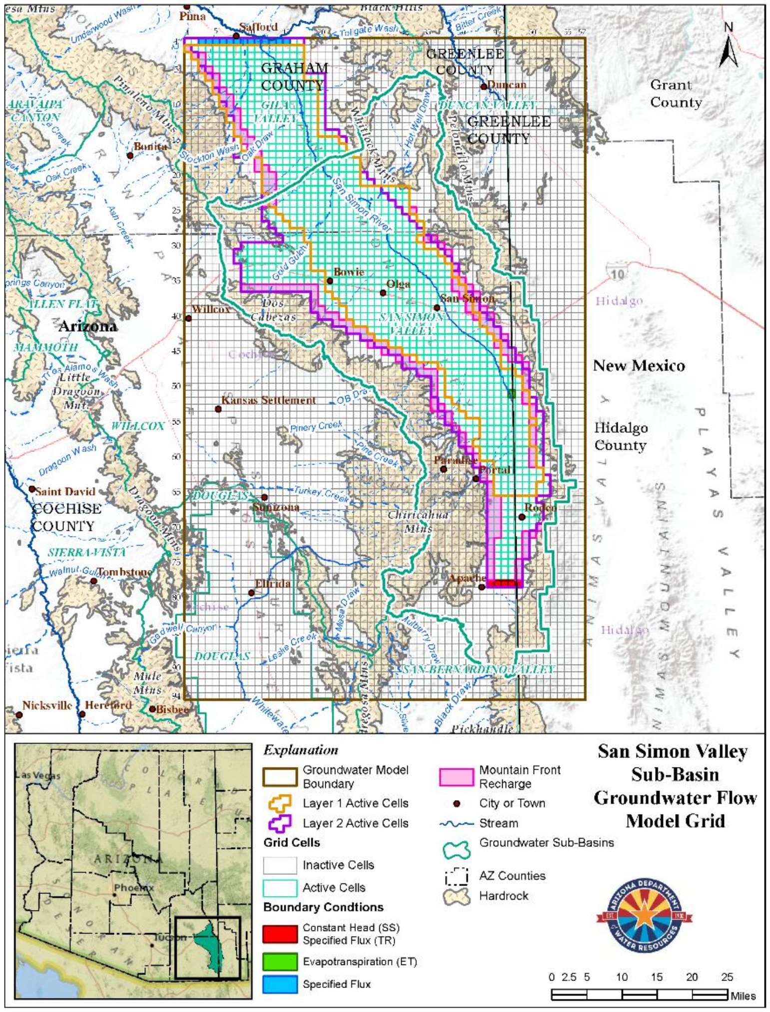
Technical Memorandum

Arizona Department of Water Resources

Groundwater Flow Model of the San Simon Valley Sub-basin



Prepared by the Arizona Department of Water Resources - Hydrology Division

6/17/2015

Table of Contents

Table of Contents 2

List of Figures 3

List of Tables 4

Model Objectives and Background 5

Hydrogeology and History of Groundwater Development of the San Simon Valley Sub-basin 5

Numerical Model Design, Boundary Conditions and Aquifer Parameters 14

Model Inputs 16

Natural Recharge 16

Agricultural Pumping and Recharge 16

Pumpage Distribution 18

Agricultural Recharge Distribution within Modeling Periods 18

1915 to 1951 (Pumping Period 1) 18

1952-1982 (Pumping Period 2) 19

1983-1999 (Pumping Period 3) 19

2000-2014 (Pumping Period 4) 19

Model Calibration Background 22

Steady State (Pre-development 1915) 22

Transient Calibration (1915 to 2015) 24

Model Calibration Results 25

Steady-State (Pre-development 1915) 25

Transient (1915-2015) 30

Model Projection Results (2016 – 2115) 44

Model Limitations 56

References 57

Appendix A - Parameter Sensitivity Data 58

Appendix B - Summary of Simulated Water Budgets for San Simon Valley Sub-basin Model From MODFLOW (LST) Files 60

Appendix C - Projected Depth to Water In 2115 for Agricultural Areas of the San Simon Valley Sub-basin 62

List of Figures

Figure 1 Map of the San Simon Valley Sub-basin 6
Figure 2 Depth-to-Bedrock San Simon Valley Sub-basin 8
Figure 3 Conceptual Model of the Predevelopment Groundwater Flow in the San Simon Valley Sub-basin 9
Figure 4 Hydrograph of a Deep Agricultural Well in the Bowie Area 10
Figure 5 Hydrograph of a Shallow Agricultural Well in the San Simon Area 10
Figure 6 Conceptual Model of the Modern Groundwater Flow in the San Simon Valley Sub-basin 12
Figure 7 USGS Annual Estimated Pumpage San Simon-Bowie-Rodeo Area 13
Figure 8 San Simon Valley Sub-basin Groundwater Flow Model Grid 15
Figure 9 Location of Wells Used to Simulate Agricultural Pumping & Ag Recharge Zones San Simon Valley Sub-basin Groundwater Flow Model 21
Figure 10 Weighted Simulated Values vs. Weighted Residual Value 26
Figure 11 Steady State Weighted Residuals (Obs – Sim Head * Weight) San Simon Valley Sub-basin Groundwater Flow Model 27
Figure 12 1915 Simulated Heads (Water Level Elevations) Layer 1 San Simon Valley Sub-basin Groundwater Flow Model 28
Figure 13 1915 Simulated Heads (Water Level Elevations) Layer 2 San Simon Valley Sub-basin Groundwater Flow Model 29
Figure 14 Calibration Residuals Histogram 31
Figure 15 Hydrograph and Transient Head Calibration Target Locations San Simon Valley Sub-basin Groundwater Flow Model 32
Figure 16 Simulated and Observed Hydrographs: 1915-2115 33
Figure 17 Simulated and Observed Hydrographs: 1915-2115 34
Figure 18 Simulated and Observed Hydrographs: 1915-2115 35
Figure 19 Simulated Upward Vertical Hydraulic Gradient, 1916: Cross-Sectional View at Model Row 35 (Bowie-San Simon area) 37
Figure 20 Simulated Downward Vertical Hydraulic Gradient, 2015: Cross-Sectional View at Model Row 35 (Bowie - San Simon area) 37
Figure 21 2015 Simulated Heads (Water Level Elevations) Layer 1 San Simon Valley Sub-basin Groundwater Flow Model 38
Figure 22 2015 Simulated Heads (Water Level Elevations) Layer 2 San Simon Valley Sub-basin Groundwater Flow Model 39
Figure 23 2015 Simulated Model Drawdown & Dry Cells Layer 1 San Simon Valley Sub-basin Groundwater Flow Model 40
Figure 24 2015 Simulated Model Drawdown & Dry Cells Layer 2 San Simon Valley Sub-basin Groundwater Flow Model 41
Figure 25 2015 Saturated Thickness Layer 1 San Simon Valley Groundwater Flow Model 42
Figure 26 2015 Saturated Thickness Layer 2 San Simon Valley Sub-basin Groundwater Flow Model 43
Figure 27 Simulated AG Pumpage (Annualized in AF/yr) 46
Figure 28 Simulated AG Recharge (Annualized in AF/yr) 47
Figure 29 Simulated AG Pumpage and Recharge (Annualized in AF/yr) 48

Figure 30 2115 Simulated Heads (Water Level Elevations) Layer 1 San Simon Valley Groundwater Flow Model 49
Figure 31 2115 Simulated Heads (Water Level Elevations) Layer 2 San Simon Valley Sub-basin Groundwater Flow Model 50
Figure 32 2115 Simulated Model Drawdown & Dry Cells Layer 1 San Simon Valley Sub-basin Groundwater Flow Model 51
Figure 33 2115 Simulated Model Drawdown & Dry Cells Layer 2 San Simon Valley Groundwater Flow Model 52
Figure 34 Simulated Drawdown Between 2015 and 2115 Layer 2 San Simon Valley Groundwater Flow Model 53
Figure 35 2115 Saturated Thickness Layer 1 San Simon Valley Groundwater Flow Model 54
Figure 36 2115 Saturated Thickness Layer 2 San Simon Valley Groundwater Flow Model 55

List of Tables

Table 1 USGS Estimated Pumping in the Bowie-San Simon Area (1915-2014) 17
Table 2 Calibrated San Simon Valley Sub-basin Model Hydraulic Conductivities 23
Table 3 Calibrated San Simon Valley Sub-basin Model Storage Properties 25
Table 4 Simulated San Simon Valley Sub-basin Steady State Water Budget 26
Table 5 Simulated Transient Water Budget (1915 – 2015, 101 years): Annualized Rates for the 1915 to 2015 Period 30
Table 6 Simulated Projection Water Budget (2016 – 2115, 100 years): Annualized Rates for the 2016 to 2115 Period 45

Model Objectives and Background

This memorandum documents the Arizona Department of Water Resources (ADWR or the Department) numerical groundwater flow model (model) of the San Simon Valley Sub-basin of the Safford Groundwater Basin. The model was developed to simulate regional groundwater flow conditions in the general San Simon Valley Sub-basin area. The primary objectives for developing the model include: 1) gaining a better understanding of the regional groundwater flow system and associated parameters; and 2) using the model as a tool for projecting groundwater flow conditions in the future based on current rates of withdrawal.

The groundwater flow model was developed and calibrated to simulate groundwater flow conditions in the San Simon Valley Sub-basin during the pre-development era (steady state, circa 1915) and the transient period of groundwater development between 1915 and 2015 (101 years). In addition, the model was used to simulate a 100-year projection from 2016 to 2115 using current rates of withdrawal. This memorandum provides information about the groundwater flow system, the conceptual flow model, available calibration data, the model development and calibration process, methodology for estimating system stresses (i.e., pumping and incidental recharge) and model limitations. Also included are model results including simulated water budget information, simulated and observed groundwater levels as well as estimates of saturated thickness and drawdown over time. In addition, simulated contours representing horizontal heads and vertical heads for selected cross-sections are also presented.

Hydrogeology and History of Groundwater Development of the San Simon Valley Sub-basin

The San Simon Valley Sub-basin of the Safford Basin is an intermontaine valley which includes approximately 1,930 square miles of southeastern Arizona and adjoining southwest New Mexico. The San Simon Valley Sub-basin is bounded by mountains to the east and west, the San Bernardino Valley groundwater basin to the south and the Gila Valley Sub-basin to the north (Figure 1). The San Simon Valley Sub-basin is a large, deep trough-like depression formed by the uplift of mountain blocks relative to the blocks that underlie the basin floor (Barnes, 1991). The mountains are composed of relatively impermeable metamorphic, igneous and indurated sedimentary rocks; the groundwater sub-basin is filled with water-bearing deposits mainly derived from the erosion of the surrounding mountains. The maximum depth of the San Simon Valley Sub-basin has been estimated by Gootee (2012) to exceed 8,000 feet below land surface in the central portion of the sub-basin south of San Simon, with shallower bedrock being found along the basin margins (Figure 2).

The main source of natural recharge to the groundwater sub-basin is from runoff and infiltration of snow melt and rainfall along the higher mountain fronts and channels of ephemeral streams that flow from the mountains (Figure 3). Groundwater generally flows from recharge areas toward the axis of the valley and then northward toward the Gila Valley Sub-basin and the Safford area. Prior to extensive groundwater development in the sub-basin some groundwater was discharged as base flow and evapotranspiration (ET) to a cienega area located along the Arizona-New Mexico border that formed the headwaters of the San Simon River (Figure 1).

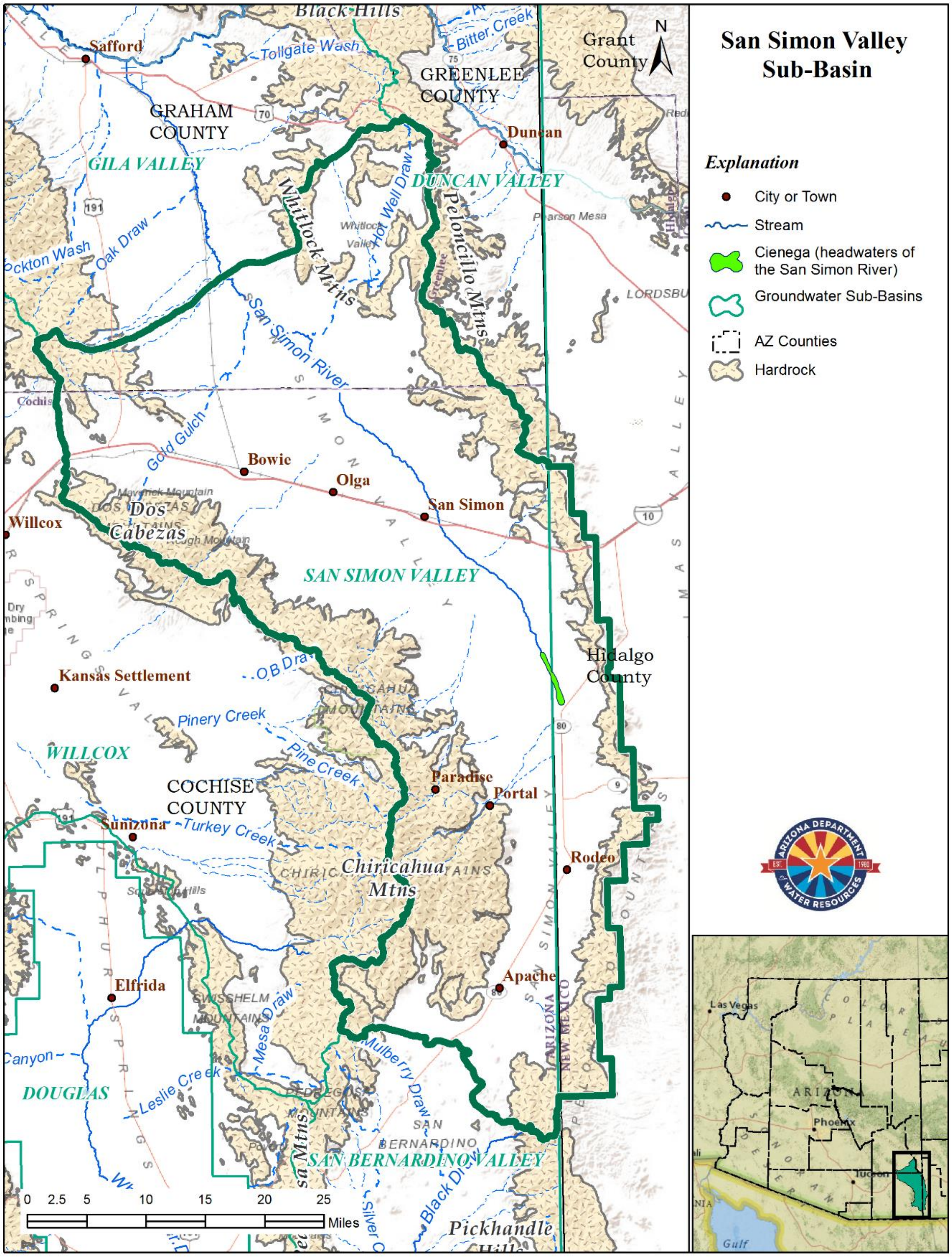


Figure 1 Map of the San Simon Valley Sub-basin

Near the mountain fronts and recharge areas the basin-fill deposits are generally coarse grained and comparatively permeable, and unconfined “water table” conditions generally exist. Near San Simon and Bowie, the “Blue Clay” is commonly present that forms an aquitard between the upper “water table” and lower confined or “artesian” basin-fill aquifer (Figure 3). Early hydrologic reports reference the existence of thick clay deposits in the San Simon and Bowie areas that created confined conditions in the lower aquifer and provided opportunities to drill “flowing” artesian wells (Schwennesen and Forbes, 1917).

From about 1910 to the early 1950s over 100 “flowing” artesian wells were drilled in the San Simon sub-basin that tapped the deeper confined aquifer for irrigation and gradually reduced the artesian pressure. Following the introduction of modern high-capacity pumps in the early 1950s, agricultural activity and groundwater demand rapidly increased in the sub-basin and water levels declined in both the shallow and deep aquifers until the early 1980s (Figures 4 and 5).

Major impacts of the increased groundwater withdrawals in the sub-basin included a substantial reduction in artesian pressure in the lower aquifer system in the Bowie and San Simon areas with the eventual elimination of flowing wells. Additionally, groundwater discharge and evapotranspiration from the shallow, unconfined aquifer in the cienega area at the headwaters of the San Simon River was essentially eliminated (Figure 6). Instances of land subsidence and earth fissuring also developed near Bowie and San Simon where fine grained sediments in the aquifer compacted.

Around 1983 there was a significant decline in the agricultural economy in the San Simon Valley Sub-basin and groundwater demand decreased sharply (Figure 7). A major effect of the reduced agricultural pumping in the sub-basin was the recovery and stabilization of water levels in many of the wells monitored in the Bowie and San Simon areas (Figures 4 and 5). Groundwater level decline trends in the basin have remained relatively constant in the sub-basin for the last 20 to 30 years, with sub-basin wide water level change rates averaging about -1.7 feet/year over the period from 2007 to 2015 (ADWR, 2015).

