that are not currently urbanized, but are expected to urbanize in the future. An expanded water-level collection program will provide baseline data for comparison to future model updates.
3. Agricultural irrigation practices, both historic and current, need to be researched to better define the volume of agricultural recharge. Deep percolation of excess irrigation water is the single largest source of recharge to the regional aquifer prior to the development of large-scale artificial recharge projects. A better understanding of past and current agricultural practices and cropping patterns is needed to help refine the currently available estimates of agricultural recharge.
4. The simulation of lagged agricultural recharge needs to evaluated in more detail. A detailed sensitivity analysis comparing lagged and non-lagged rechatrge should be conducted to determine whether it is necessary to lag agricultural recharge in long-term future projections.
5. The current numerical model software, MODFLOW, will need to be kept current to keep pace with improvements in modeling techniques. New packages and features developed for MODFLOW will need to be implemented. Inverse modeling using Parameter Estimation (PEST) needs to investigated and implemented. PEST modeling may help improve our understanding of the regional flow system and reduce model uncertainty.
6. Adding the Stream-Flow Routing (SFR) package to the model to simulate stream recharge may help better define annual stream recharge in the TAMA.

7. Although historic subsidence in the TAMA has not been large compared to subsidence in other AMAs, some historic subsidence has been recorded in both Avra Valley and central Tucson. To account for subsidence the U.S. Geological Survey's latest subsidence package could be incorporated into the model.
8. Implementing the Multi-Node Well (MNW) package to make simulation of past, present, and future groundwater withdrawals more efficient. The MNW package can help alleviate the loss of assigned pumpage due to cell dewatering inherent with the existing well package.

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APPENDIX A

Tucson AMA Stream Gage Data

In Separate File

APPENDIX B

Mine Tailings Seepage Estimates

In Separate File

APPENDIX C

Model Calibration Statistics

In Separate File

APPENDIX D

Model Simulated Water Budget Data

In Separate File

APPENDIX E

Hydrographs: Model Simulated vs. Observed

In Separate File