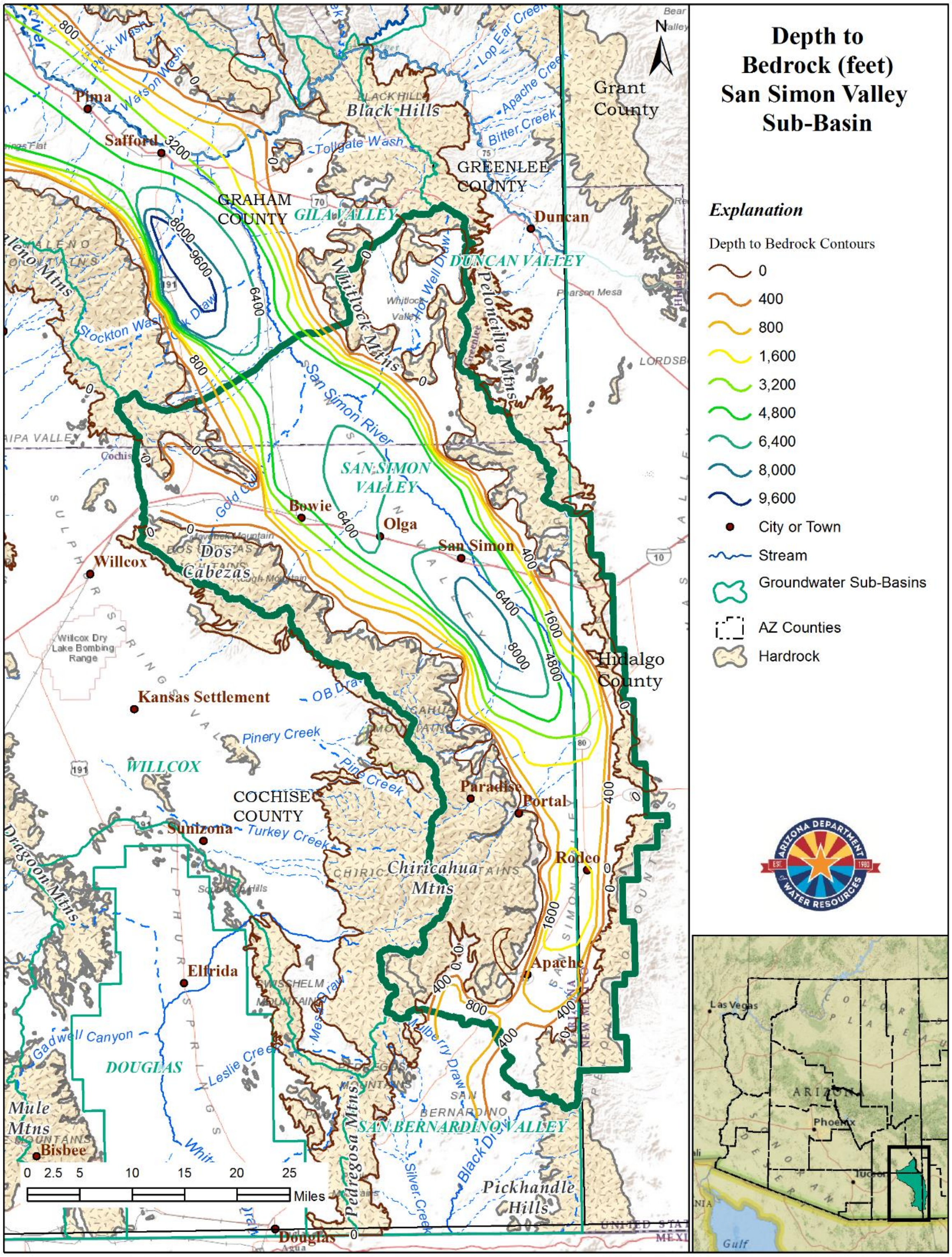


Figure 2 Depth-to-Bedrock San Simon Valley Sub-basin

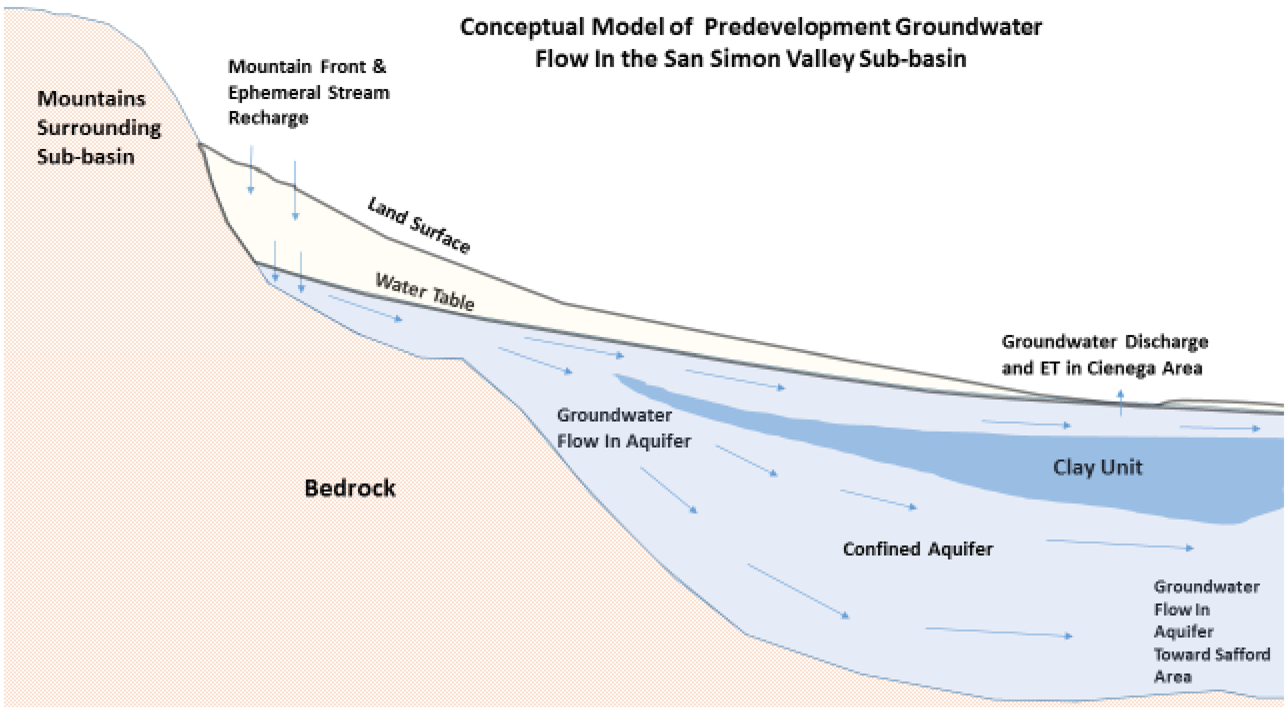
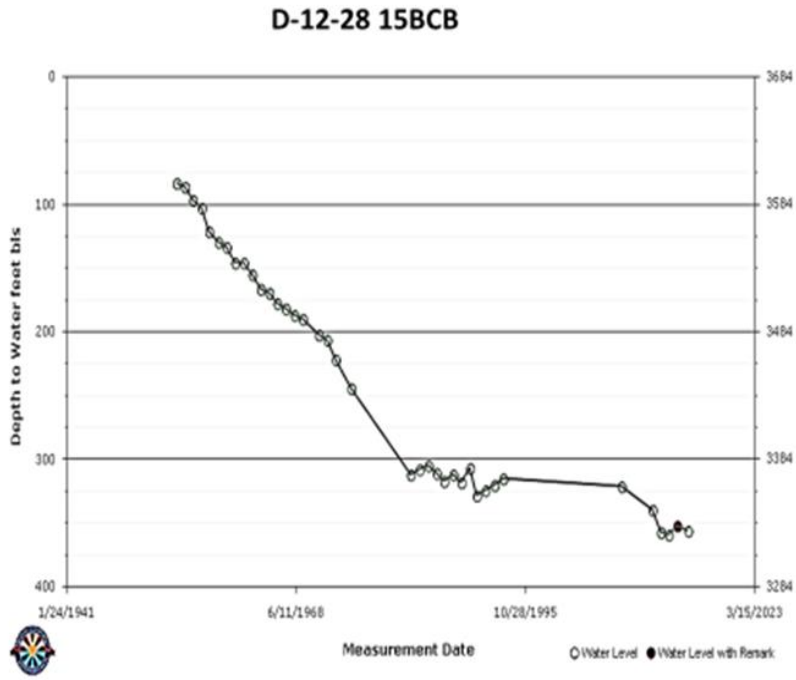
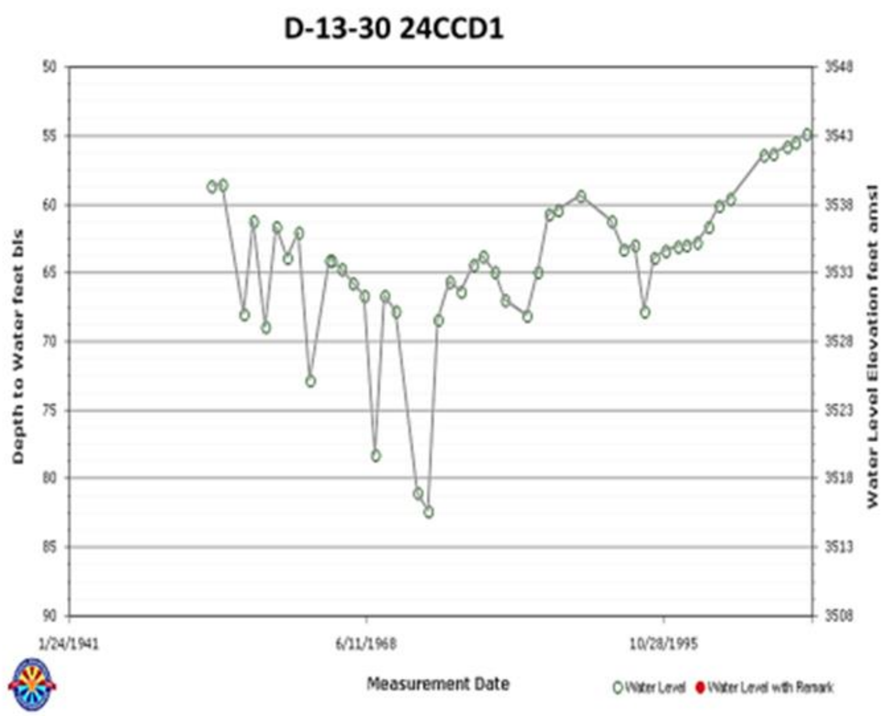


Figure 3 Conceptual Model of the Predevelopment Groundwater Flow in the San Simon Valley Sub-basin



Site ID = 322334109285801
Regno = 55-625831
Well Depth = 1,000'
Diameter = 16"
Irrigation
DTW = 355.6' 2/25/2015

Figure 4 Hydrograph of a Deep Agricultural Well in the Bowie Area



Site ID = 321648109142301
Regno = 55-624464
Well Depth = 120'
Diameter = 16"
Unused
DTW = 54.8' 11/18/08

Figure 5 Hydrograph of a Shallow Agricultural Well in the San Simon Area

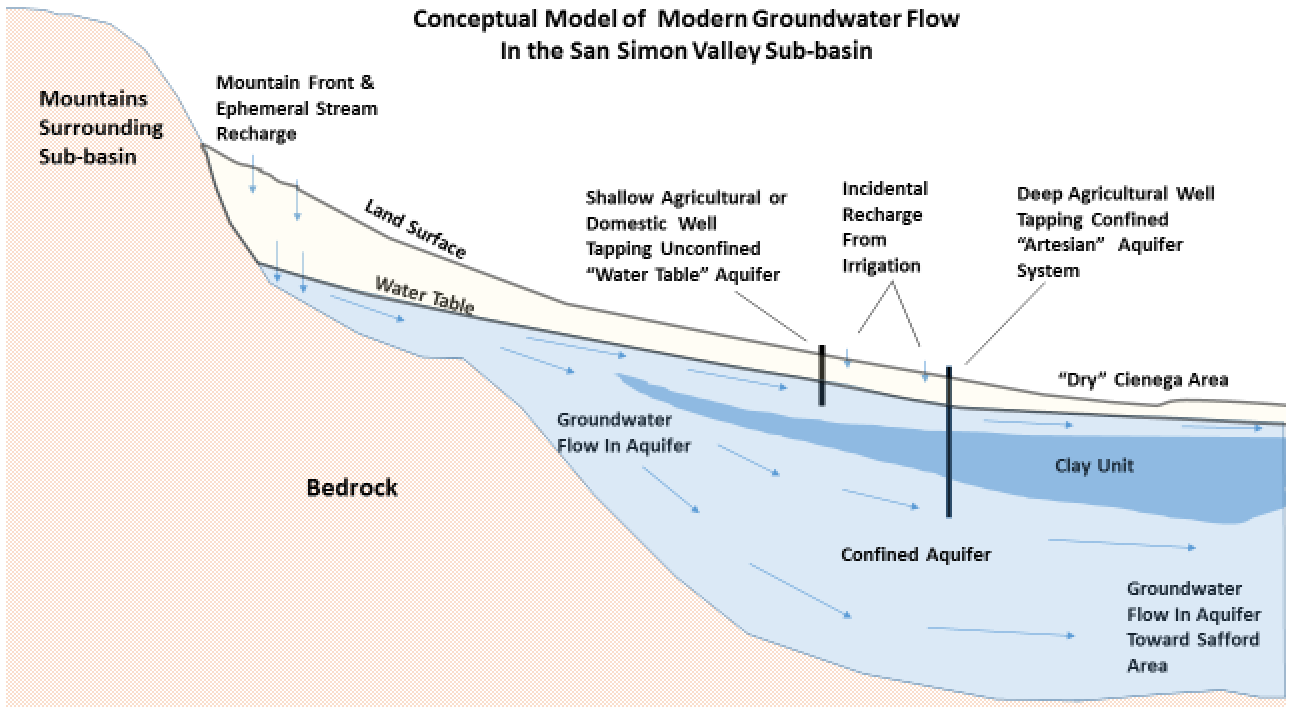


Figure 6 Conceptual Model of the Modern Groundwater Flow in the San Simon Valley Sub-basin

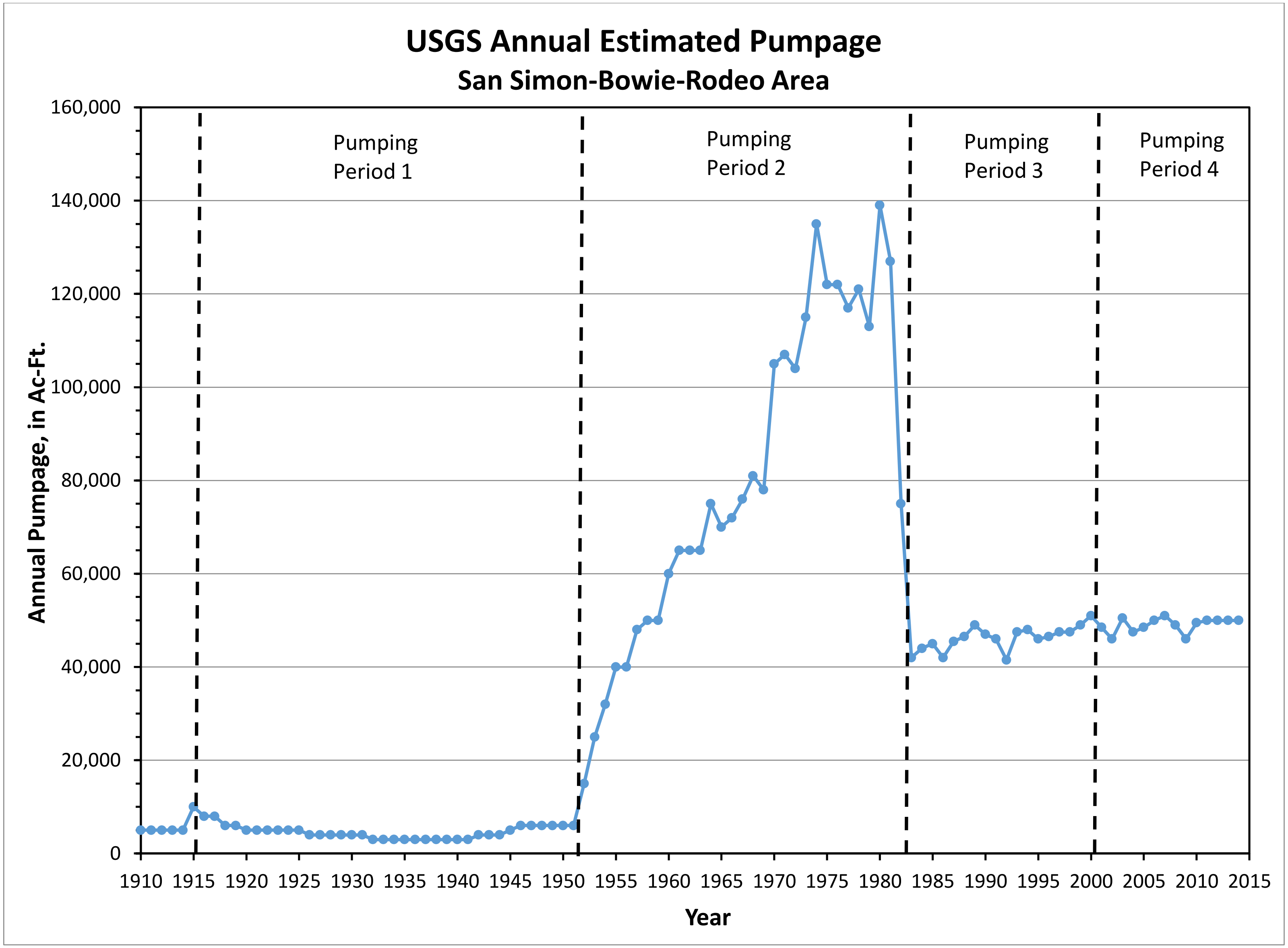


Figure 7 USGS Annual Estimated Pumpage San Simon-Bowie-Rodeo Area

Numerical Model Design, Boundary Conditions and Aquifer Parameters

ADWR has developed a numerical groundwater flow model of the San Simon Valley Sub-basin to evaluate groundwater conditions for the pre-development era (steady-state, circa pre-1915), the period of groundwater development (transient, 1915 – 2015) and for projected future groundwater conditions (2016 – 2115). The model was developed using the U.S. Geological Survey (USGS) MODFLOW-2000 Modular Finite-Difference Groundwater Flow Model (Version 1.19.01) (Harbaugh, and others, 2000). The Visual MODFLOW Flex Graphical User Interface (GUI) was used to facilitate model construction and calibration (Waterloo Hydrogeologic, 2015).

The model has a uniform grid of square mile cells composed of 94 rows, 57 columns and 2 layers (Figure 8). The model bottom (the bottom of model Layer 2) corresponds to the estimated depth-to-bedrock, but was truncated at an elevation of -3,000 feet below mean sea level in the central portions of the sub-basin. Estimates of basin-fill unit thicknesses presented by Gootee (2012) were modified in some areas using available well log data.

The active model area is bounded by no-flow cells to the east and west to simulate the surrounding mountainous areas. Constant heads were chosen to simulate steady-state groundwater flow into the model area from the south that originates in the area of the groundwater divide between the San Simon Valley Sub-basin and the San Bernardino Basin. Constant flux cells are used to simulate northerly flow from the model in the Gila Valley area, near Safford. Natural recharge is simulated along mountain fronts and ephemeral streams flowing from the mountains using recharge cells (Figure 8).

Layer 1 of the groundwater model is simulated as an unconfined layer MODFLOW- LAYCON (1); mainly composed of younger, unconsolidated alluvial sediments (sands, gravels, silts, clays and conglomerates) and generally corresponds to the upper basin-fill deposits described by Gootee (2012). Model Layer 2 is a fully convertible confined/unconfined layer MODFLOW- LAYCON (3); consisting of older, more consolidated basin-fill sediments and evaporites (including conglomerate, clay, anhydrite, halite, etc.) with some inter-bedded volcanics. Layer 2 generally corresponds to the lower basin-fill deposits described by Gootee (2012). Layer 2 may be confined or unconfined in different areas depending on local conditions.

The Blue Clay aquitard separates the upper and lower basin-fill aquifers and restricts vertical flow. The vertical restriction of groundwater flow associated with the aquitard is simulated in an implicit manner through the calibration of independent vertical hydraulic conductivity parameters (K_z), and horizontal hydraulic conductivity parameters (K_x and K_y). The implicit simulation of vertical flow allows for a simpler model with fewer parameters yet facilitates full, 3-D groundwater flow properties.

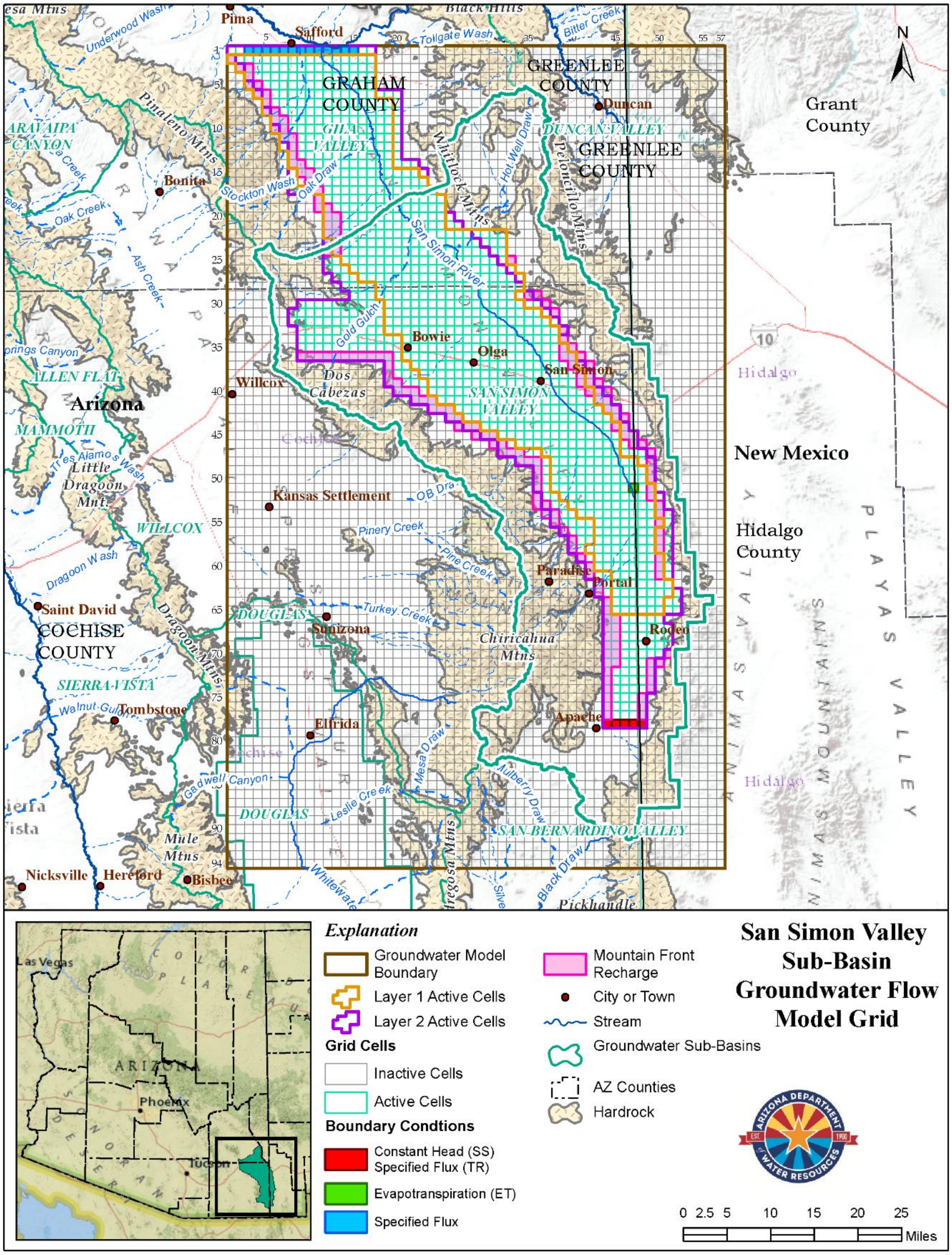


Figure 8 San Simon Valley Sub-basin Groundwater Flow Model Grid

Model Inputs

Natural Recharge

The main source of natural recharge to the San Simon Valley Sub-basin is from runoff and infiltration of snow melt and rainfall along the higher mountain fronts and channels of ephemeral streams that flow from the mountains. The conceptual model generally assumes that groundwater continues to flow horizontally down-gradient (to the north-northwest) towards the Gila Valley Sub-basin and the Safford area. Groundwater flow to the north, originating as natural recharge, was estimated at 30,000 AF/yr. This underflow/natural recharge rate includes flux from the San Simon Valley Sub-basin estimated at 17,000 AF/yr (Freethey and Anderson, 1986), as well as additional groundwater flow from mountain front areas to the northwest (Mt. Graham) and northeast, estimated at about 13,000 AF/yr. Natural recharge in the San Simon Valley Sub-basin model was simulated using recharge cells that are shown in Figure 8. Natural recharge was assumed to be constant throughout the analysis.

Agricultural Pumping and Recharge

Agricultural development began in the San Simon-Bowie-Rodeo area of the Safford Groundwater basin in 1910 when flowing artesian water conditions were discovered near San Simon, Arizona. Schwennesen (1917) reported that by 1915 there were about 125 flowing artesian wells and another 60 to 70 non-flowing wells supplying irrigation water in the San Simon-Bowie area. Schwennesen (1917) mapped almost 1,900 acres of irrigated lands in the San Simon-Bowie area and estimated total annual irrigated water use for 1915 to be about 11,000 acre-feet. Many farms were abandoned after World War I and pumpage declined to about 3,000 acre-feet annually until just after World War II. Agricultural development increased after 1946 and then again in the very early 1950s with groundwater pumpage peaking in the mid-1970s at 135,000 acre-feet (Table 1). Groundwater withdrawals decreased markedly in the early 1980s, and have remained relatively stable since then, averaging between 45,000 and 50,000 AF/yr (Table 1). The estimated annual groundwater withdrawals used for the San Simon Valley Sub-basin model are presented graphically in Figure 7.

Total cropped acreage and the distribution of individual agricultural fields through time is not well documented for the San Simon-Bowie-Rodeo area. As discussed above, Schwennesen (1917) mapped approximately 1,900 acres of cropped fields in 1915. There are no documented maps showing the distribution of agriculture fields in the San Simon-Bowie-Rodeo area until the early 1970s when the University of Arizona's College of Agriculture and the USGS published maps delineating croplands in Arizona (U. S. Geological Survey, 1972, University of Arizona, 1974). Beginning in 2006, the USGS started developing GIS shape files that delineated individual cropped fields in San Simon-Bowie-Rodeo area. These shape files are currently available for 2006-07, 2009, 2013, and 2014.

The distribution of cropped fields for the model simulation period, 1915 to 2014, was divided into four modeling periods (Figure 7) based on the available cropped acreage maps. In each modeling period one of the available crop maps was used to distribute agricultural pumpage and recharge within the model domain. The modeling periods, map source used, and the method of calculating and distributing pumpage and agricultural recharge are described below.

Table 1 USGS Estimated Pumping in the Bowie-San Simon Area (1915-2014)

Year	Pumpage		Year	Pumpage		Year	Pumpage
1910	5,000		1945	5,000		1980	139,000
1911	5,000		1946	6,000		1981	127,000
1912	5,000		1947	6,000		1982	75,000
1913	5,000		1948	6,000		1983	42,000
1914	5,000		1949	6,000		1984	44,000
1915	10,000		1950	6,000		1985	45,000
1916	8,000		1951	6,000		1986	41,500
1917	8,000		1952	15,000		1987	45,500
1918	6,000		1953	25,000		1988	46,500
1919	6,000		1954	32,000		1989	49,000
1920	5,000		1955	40,000		1990	47,000
1921	5,000		1956	40,000		1991	46,000
1922	5,000		1957	48,000		1992	41,500
1923	5,000		1958	50,000		1993	47,500
1924	5,000		1959	50,000		1994	48,000
1925	5,000		1960	60,000		1995	46,000
1926	4,000		1961	65,000		1996	46,500
1927	4,000		1962	65,000		1997	47,500
1928	4,000		1963	65,000		1998	47,500
1929	4,000		1964	75,000		1999	49,000
1930	4,000		1965	70,000		2000	51,000
1931	4,000		1966	72,000		2001	48,500
1932	3,000		1967	76,000		2002	46,000
1933	3,000		1968	81,000		2003	50,500
1934	3,000		1969	78,000		2004	47,500
1935	3,000		1970	105,000		2005	48,500
1936	3,000		1971	107,000		2006	50,000
1937	3,000		1972	104,000		2007	51,000
1938	3,000		1973	115,000		2008	49,000
1939	3,000		1974	135,000		2009	46,000
1940	3,000		1975	122,000		2010	49,500
1941	3,000		1976	122,000		2011	50,000
1942	4,000		1977	117,000		2012	50,000
1943	4,000		1978	121,000		2013	50,000
1944	4,000		1979	113,000		2014	43,750

Pumpage Distribution

Pumpage for the San Simon Model was derived from annual estimates of ground-water pumpage developed by the USGS (Anning and Duet, 1994, USGS, 2015). Much of the historic pumpage estimates, pre-2006, are based on power records obtained by the USGS. Since 2006, the U.S. Geological Survey has used satellite imagery, ground-based surveys of field crops, irrigation efficiency estimates, and consumptive use values for individual crop types to estimate pumpage for the Sam Simon-Bowie-Rodeo area (Table 1).

The distribution of model pumpage (Figure 9) was based on well locations obtained from ADWR's Ground Water Site Inventory (GWSI) well database, the ADWR Well Registry (55 File) database, and the inactive Arizona State Land Department's Well Registry (35 File) database. The 35 File is an inactive database of wells registered with the state prior to the creation of ADWR. However, the file contains extremely valuable historical well construction data that is not always available in either the GWSI or the 55 File databases.

Well locations, water use, and construction data from all three databases for wells in the model domain were collated into a spreadsheet. The well records were then analyzed and duplicate wells were matched. Any relevant water use and construction information from multiple entries were combined into a single entry representing all available data regarding a specific well. Small diameter wells used for stock watering and domestic use were eliminated from the spreadsheet for this analysis, leaving only wells believed to be supplying irrigation water. The USGS has estimated total annual non-irrigation pumping within the San Simon Valley Sub-basin to be less than 300 AF/yr.

The agricultural wells were then grouped by cell and an average depth for wells within a cell was calculated. Cell-specific annual pumpage was assigned based on the percentage of estimated active agricultural fields that fell within a cell for each modeling period and the estimated annual pumpage. The recharge distribution discussion below provides more details regarding crop acreage distributions for each modeling period. The initial vertical distribution of pumpage was based on the cell-averaged well depth, and was modified during model calibration.

Agricultural Recharge Distribution within Modeling Periods

1915 to 1951 (Pumping Period 1)

The first 36 years of the model simulation used the agricultural crop map developed by Schwennesen (1917) as the basis for distributing agricultural recharge. For modeling purposes, it is assumed that the distribution of cropped fields remained static for this period of time and agricultural recharge was distributed to cells with cropped fields.

The maximum annual agricultural recharge was calculated by multiplying the estimated annual pumpage by the remainder of: *one minus the irrigation efficiency factor* (Note that irrigation efficiency factors range from 50 % to 90%). For this first modeling period flood irrigation was assumed to have been used to deliver water to fields and the irrigation efficiency factor ranged from 50 percent in 1915 to 65 percent in 1951. Using Schwennesen's 1917 distribution of agricultural fields, the number of acres and the percentage of the total agricultural acres per cell were calculated. Cell-specific agricultural recharge (Figure 9) was calculated by multiplying the estimated maximum annual agricultural recharge times a cell's percentage of the total cropped acreage, as determined by overlaying the model cell grid over the map of cropped fields.

1952-1982 (Pumping Period 2)

The period 1952 to 1982 represents the time of maximum agricultural development in the San Simon-Bowie-Rodeo area. Estimated agricultural pumpage increased from 6,000 acre-feet per year to as much as 135,000 acre-feet per year. There are two sources that depict the distribution of irrigated areas that fall within this time period. The USGS produced a report in 1972 that showed cropped areas in Arizona from the early 1960s. This map delineated 23,000 acres of irrigated lands in the San Simon-Bowie-Rodeo area. A second report, published in 1974 from the University of Arizona, is a state-wide atlas of cropland by county for the 1972-1973 irrigation season. This atlas mapped 34,800 acres of cropped lands in the San Simon-Bowie-Rodeo area. The general distribution of cropped areas is very similar for both sources; however, the University of Arizona atlas shows larger cropped areas, particularly in the vicinity of San Simon.

The distribution of cropped acreage from the University of Arizona's atlas was deemed to represent the maximum extent of agriculture for this modeling period. All the cropped areas in the atlas are assumed to have been continuously active during this modeling period, and agricultural recharge was assigned to cells with cropped areas. Total annual agricultural recharge and the cell-specific agricultural recharge were calculated using the method described above. For this second modeling period irrigation efficiency was assumed to increase through time with the introduction of improved water delivery methods. The irrigation efficiency factor ranged from 65 percent in 1952 to 70 percent in 1982.

1983-1999 (Pumping Period 3)

After 1982, agricultural pumpage decreased rapidly from over 100,000 acre-feet per year to less than 45,000 acre-feet per year (Table 1). It was assumed that the cropped acreage footprint decreased as the pumpage decreased over this time. An estimated cropping distribution pattern for 1982 to 1999 was developed using the 2006 USGS cropping data and an air photo overlay. This crop distribution identified fields that may have been active during this modeling period and totaled about 27,000 acres. This estimated crop distribution was assumed to have been active during the modeling period and agricultural recharge was distributed to the cells containing crops. Total annual agricultural recharge and the cell-specific agricultural recharge were calculated using the methods described above. Irrigation efficiency was again assumed to have increased during the third modeling period, with the irrigation efficiency factor increasing from 70 percent in 1983 to 75 percent by 1999.

2000-2014 (Pumping Period 4)

The final agricultural modeling period runs from 2000 to 2014. Beginning in 2006, much more information is available on cropping pattern in the San Simon-Bowie-Rodeo area. Not only is the general crop distribution pattern known, but individual fields and their crop types have been mapped by the USGS.

This increases not only the accuracy of the recharge distribution, but also enables a more accurate estimation of the volume of recharge. For the period from 2000 to 2014, the data used to calculate and distribute agricultural recharge are based on crop survey data from 2006, 2007, 2009, 2013, and 2014. The crop data from 2006 was used to assign recharge for 2000 to 2006, recharge from 2007 to 2011 was assigned using 2007 and 2009 crop data, recharge for 2012 and 2013 was assigned using 2013 crop survey data, and the 2014 crop survey data was used to assign the 2014 agricultural recharge.

Agricultural recharge calculations for the previous recharge periods were based on general outlines of irrigated areas. The generalized irrigated outlines were then overlain with the model cell grid and the percentage of those irrigated areas that fell within a specific cell were calculated. The irrigated area percentages were then multiplied with the total estimated agricultural recharge to determine cell-specific recharge. Recent data, from 2006 to 2014, delineates individual fields, the crops grown in the field and the delivery method for the irrigation water. This allows field specific recharge to be calculated using the USGS values for the consumptive use (CU) of the crop, the irrigation efficiency of the irrigation system delivering water to the field, and the size of the field. Using this method, the cell-specific recharge for a cell can be summed by multiplying the percentage of a field that falls within a cell by the field's calculated recharge. If multiple field fragments fall within a cell, then summing the various field fragments will yield the cell-specific agricultural recharge.

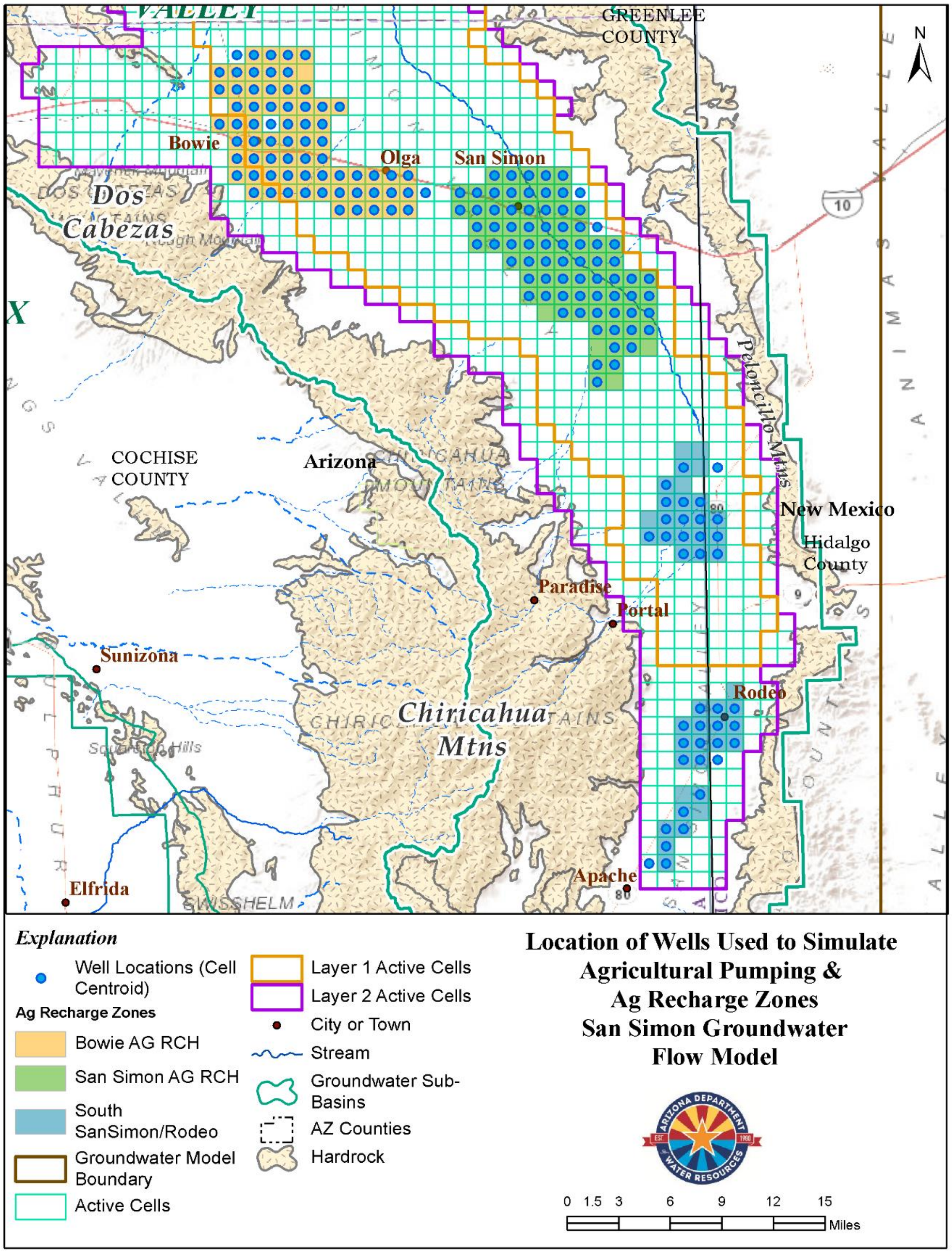


Figure 9 Location of Wells Used to Simulate Agricultural Pumping & Ag Recharge Zones San Simon Valley Sub-basin Groundwater Flow Model

Model Calibration Background

Non-linear regression (PEST)[1] was used extensively to develop, calibrate and better understand the model and associated model parameters, boundary conditions and groundwater system stresses (WinPEST, 2003). One of the objectives of non-linear regression is to minimize model error with respect to observation data, or to minimize a weighted "objective function". Accordingly, observation data including heads (measured groundwater elevations), estimated groundwater flows, and a-priori data on hydraulic conductivity were used directly to calibrate model parameters. The results of non-linear regression analyses can make the calibration of model parameters transparent to the modeler and audience, and can facilitate the evaluation of alternative conceptual models. To the extent possible, alternative conceptual models were explored during this investigation. The methods used for model development and calibration generally follow guidelines established by the USGS (Hill, 1998)

Steady State (Pre-development 1915)

To represent the significant early-period pressure head associated with the lower artesian aquifer in the Bowie and San Simon areas, mountain front recharge (MFR) was applied along the edges of the sub-basin in model layer 2. By imposing MFR at comparatively high elevations, relatively high hydraulic pressure is partially retained down-gradient within layer 2 towards the valley floor by values of horizontal hydraulic conductivity that are, typically, many orders-of-magnitude greater than vertical hydraulic conductivity. In the Bowie and San Simon areas, groundwater flow in layer 2 is greatly restricted in the vertical direction by the Blue Clay aquitard (Figure 3). During model development, alternative recharge zones, boundary condition underflow zones (both inflow and outflow), hydraulic conductivity zones (both K_x (horizontal) and K_z (vertical) zones) and aquifer storage values were tested and calibrated. Available observation data, used to constrain model solutions, indicate that most natural recharge within the groundwater flow system originates along MFR areas associated with the Chiricahua Mountains.

The steady state model was calibrated to available pre-development head targets including: 1) the pressure head distribution associated with the lower artesian aquifer system (White, 1963); and 2) groundwater level data in the ADWR Groundwater Site Inventory (GWSI) database where available water level records suggest long-term dynamic equilibrium conditions could be inferred back in time to approximately pre-development conditions; in other words, only groundwater level data not impacted by development were used as head targets in the steady state model. Zones were established for the distribution of K_{xy} K_z, recharge, and underflow.

[1] PEST is a program that couples to MODFLOW using non-linear regression (or inverse modeling) to estimate groundwater flow model parameters by minimizing an objective function error. The objective function error is the sum of weighted squared residuals, where residuals are the difference between simulated and observed: (1) heads; (2) flows (groundwater discharge); and in many cases (3) a-priori information. An important feature of inverse models is the calculation of parameter sensitivities and associated by-products (covariance matrix; parameter correlation, etc.) which provides information about the reliability of model parameters, improving transparency of the model calibration to both the modeler and audience

A total of 61 head targets were used in the steady state calibration. Head target weighting was based on interpolation errors, measurement error, model error (discretization; assumptions) and feedback from evaluation of standard error of regression. Although most model parameters were relatively sensitive using only head targets as constraints, parameter correlation was problematic (see Hill, 1998).

To better constrain steady state solutions, three flow targets and a-priori information associated with three hydraulic conductivity zones were added as target observations in the non-linear regression. Steady state flow targets included: 1) groundwater underflow to the north, estimated at 30,000 AF/yr; 2) historical groundwater discharge at the cienega near the San Simon River headwaters, estimated at 5,000 AF/yr; and 3) zero groundwater flow associated with alluvial materials along the southern model boundary condition, based on the assumption that the Safford Groundwater Basin divide represents hydro-static groundwater "saddle" contour conditions.

For steady state conditions, the application of head-dependent boundaries was minimized during model development in order to increase parameter sensitivity, for non-linear regression purposes.

Initial estimates of hydraulic conductivity that were used for the steady-state model calibration were based on driller's log descriptions, specific capacity data, and available pump test data. In the Bowie and San Simon areas, two K_{xy} zones (K_x2 and K_x11) and one K_z zone (K_z11) were assigned a-priori weighting based on estimates of horizontal hydraulic conductivity (K_{xy}) and horizontal-to-vertical flow ratios, respectively. The assignments of non-linear regression weights were inversely proportional to the standard deviation associated with the estimates, and yielded standard error of regression values on the same order as the head components, consistent with guidelines established by the USGS (Hill, 1998). While the addition of the flow and a-priori terms added little magnitude to the objective function, their inclusion greatly reduced parameter correlation and improved model uniqueness. The range of calibrated hydraulic conductivity values used in the model are summarized in Table 2.

Table 2 Calibrated San Simon Valley Sub-basin Model Hydraulic Conductivities

	Kx Layer 1 (Ft/D)	Kz Layer 1 (Ft/D)	Kx Layer 2 (Ft/D)	Kz Layer 2 (Ft/D)
Average	8.6	0.7	6.7	0.9
Median	3.6	1.1	3.6	1.1
Minimum	0.7	.0000487	0.9	.00014
Maximum	22.9	2.3	22.9	2.3

Transient Calibration (1915 to 2015)

An important hydrologic feature associated with the groundwater flow system in the Bowie and San Simon areas is the Blue Clay. The Blue Clay is an aquitard that acts as a confining layer between the upper and lower basin-fill aquifers. Estimates of vertical hydraulic conductivity suggest minimal vertical leakage between the upper and lower aquifers. Prior to, and during early periods of groundwater development, significant hydraulic pressure existed in the lower basin-fill aquifer, and many artesian flowing wells, were developed in the San Simon area. Due to continuous groundwater pumping over the last century (1915-2015), hydraulic pressure in the lower aquifer system decreased significantly, and the vertical hydraulic flow gradient reversed direction over time from an upward, to a downward direction. Current groundwater level data in some areas indicate heads in portions of the upper aquifer exceed lower aquifer heads by approximately 200 feet. Therefore, simulating the reversal of the vertical hydraulic gradient over time in the major pumping centers, was a key objective of the transient groundwater flow model calibration process.

For the transient calibration (1915-2015), system stresses that were simulated include: 1) mountain front recharge; 2) groundwater pumpage; 3) groundwater discharge from artesian flowing wells with an estimated discharge of 11,000 AF/yr; and 4) application of incidental agricultural recharge (AG recharge). These stresses were applied to the groundwater system and evaluated against observed head calibration target data for the 1915 to 2015 period. The vast majority (96%) of simulated groundwater pumpage and groundwater discharge from the artesian flowing wells without pumps was assigned to the lower aquifer system (Layer 2). The layer 2-to-layer 1 pumping ratio had to be on the order of 20:1 (or greater) to reverse the direction of the vertical hydraulic gradient, from upwards to downwards, over time.

For the transient model calibration, pumping rates assigned in the model during the first few decades in the Bowie and San Simon areas, were higher than initial conceptual estimates in order to account for artesian flowing wells discharging groundwater that remained uncapped during dormant seasons and/or were left abandoned and uncapped after World War I, which represent a significant discharge component (11,000 AF/yr) from the aquifer system (Schwennesen, 1917). Higher rates of early-period simulated groundwater pumpage were required in the Bowie and San Simon areas in order to reduce an over-simulated (simulated heads > observed heads) residual head bias. Even with increased rates of early-time pumpage, there remains a small over-simulated head bias for both the full suite of transient head residuals (unweighted, time-interpolated; sample number = 76,211); as well as a smaller subset of weighted, transient head residuals (1,561 weighted head targets), focused primarily in the Bowie, San Simon and Rodeo areas, and used exclusively for PEST transient simulations. However, higher rates of early-time simulated groundwater pumpage resulted in less than a 10 percent cumulative increase, with respect to the original conceptual estimates.

Storage properties used in the transient model include specific yield (Sy) (dimensionless) and Specific Storage (Ss) (1/Ft). These properties were initially estimated for both model layers from typical literature values. Calibrated values of Sy and Ss are listed in Table 3.

Table 3 Calibrated San Simon Valley Sub-basin Model Storage Properties

	L1 Ss (1/Ft)	L1 Sy	L2 Ss (1/Ft)	L2 Sy
Average	0.000001	0.075	0.0000036	0.04
Median	0.000001	0.075	0.000004	0.05
Minimum	0.000001	0.075	0.000001	0.03
Maximum	0.000001	0.075	0.000004	0.05

Model Calibration Results

Steady-State (Pre-development 1915)

A total of nine independent model parameters were calibrated for the steady state period (1915), including: six horizontal K_x zones, one vertical K_z zone, one total natural MFR parameter and one underflow zone parameter to the north (Appendix A). To simplify the model and increase parameter sensitivity, other model parameters were either directly tied, or scaled, to estimable parameters. All K zones, recharge zones and underflow zones were spatially represented in the model and resulting model statistics. Note that the model assumes horizontal isotropy.

The simulated steady state (pre-development) water budget is presented in Table 4 below. Information about the steady state calibration including the relation between weighted simulated values and weighted residuals (Hill, 1998), and the distribution of weighted head residuals are shown in Figure 10 and Figure 11, respectively. Despite the assignment of a flow target "penalizing" underflow rates deviating from zero, all conceptual models tested during development resulted in underflow into the model area from the south. Although most head calibration target data were measured during the post-development transient period, transient based parameter sensitivity is relatively low and hampered by serial correlation. Thus high steady state parameter sensitivity suggest that the steady state solution and initial conditions are important, even for the long-term transient calibration.

Simulated groundwater elevation contours for model Layers 1 and 2 from the steady state model calibration are shown in Figures 12 and 13, respectively. The figures show that simulated groundwater flow was consistent with the conceptual model that recognizes that most flow originates in recharge areas along the higher mountain fronts and steady state flow in both model layers generally followed a north-northwest flow path towards the Gila Valley Sub-basin and the Safford area.

Table 4 Simulated San Simon Valley Sub-basin Steady State Water Budget

In Flow	Rate (Af/yr)	Comments
Underflow from South (Constant Head Boundary (CHB))	3,031	Conceptual estimate: 0 AF/yr
Natural Recharge	31,240	Approximately 70% from Chiricahua Mountains**
Total System In Flow	34,271	
Out Flow		
Groundwater Discharge as Evapotranspiration (ET)	4,838	Conceptual estimate: 5,000 AF/yr
Underflow to Gila Valley/Safford area	29,433	Conceptual estimate: 30,000 AF/yr
Total System Outflow	34,271	

*See text for further discussion about CHB groundwater divide constraint; assigned CHB slightly north of San Simon sub-basin divide, based on Index well record; assigned head (CHB) elevation to 4,100 feet.
**Other natural recharge from Peloncillo Mountains (largely in New Mexico) and Mt. Graham area
Used PEST solution for budget and transient initial conditions. Some *ending* recharge scaler values used during PEST routine and resulting simulated water budget (i.e., relative factor upgrading) may reflect slightly different values than presented in final optimal results. This may result in small simulated water budget differences between optimal values and list file presented values (Appendix B).

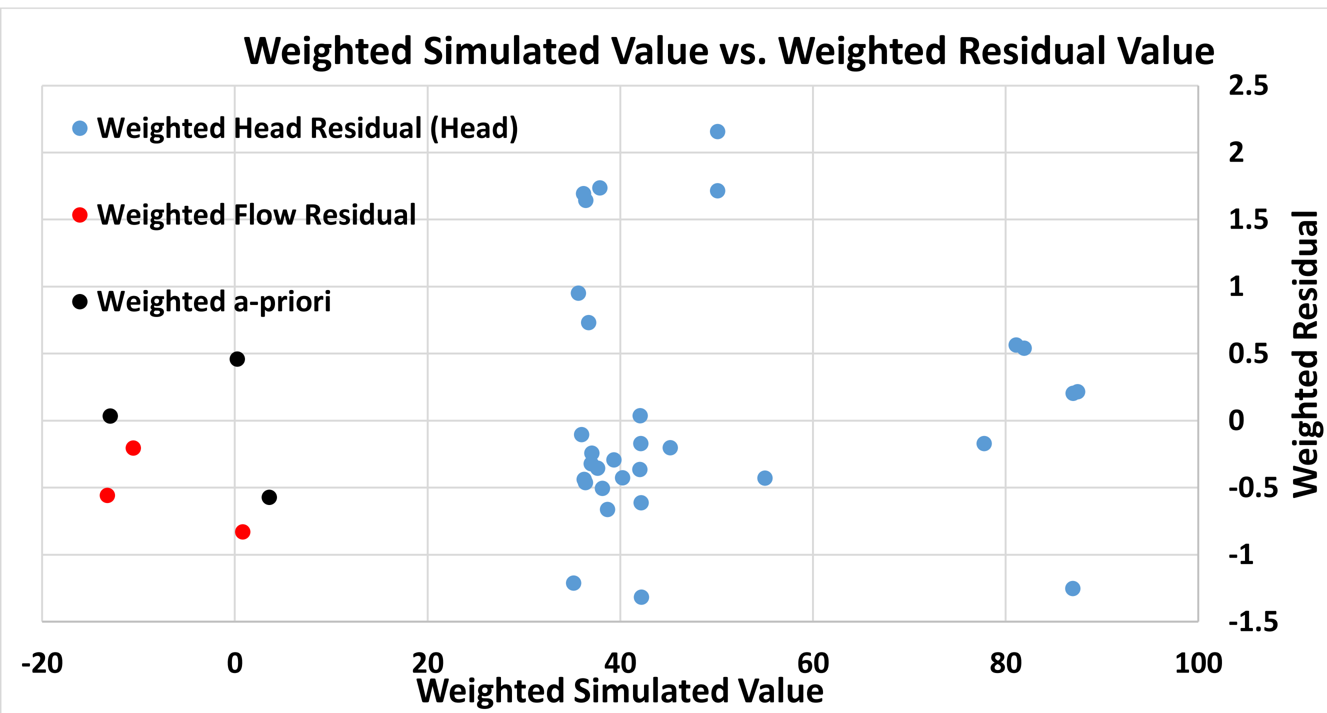


Figure 10 Weighted Simulated Values vs. Weighted Residual Value

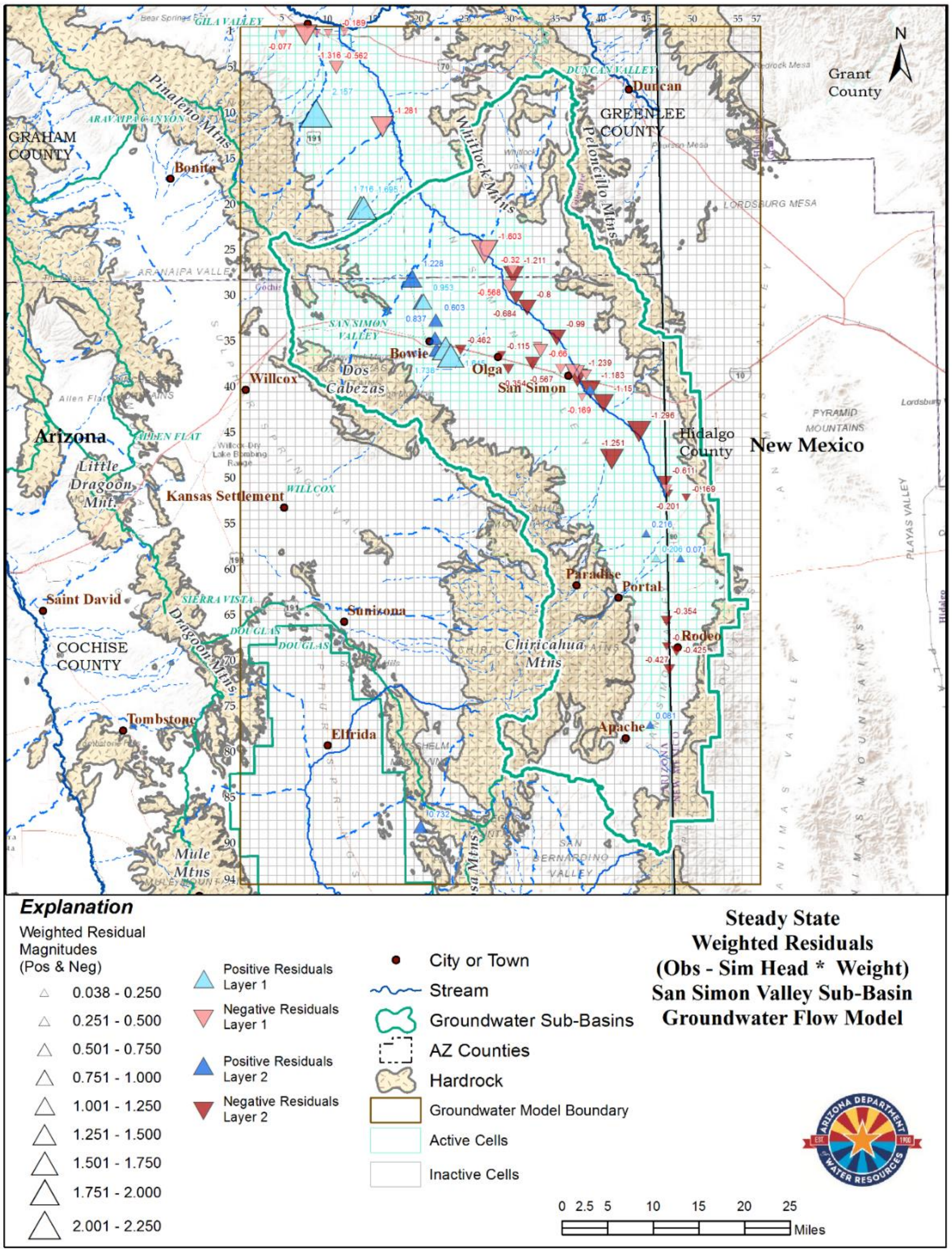


Figure 11 Steady State Weighted Residuals (Obs – Sim Head * Weight) San Simon Valley Sub-basin Groundwater Flow Model

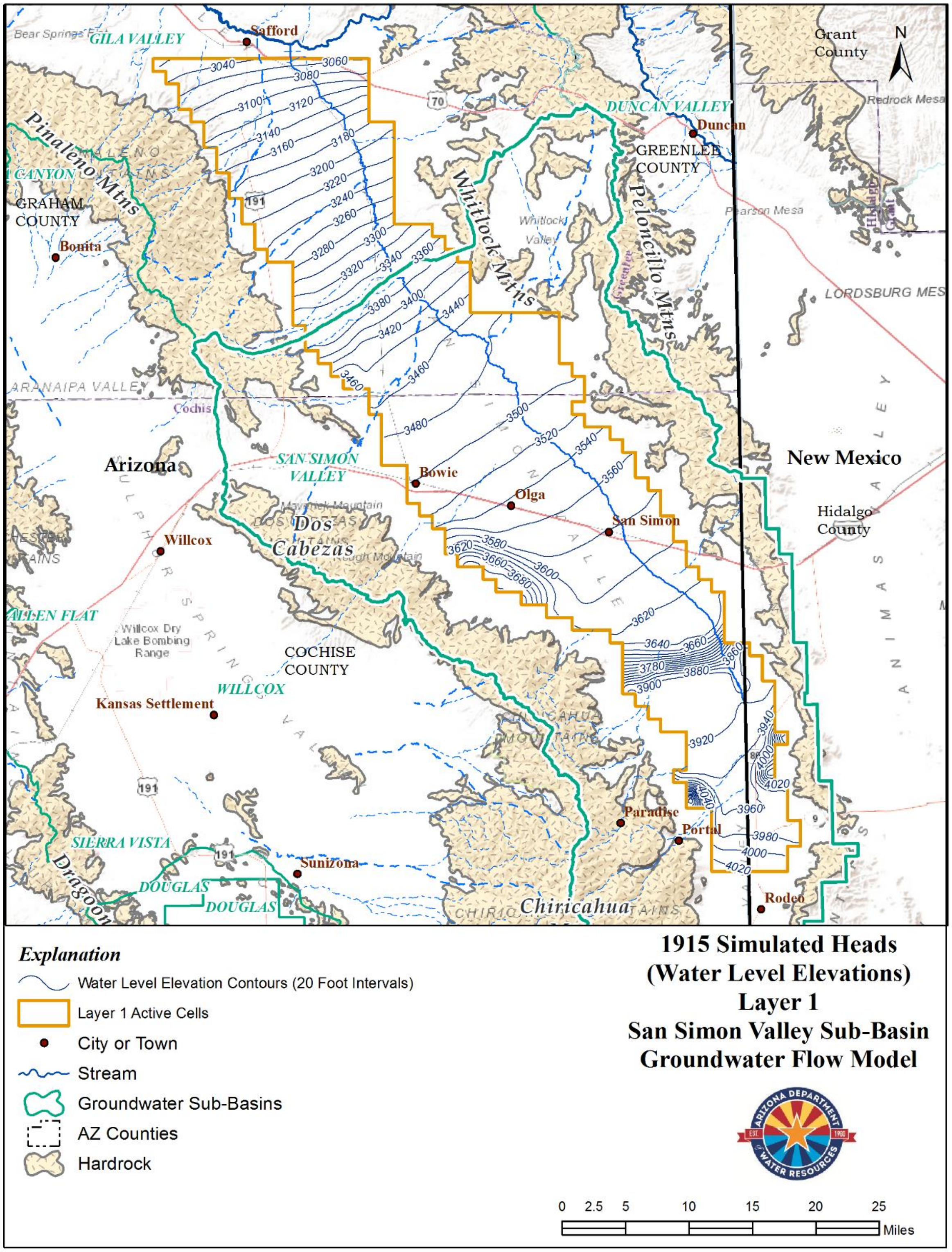


Figure 12 1915 Simulated Heads (Water Level Elevations) Layer 1 San Simon Valley Sub-basin Groundwater Flow Model

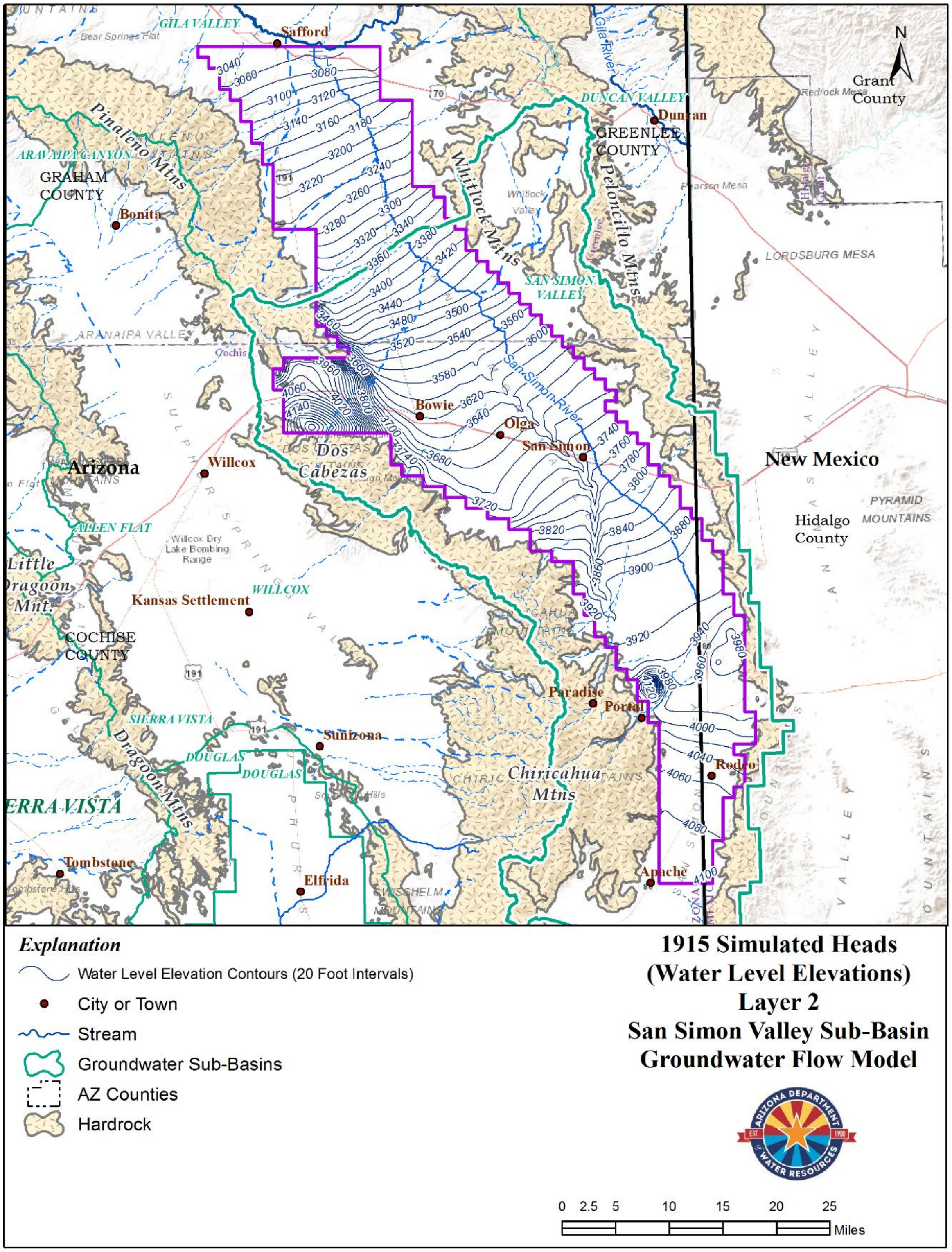


Figure 13 1915 Simulated Heads (Water Level Elevations) Layer 2 San Simon Valley Sub-basin Groundwater Flow Model

Transient (1915-2015)

For the transient calibration period (1915-2015), groundwater system stresses including pumping, groundwater discharge of artesian flowing wells, natural recharge and AG recharge were simulated at rates described above. Effectively, all assigned pumpage and AG recharge were preserved through the transient calibration period (no agricultural pumping or recharge cells dewatered). During the transient period, natural MFR, underflow to the north and inflow from the south were simulated at rates consistent with the steady-state calibration. Based on results associated with the transient non-linear regression, as well as manual calibration, minor adjustments and rounding were made to some model parameters for better model fit to data. Transient non-linear regression was also used to provide guidance for the estimation of storage (Sy, Ss), and to calculate sensitivities for selected parameters, including underflow and all assigned recharge including AG recharge.

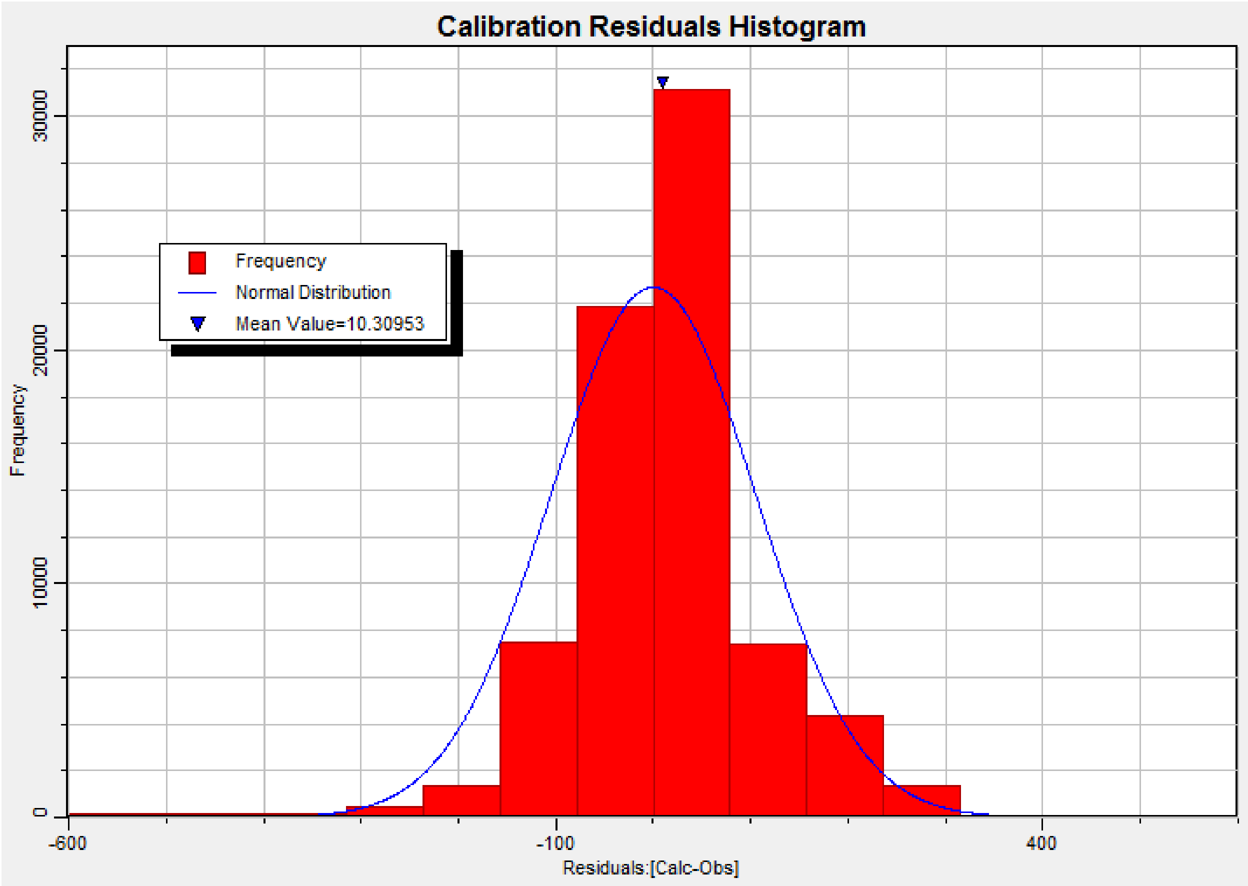
The simulated transient water budget for the 1915 to 2015 period is presented in Table 5.

Table 5 Simulated Transient Water Budget (1915 – 2015, 101 years): Annualized Rates for the 1915 to 2015 Period

In Flow	Rate (AF/yr)	Comments
Storage IN	41,494	
Underflow from South*	2,570	
Natural Recharge**	29,329	Approximately 70% from Chiricahua Mountains**
Total AG Recharge	12,435	Bowie area 35%; San Simon 46%; South/Rodeo 19%
Total System In Flow	85,828	
Out Flow		
Storage OUT	6,492	
Well Pumpage	46,448	Bowie 40%; San Simon43%; South/Rodeo 17%: Cumulative pumpage: 4.68M AF
Groundwater discharge as ET	2,286	ET decays to zero in the mid-1970's.
Underflow to Gila Valley ***	30,389	
Total System Outflow	85,615	
Change-in-Storage	35,002	Cumulative change-in-storage: 3.535 M AF

*Assumed as constant rate during transient simulation, generally based on initial condition rate plus a small decrease due to a combination of: 1) decrease in saturated thickness due to continuous head declines; and 2) the fact that the southern boundary is associated with a groundwater divide ("saddle") and that minimal induced recharge would result because of the assumed hydro-static divide condition. Note that alternative conceptual models (ACMs) were tested and PEST results suggest some induced recharge may occur along this boundary. Nonetheless for this simulation, a conservative approach was taken. **Natural recharge was rounded down slightly with respect to steady-state defined rates because of transient PEST results. ***Results from the non-linear regression transient period (1915-2015) suggest slightly higher underflow rates with respect to initial steady-state rates. As a result, transient underflow to the north was increased by about 3%. Note that all recharge and underflow components are relatively insensitive for transient flow conditions, with respect to steady state flow conditions. Simulated mass balance error for the first 101 years (1915-2015) is 0.25% or 0.0025. The mass balance error appears due to a few problematic cells with thin saturated thickness.

Additional information about the transient calibration is presented graphically and includes: 1) a histogram of un-weighted transient head residuals (Figure 14); 2) a figure showing location transient head calibration targets, including locations of selected hydrographs (Figure 15); and 3) selected simulated and observed hydrographs (Figures 16, 17, and 18).



Sample size 76,211. Residual mean = 10.3 (indicates slight over-simulation bias); absolute residual mean = 72.6; RMS = 106; *normalized* RMS 7.51

Figure 14 Calibration Residuals Histogram

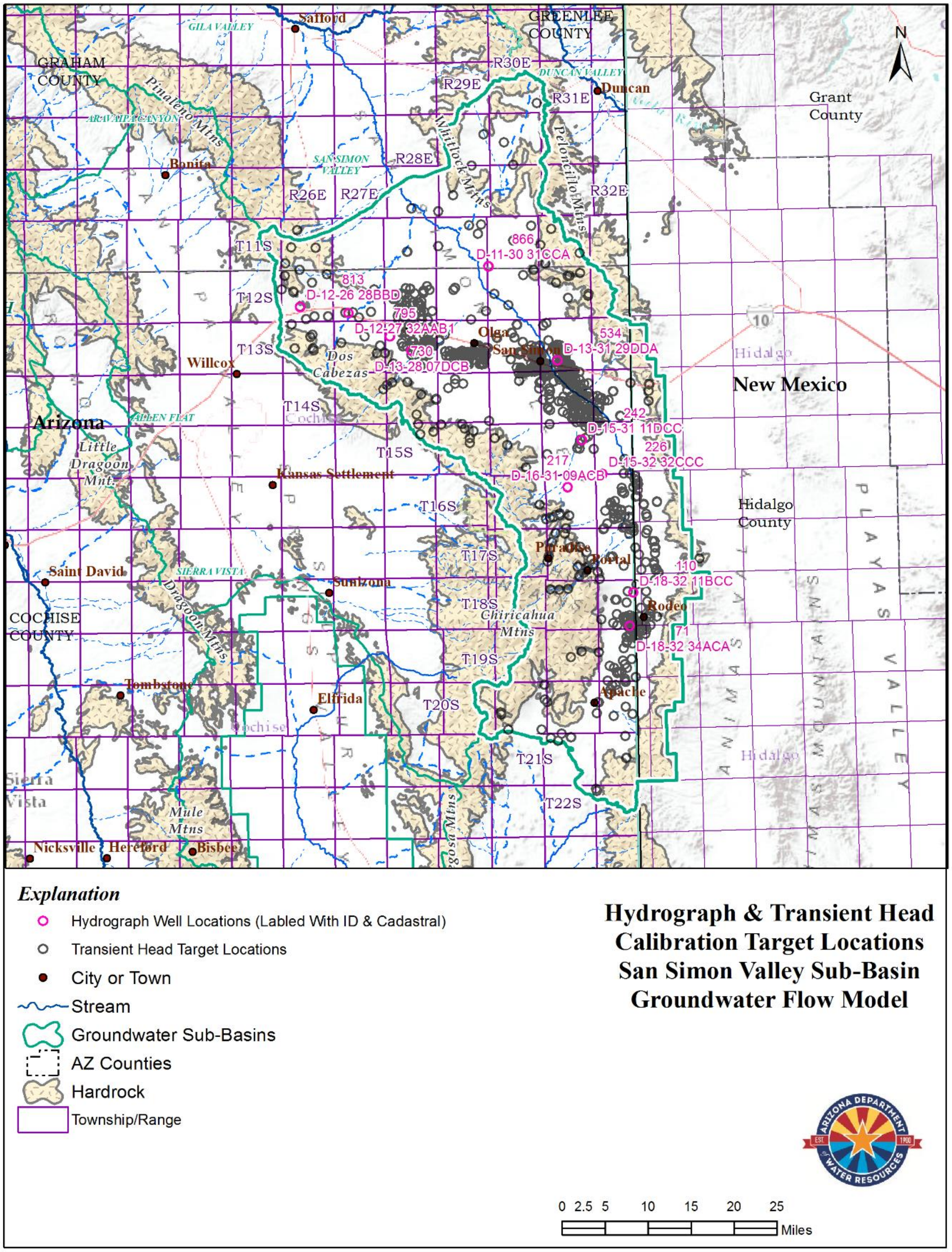


Figure 15 Hydrograph and Transient Head Calibration Target Locations San Simon Valley Sub-basin Groundwater Flow Model

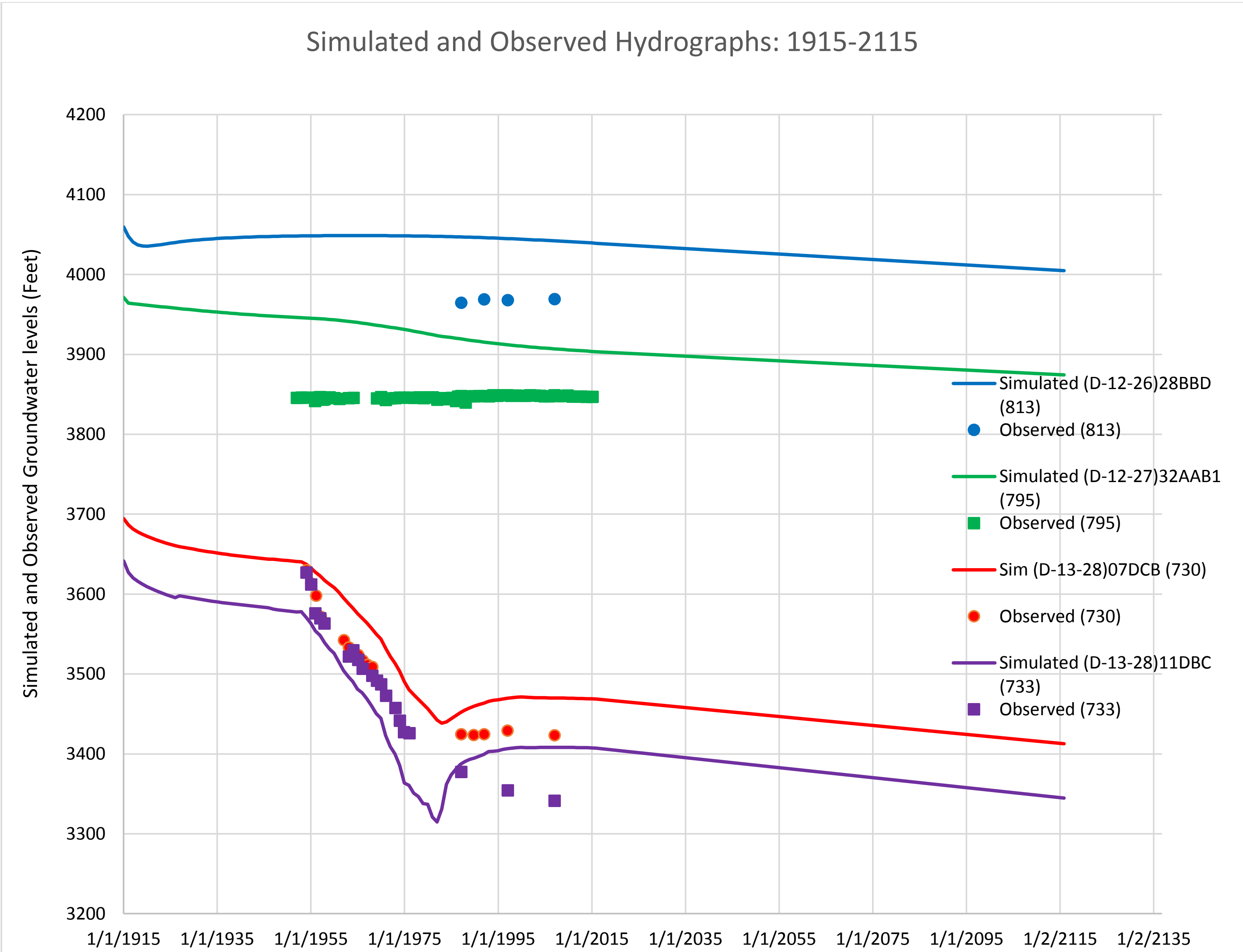


Figure 16 Simulated and Observed Hydrographs: 1915-2115

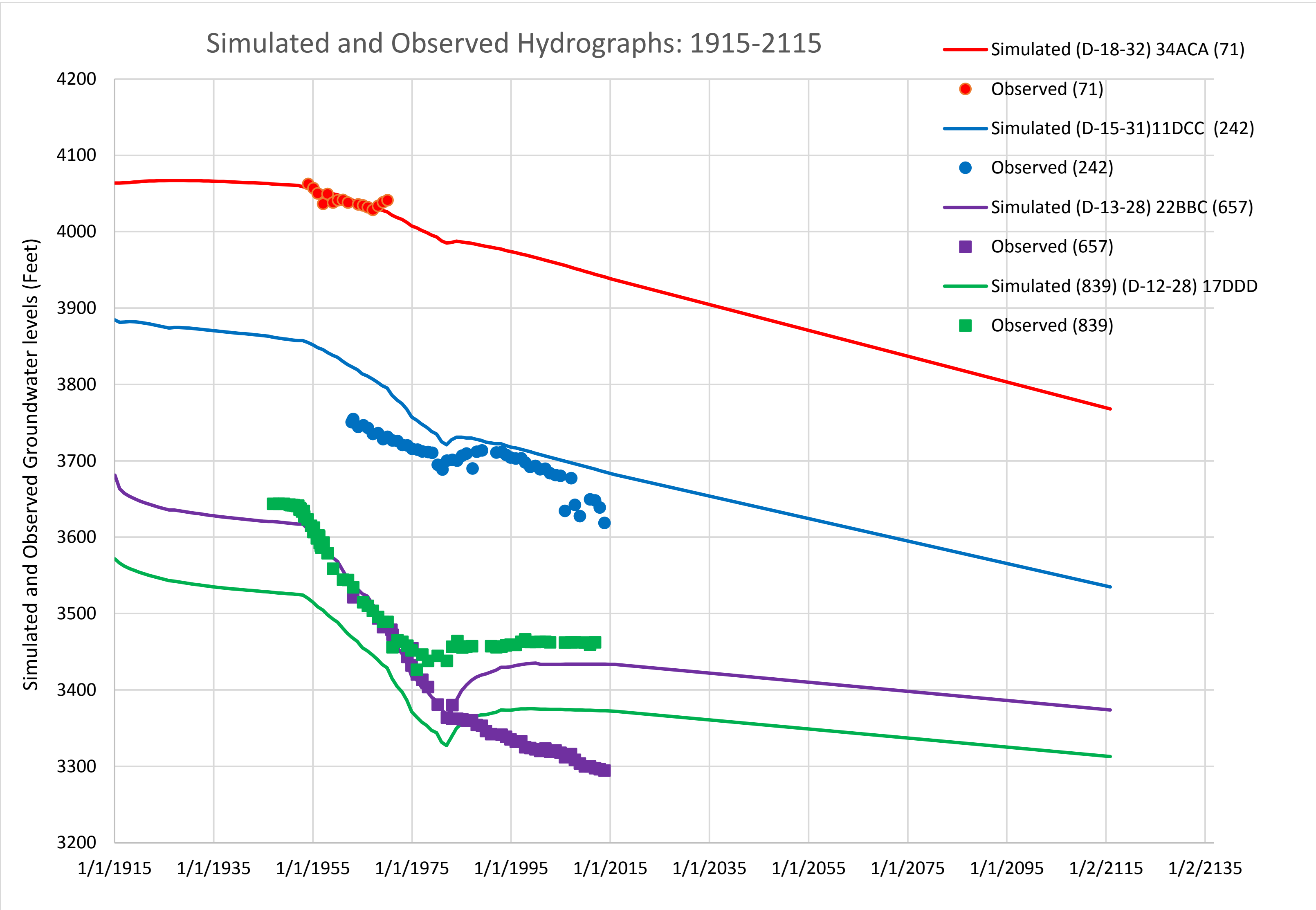


Figure 17 Simulated and Observed Hydrographs: 1915-2115

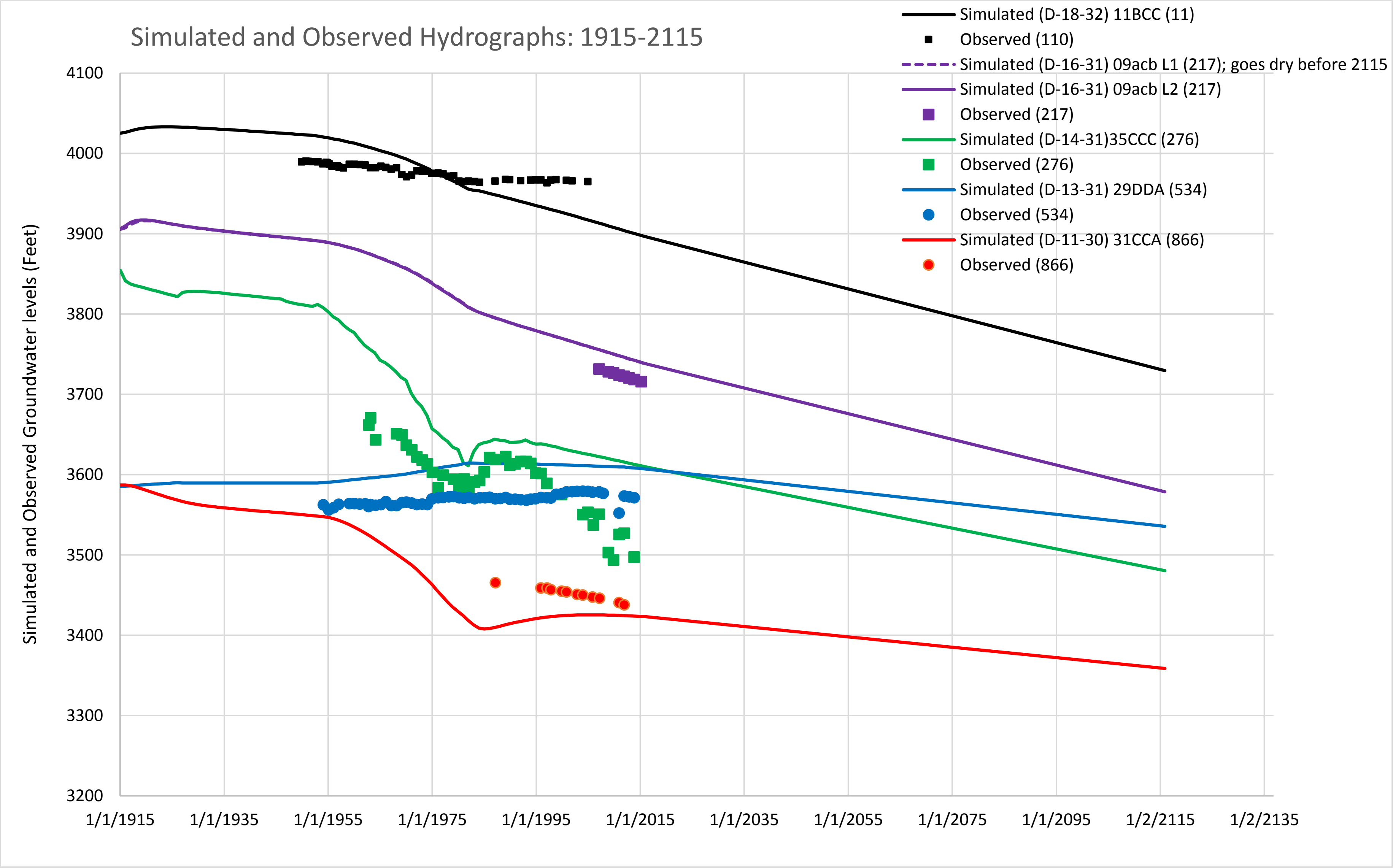


Figure 18 Simulated and Observed Hydrographs: 1915-2115

Although there are locations which exhibit local model error, on a collective, regional-scale basis, the model residuals show only a relatively minor, over-simulated head bias (simulated > observed heads). The mean residual error (simulated minus observed) was +10.3 feet. The model simulates the vertical hydraulic gradient reversal observed between the early periods (strong upward vertical hydraulic gradients) and later periods, which show strong downward vertical hydraulic gradients (see Figures 19 and 20). In addition, transient-simulated heads represent head declines observed in the lower aquifer, including the period having the highest pumping rates and greatest groundwater level declines in the 1970's.

The groundwater system has been subject to losses of groundwater from storage, due to long-term groundwater pumping during the last century (1915-2015). For the 1915-2015 calibration period the total simulated loss in groundwater storage was about 3.5 million AF (Table 5). Results from the transient simulation indicate that the cones-of-depression, originating from the primary pumping centers in Bowie and San Simon, propagate outwards away from these pumping centers (Figures 21 and 22).

Results from a MODFLOW ZONEBUDGET analysis comparing storage losses between the primary pumping centers in Bowie and San Simon (model rows 30 to 49) and the collective areas outside the pumping centers (external areas), indicate that more water is actually removed from storage in the external areas, even though the majority of pumping was not conducted in the external areas. The model simulation indicates that the spreading cones-of-depression radiate from the pumping centers, and have consequently altered hydraulic gradients throughout much of the regional aquifer over time. The spreading cones-of-depression reflect the removal of water from storage on a regional scale.

For the transient (1915 – 2015) and projection (2016 – 2115 (described below)) model simulations, the lateral boundary conditions assigned to the north and south, were posed as specified flux boundaries, in part, because they generally provide higher degrees of parameter sensitivity for parameters subject to correlation, all else equal. However, these boundaries could be posed as head-dependent boundaries (HDB), which could result in: 1) a reduction of underflow to the north (or "capture"); and/or 2) increased rates of underflow from the south into the model domain (or induced recharge). If the specified flux boundaries were replaced with HDB's, and capture and/or induced recharge were simulated, less water would be mined from storage at the expense of: 1) increased inflow from the south; and/or 2) less outflow to the north, all else equal. The only active HDB assigned in the transient simulation is the ET boundary, where groundwater discharge decreased over time due to lowering of the water table. For these simulations, ET groundwater discharge continued to occur until the water table dropped at the cienega below the assigned extinction depth (45 feet below land surface), which occurred in the mid-1970s.

With respect to initial conditions, by the end of the transient simulation through 2015, a total of 78 cells went dry in model layer 1 (Figure 23), while one cell went dry in layer 2 (Figure 24). Water levels rose south of San Simon in the upper aquifer (Layer 1) due to excess agricultural recharge (Figure 23). Maximum simulated drawdown in the lower aquifer in the Bowie and San Simon areas exceeded 240 and 260 feet, respectively (Figure 24). The simulated remaining saturated thickness in 2015 is shown for Layers 1 and 2 in Figures 25 and 26.

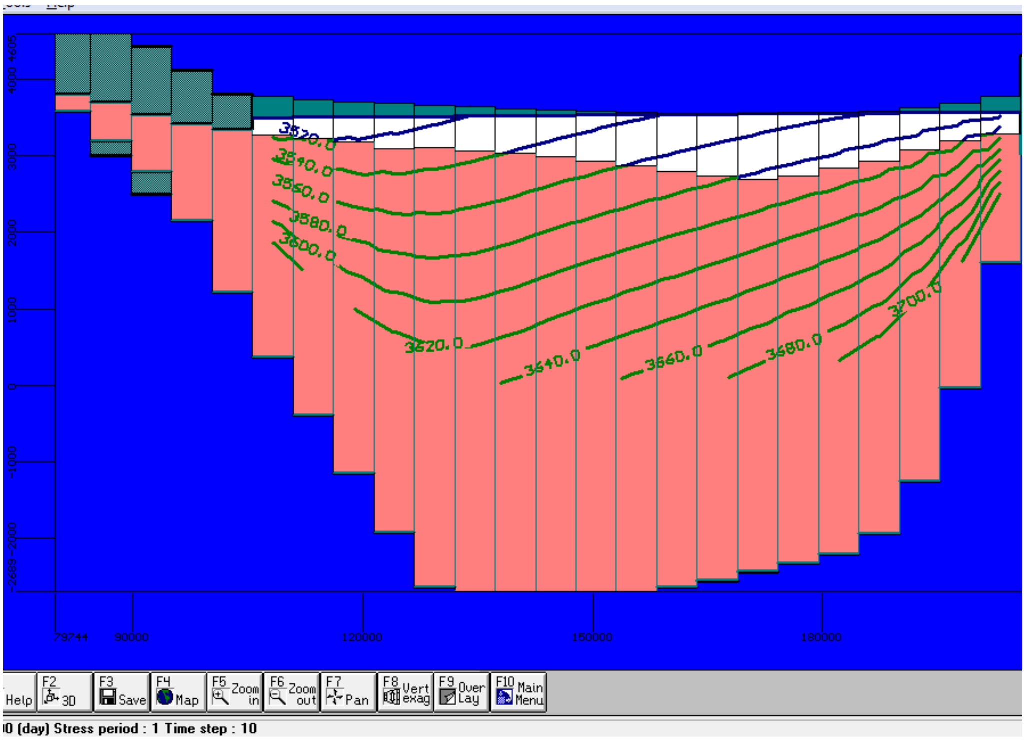


Figure 19 Simulated Upward Vertical Hydraulic Gradient, 1916: Cross-Sectional View at Model Row 35 (Bowie-San Simon area)

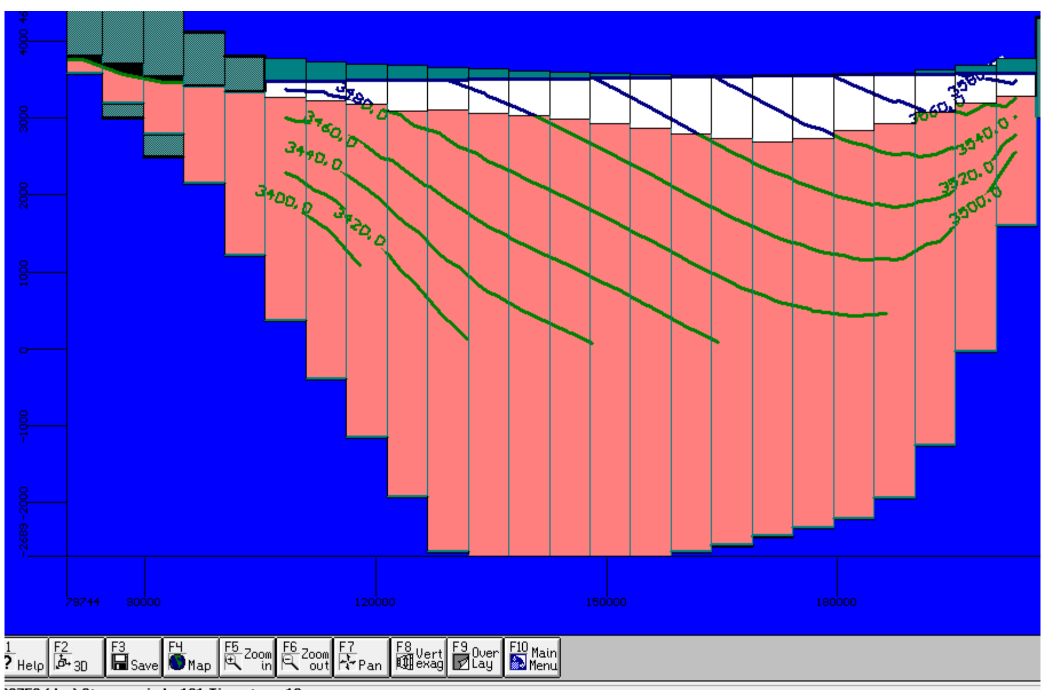


Figure 20 Simulated Downward Vertical Hydraulic Gradient, 2015: Cross-Sectional View at Model Row 35 (Bowie - San Simon area)

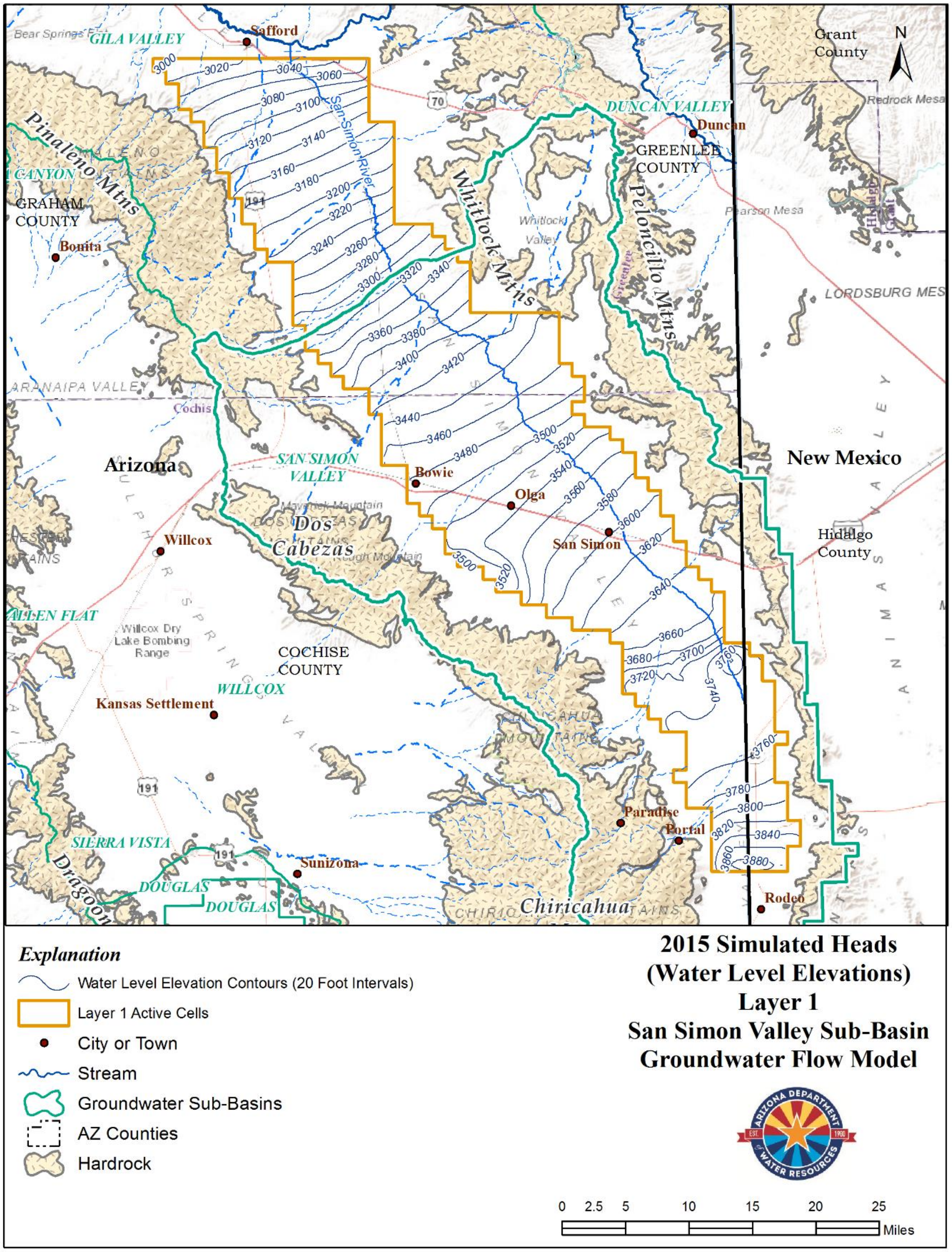


Figure 21 2015 Simulated Heads (Water Level Elevations) Layer 1 San Simon Valley Sub-basin Groundwater Flow Model

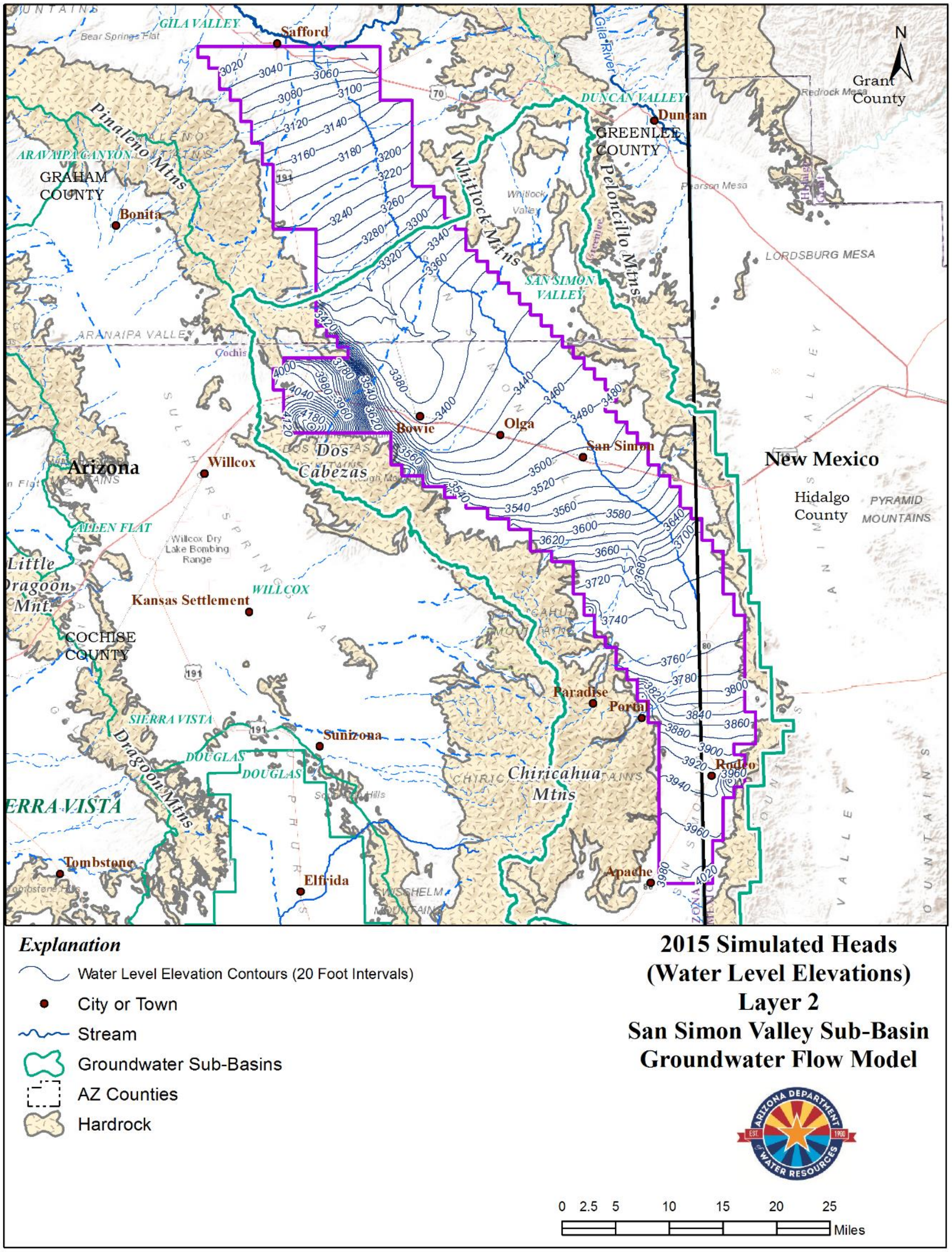


Figure 22 2015 Simulated Heads (Water Level Elevations) Layer 2 San Simon Valley Sub-basin Groundwater Flow Model

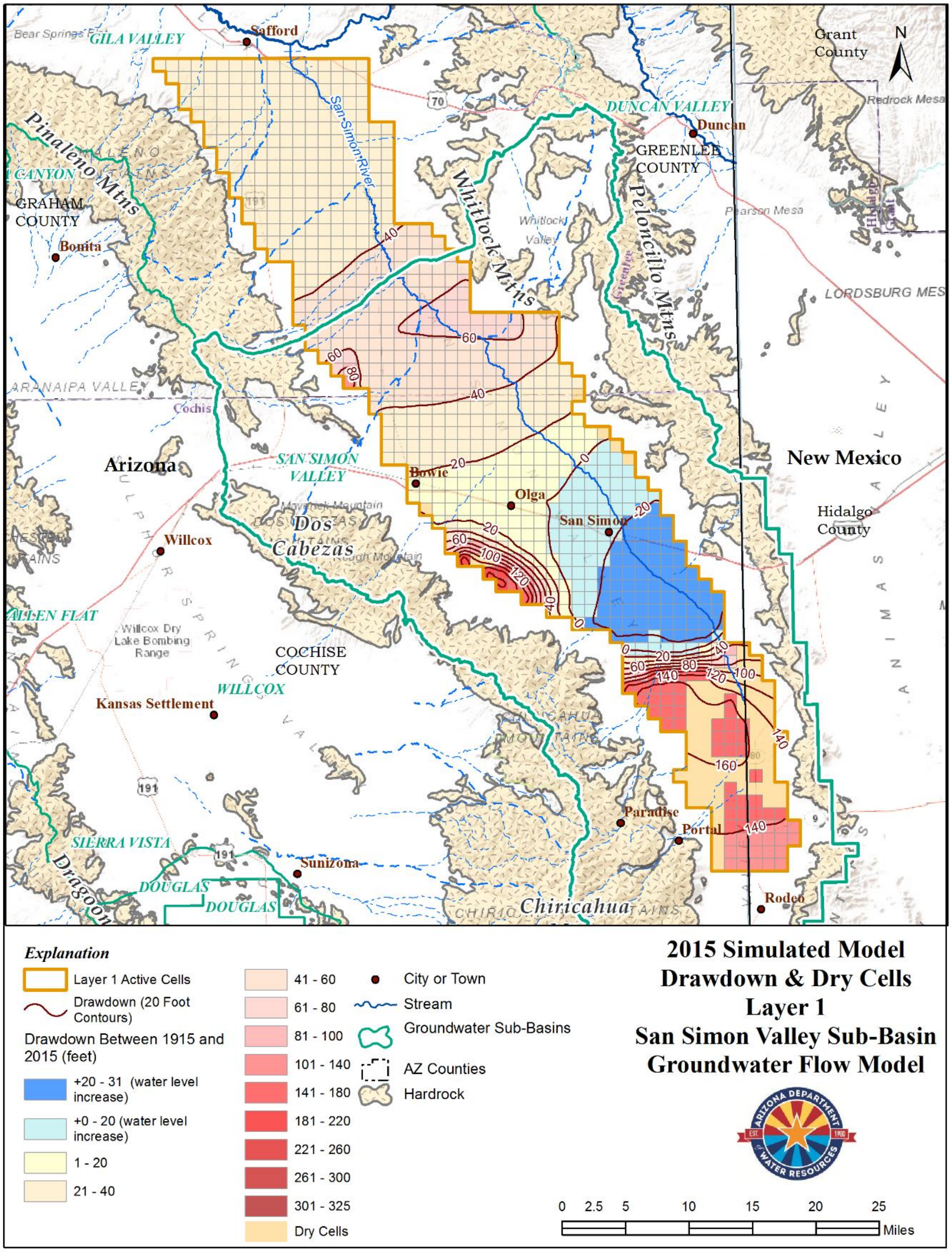


Figure 23 2015 Simulated Model Drawdown & Dry Cells Layer 1 San Simon Valley Sub-basin Groundwater Flow Model

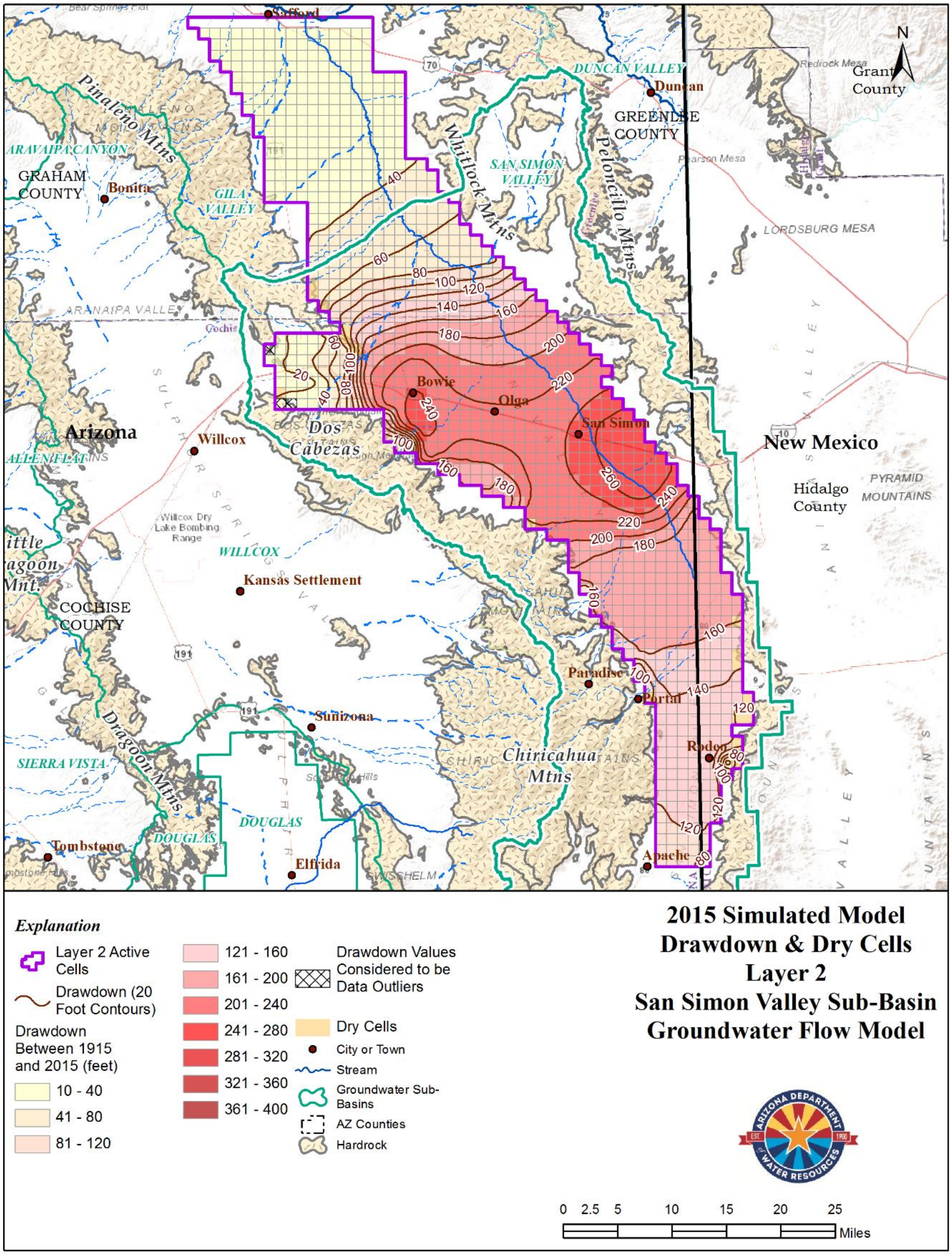


Figure 24 2015 Simulated Model Drawdown & Dry Cells Layer 2 San Simon Valley Sub-basin Groundwater Flow Model

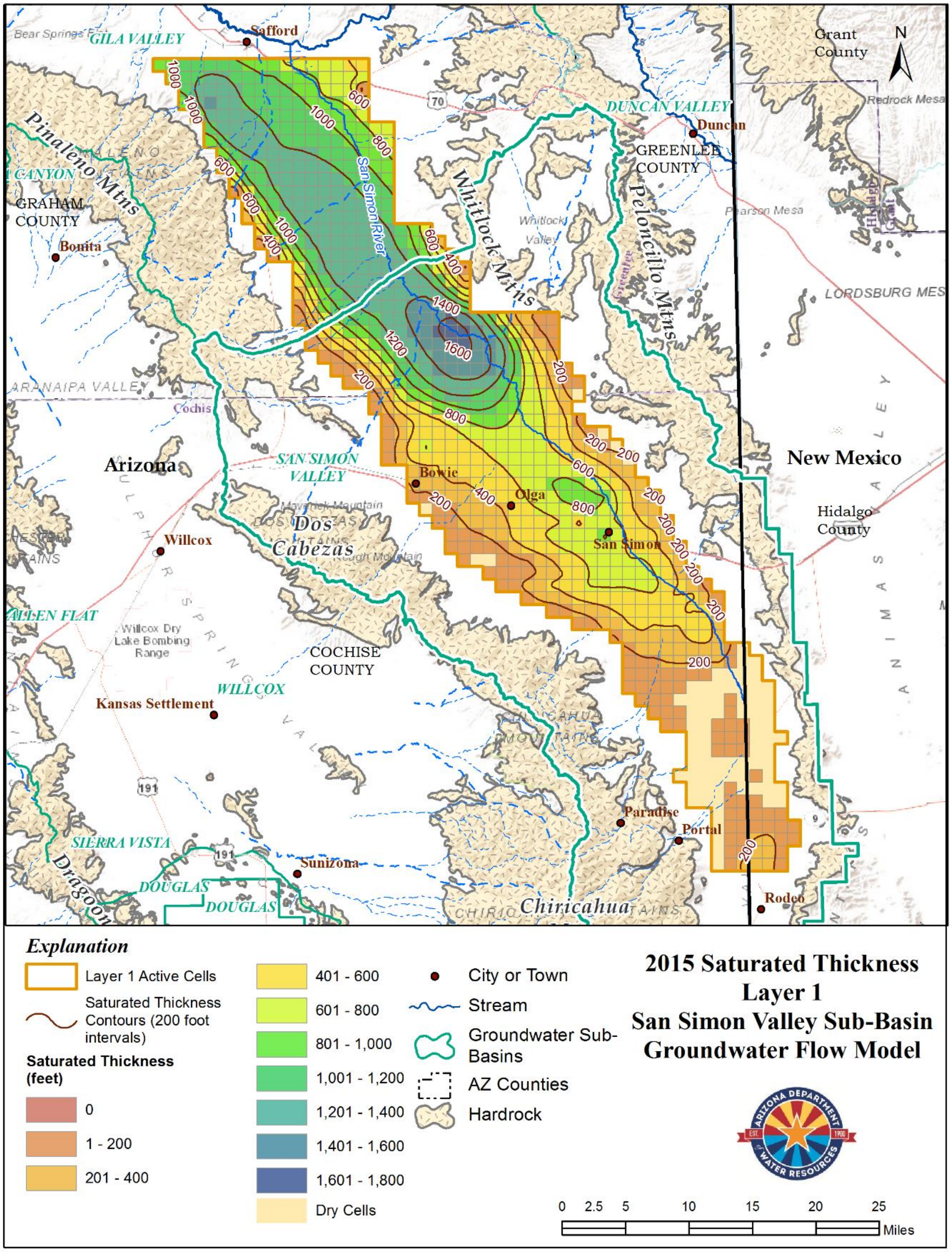


Figure 25 2015 Saturated Thickness Layer 1 San Simon Valley Groundwater Flow Model

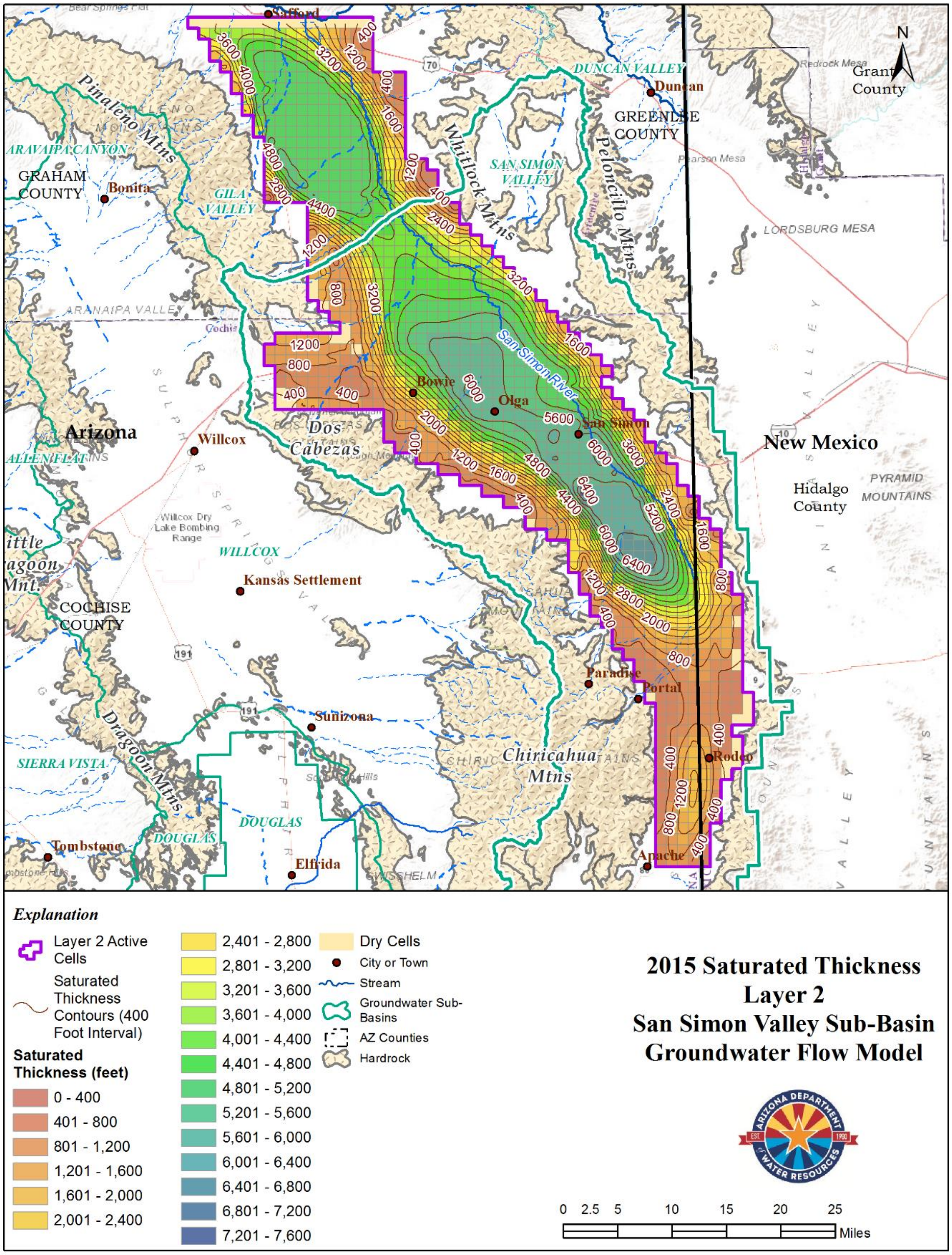


Figure 26 2015 Saturated Thickness Layer 2 San Simon Valley Sub-basin Groundwater Flow Model

Model Projection Results (2016 – 2115)

The calibrated 1915-2015 model was used to provide initial conditions for the 100-year projection simulation from 2016 to 2115. Stresses applied (pumping and recharge) for the projection simulation (2016-2115), were the same as stresses applied during the last calibration stress period (2015) of the transient simulation (Figures 27, 28 and 29).

The 2016 to 2115 simulated water budget is shown below (Table 6). During the 2016-2115 projection period, 4.1 million acre-feet of water was simulated to be removed from groundwater storage. Results from the 2016-2115 projection simulation indicate that the cones-of-depression that had developed in the Bowie and San Simon areas continued to deepen and propagate outward from those pumping centers (Figures 30 and 31).

With respect to initial conditions, by the end of the projection simulation through 2115, a total of 150 cells went dry in model layer 1 (Figure 32), while a total of 15 cells went dry in layer 2 (Figure 33). One of the model cells that went dry during the projection simulation, included a boundary condition cell, which simulated underflow into the model domain. Agricultural pumping cell dewatering had negligible impact on the actual volume of pumping that was simulated during the 2016-2115 projection period. For example, 49,739 AF/yr of agricultural pumping was projected for the 2016-2115 period and 49,726 AF/yr was actually simulated.

Model projected drawdown from 1915 to 2115 indicated upper basin-fill aquifer (Layer 1) dewatering mainly in an area several miles south of San Simon (Figure 32). The simulated dewatering of model cells in that area is mainly attributable to the comparatively thin initial saturated thickness and the local agricultural pumping. Maximum simulated drawdown from 1915 to 2115 in the lower aquifer in the Bowie and San Simon areas is approximately 300-320 and 380-400 feet, respectively (Figure 33).

The 2115 depth-to-water in agricultural areas was projected for deeper agricultural wells (with depths greater than or equal to 400 feet) that mainly tap the lower basin fill aquifer by adding the projected Layer 2 drawdown (Figure 34) to the wells' 2015 measured depths-to-water. Using this approach local model bias associated with the 2015 simulated head distribution was reduced or eliminated. Maps and data from the projected 2115 depth-to-water analysis are presented in Appendix C.

Figures 35 and 36 show the projected remaining saturated thickness in 2115 for Layers 1 and 2, respectively. The projections indicate dewatering of some Layer 1 model cells in areas south and west of Bowie and also in the agricultural area located several miles south of San Simon (Figure 35). The projections indicate less than 100 to over 400 feet of saturated thickness would remain in the upper basin-fill aquifer in other agricultural areas of the sub-basin. Figure 36 indicates several hundred to several thousand feet of remaining saturated thickness in Layer 2 are projected for agricultural areas in the sub-basin.

Table 6 Simulated Projection Water Budget (2016 – 2115, 100 years): Annualized Rates for the 2016 to 2115 Period

	Rate (AF/yr)	Comments
Storage IN	41,523	
Underflow from South*	2,200	
Natural Recharge**	29,286	Approximately 70% from Chiricahua Mountains**
Total AG Recharge	7,659	Bowie area 22.5%; San Simon 61.8%; South/Rodeo 15.7%
Total System In Flow	80,668	
Out Flow		
Storage OUT	200	
Well Pumpage	49,760	Bowie 37%; San Simon 46; South/Rodeo 17%
Groundwater discharge as ET	0	ET eliminated by mid-1970's.
Underflow to Gila River Valley***	30,389	
Total System Outflow	80,349	
Change-in-Storage	41,323	Cumulative change-in-storage: 4.129 M AF

*Assumed as constant rate during transient simulation, generally based on initial condition rate plus a small decrease due to a combination of: 1) decrease in saturated thickness due to continuous head declines; and 2) the fact that the southern boundary is associated with a groundwater divide ("saddle") and that minimal induced recharge would result because of the assumed hydro-static divide condition. Note that ACM's were tested and PEST results suggests some induced recharge may occur along this boundary. Nonetheless for this simulation, a conservative approach was taken. Underflow associated with cell, row 78, column 48 went dry at stress-period 102, time step #3; thus underflow into the system was reduced; rate in budget reflects a composite estimate ** Natural recharge was rounded down slightly with respect to steady-state defined rates because of transient PEST results. In addition a few RCH cells went dry during stress period 102 (2016-2115); above rate reflect composite estimate. ***Results from the non-linear regression transient period (1915-2015) suggest slightly higher underflow rates with respect to initial steady rates; as a result, transient underflow to the north was increased by about 3%. Note that all recharge and underflow components are relatively insensitive for transient flow conditions, with respect to steady state flow conditions. The 2016-2115 small mass balance error (total 201 year simulation mass balance error of 0.0035 is likely due to a few problematic cells with thin saturated thickness.

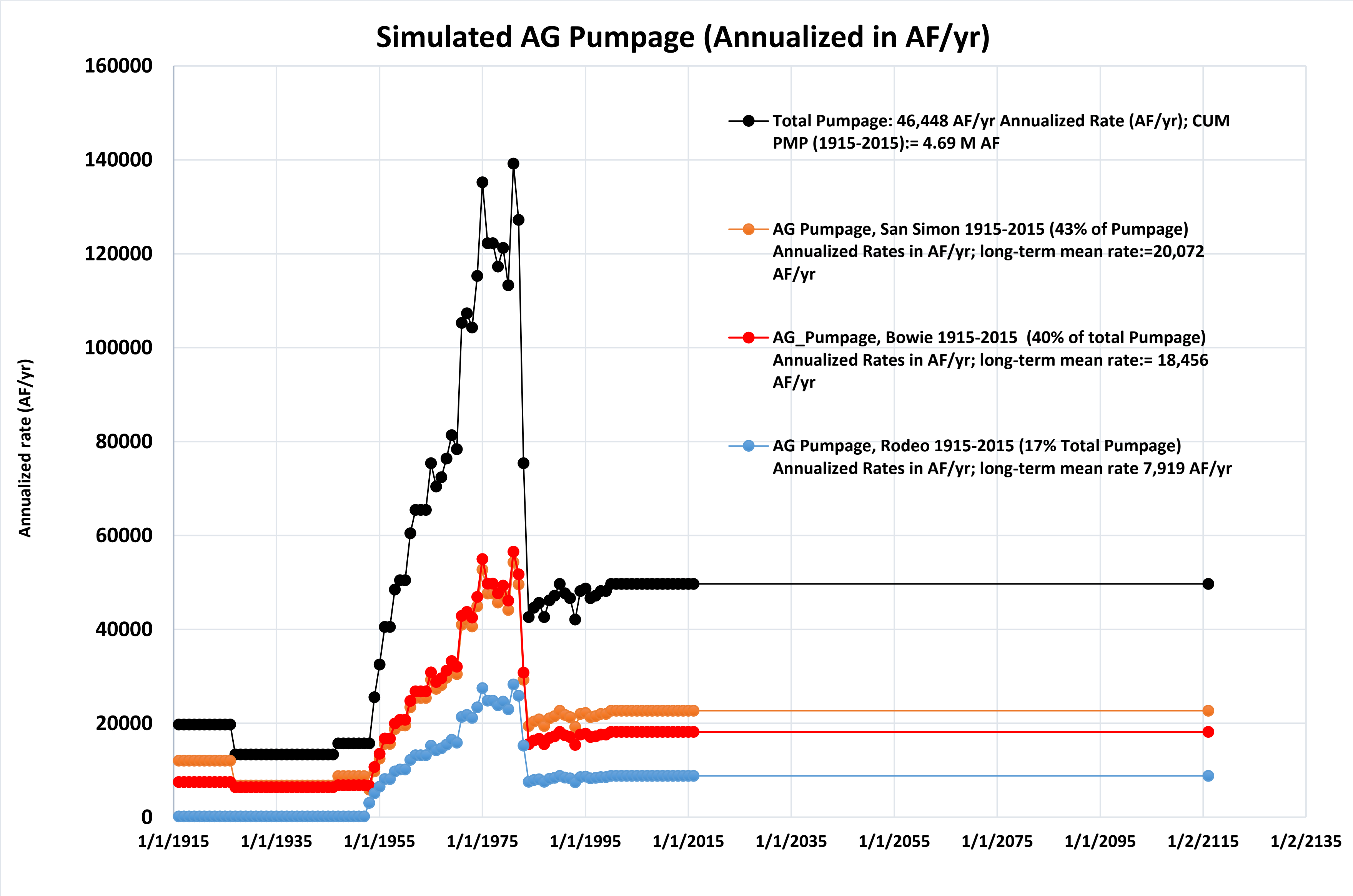


Figure 27 Simulated AG Pumpage (Annualized in AF/yr)

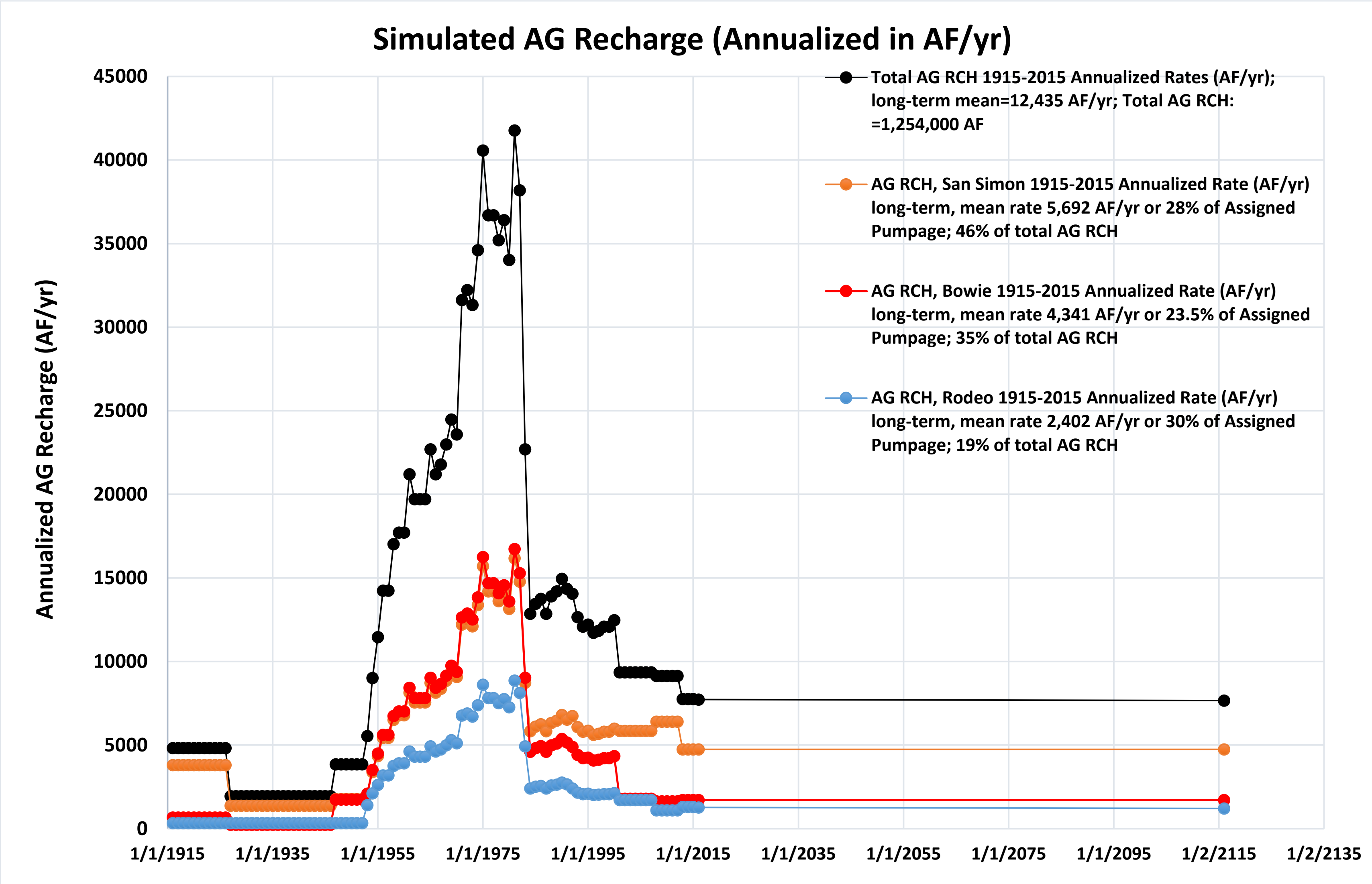


Figure 28 Simulated AG Recharge (Annualized in AF/yr)

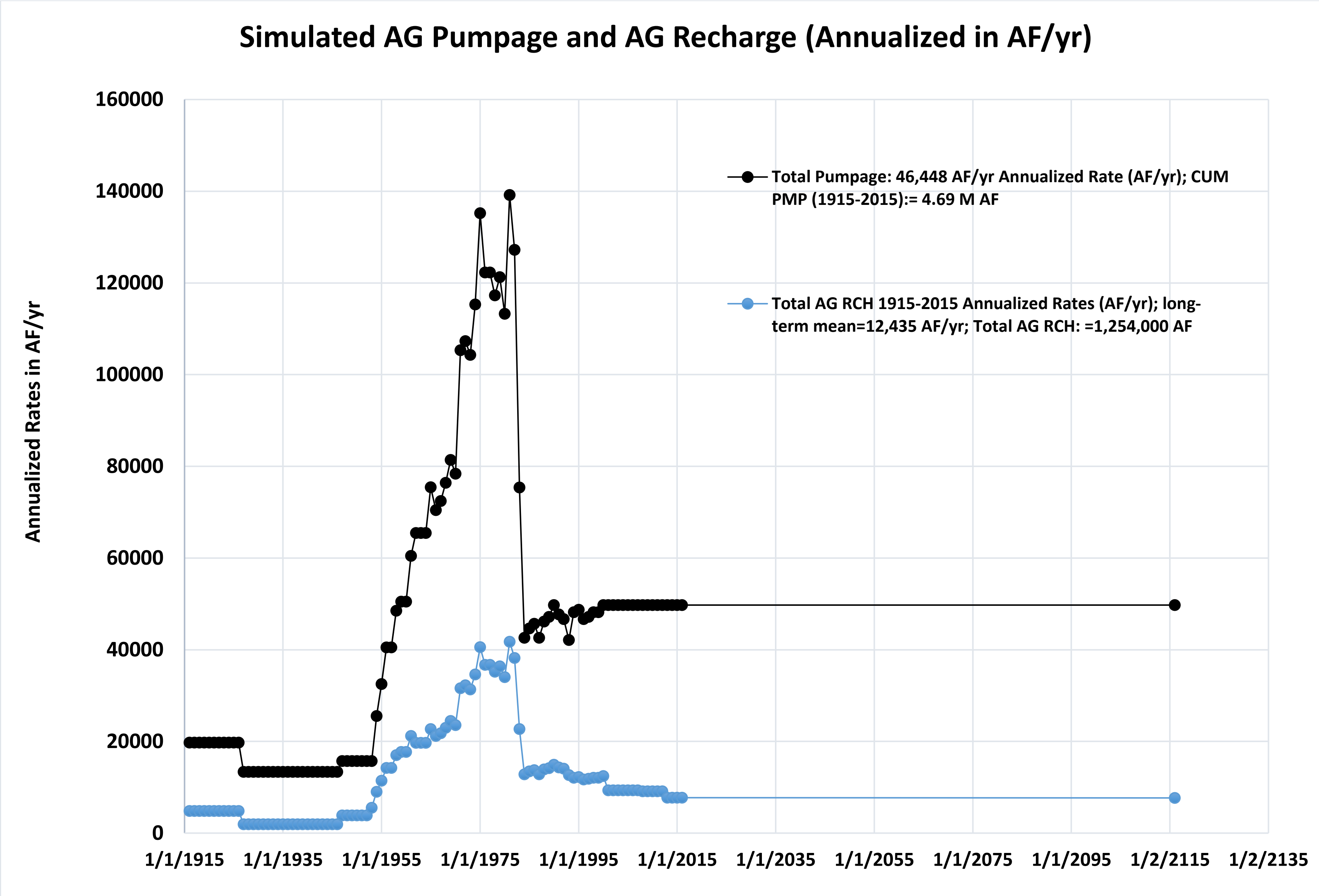


Figure 29 Simulated AG Pumpage and Recharge (Annualized in AF/yr)

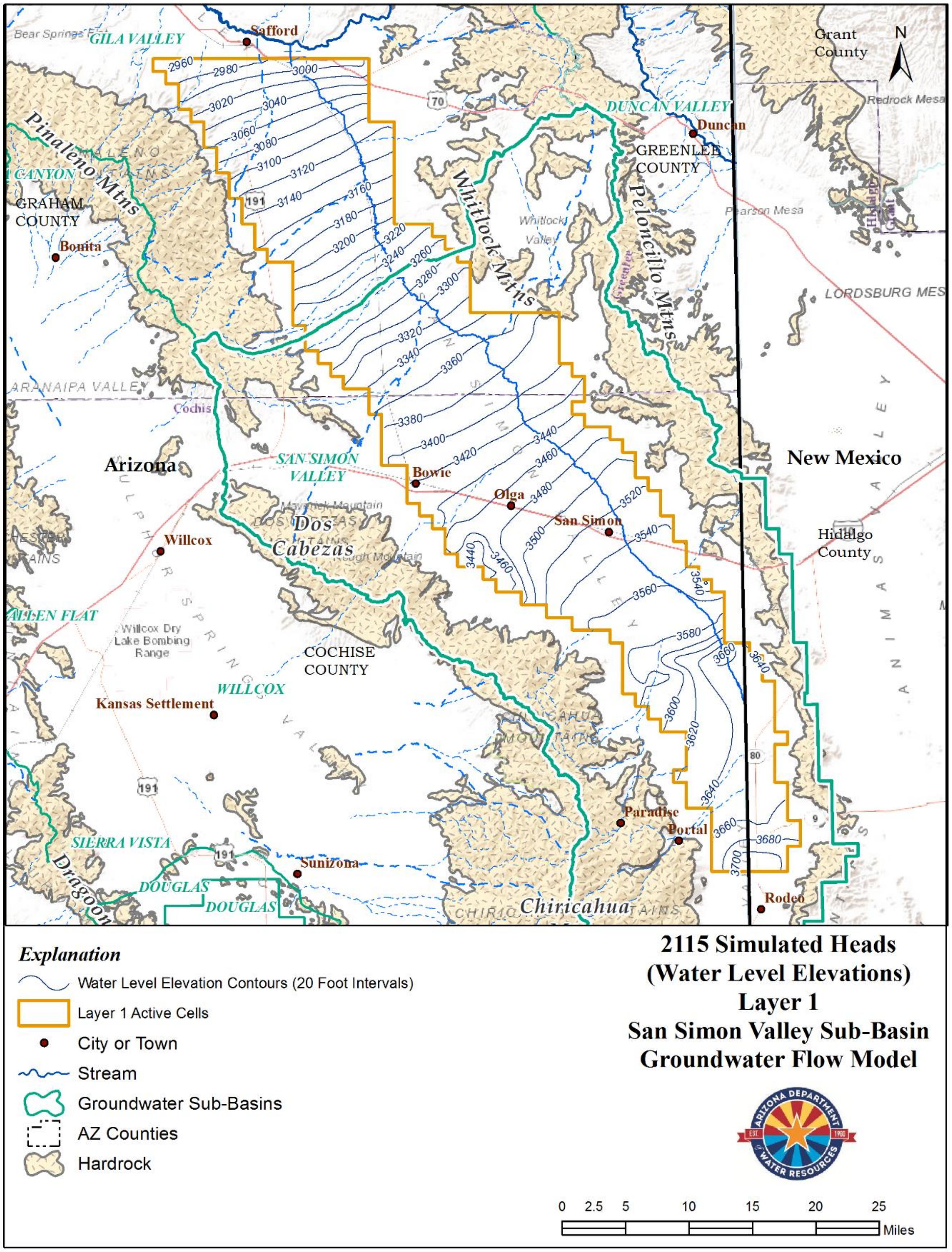


Figure 30 2115 Simulated Heads (Water Level Elevations) Layer 1 San Simon Valley Groundwater Flow Model

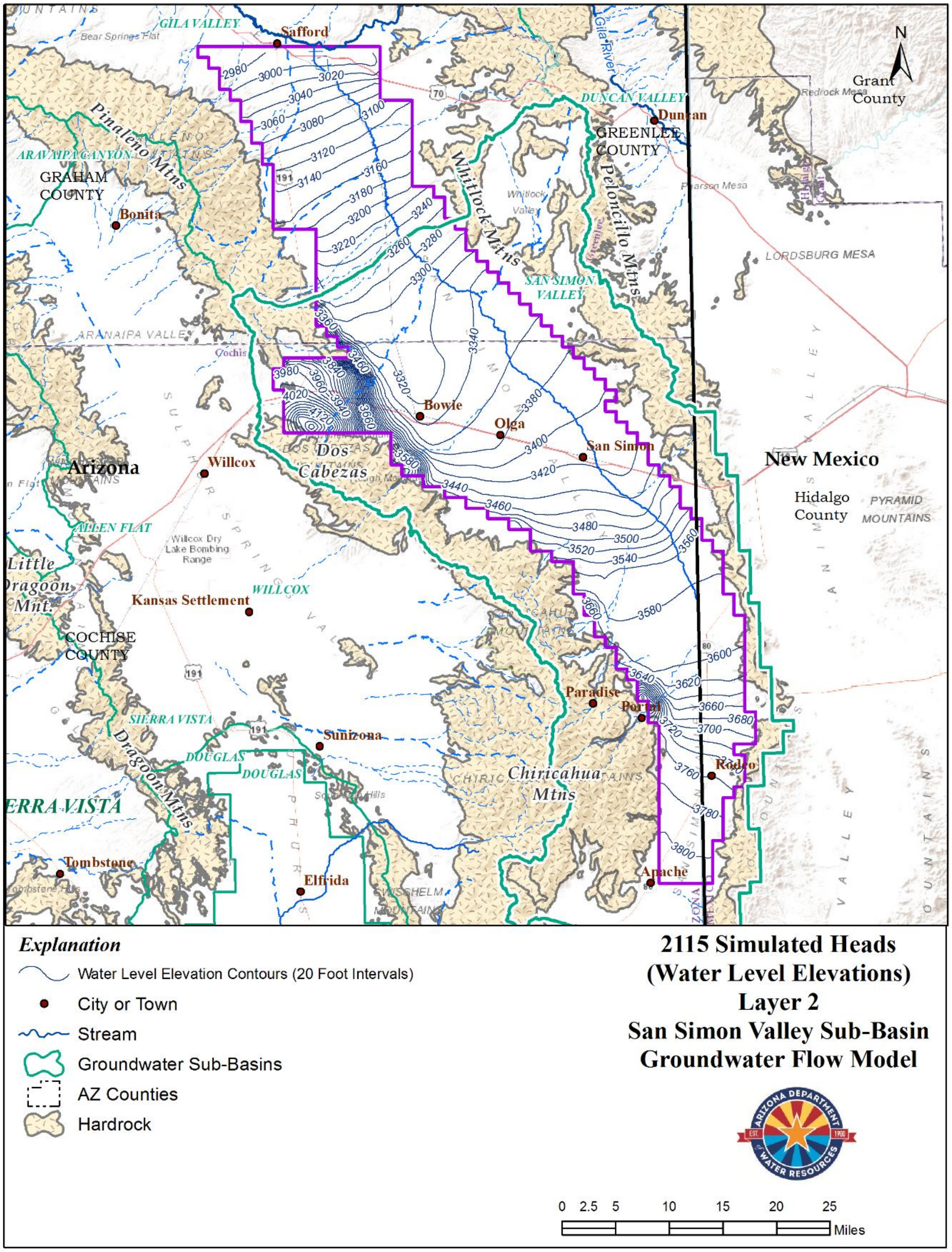


Figure 31 2115 Simulated Heads (Water Level Elevations) Layer 2 San Simon Valley Sub-basin Groundwater Flow Model

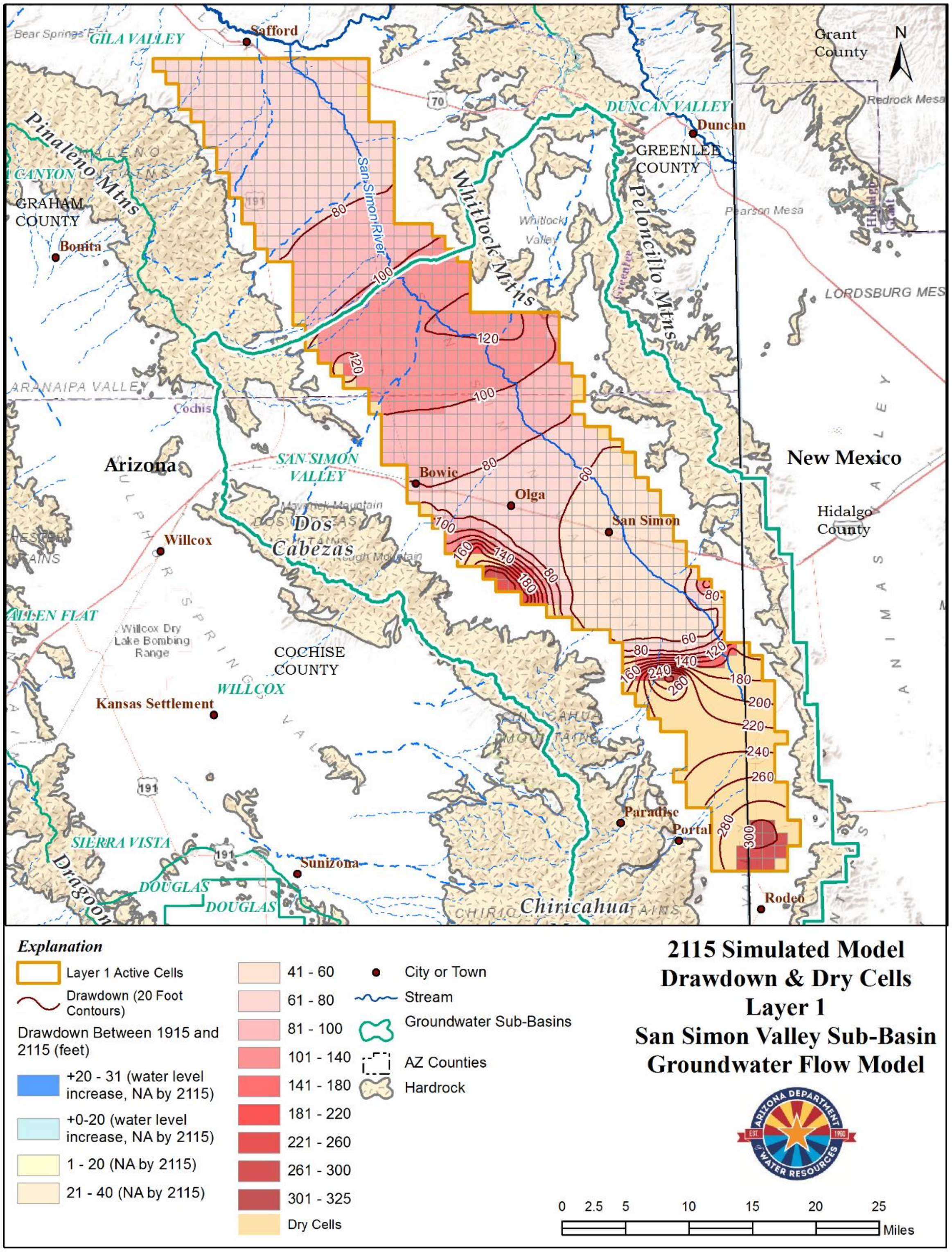


Figure 32 2115 Simulated Model Drawdown & Dry Cells Layer 1 San Simon Valley Sub-basin Groundwater Flow Model

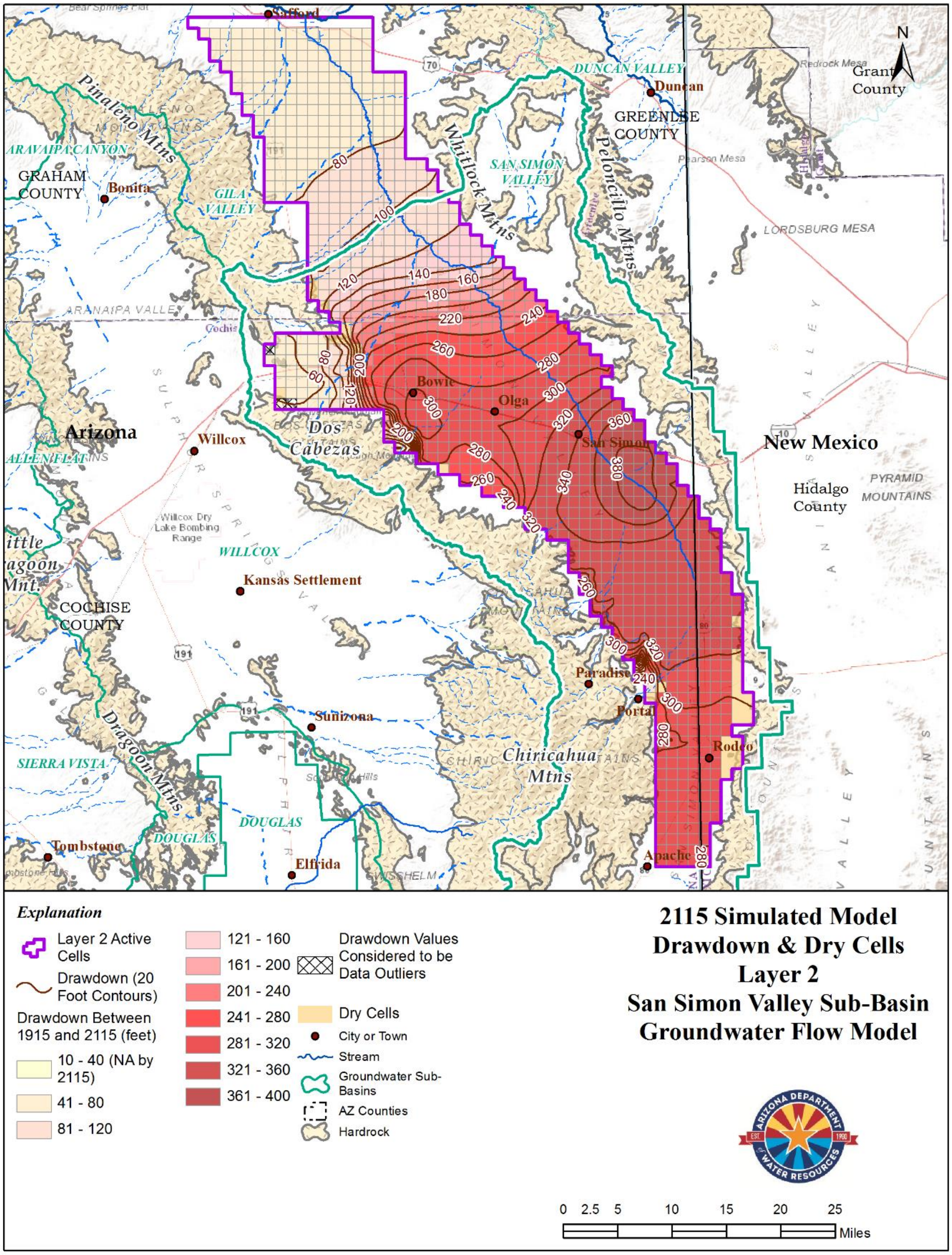


Figure 33 2115 Simulated Model Drawdown & Dry Cells Layer 2 San Simon Valley Groundwater Flow Model

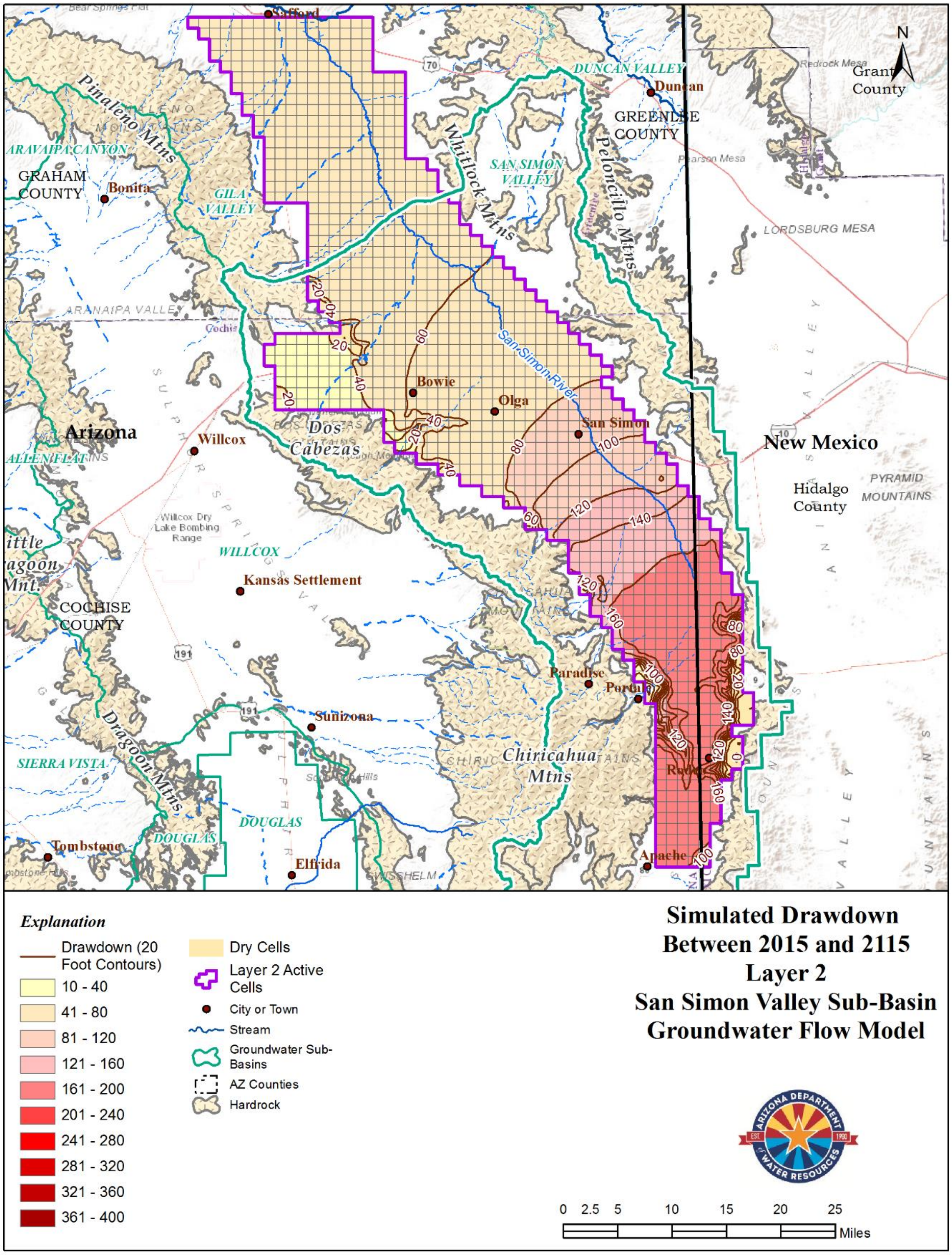


Figure 34 Simulated Drawdown Between 2015 and 2115 Layer 2 San Simon Valley Groundwater Flow Model

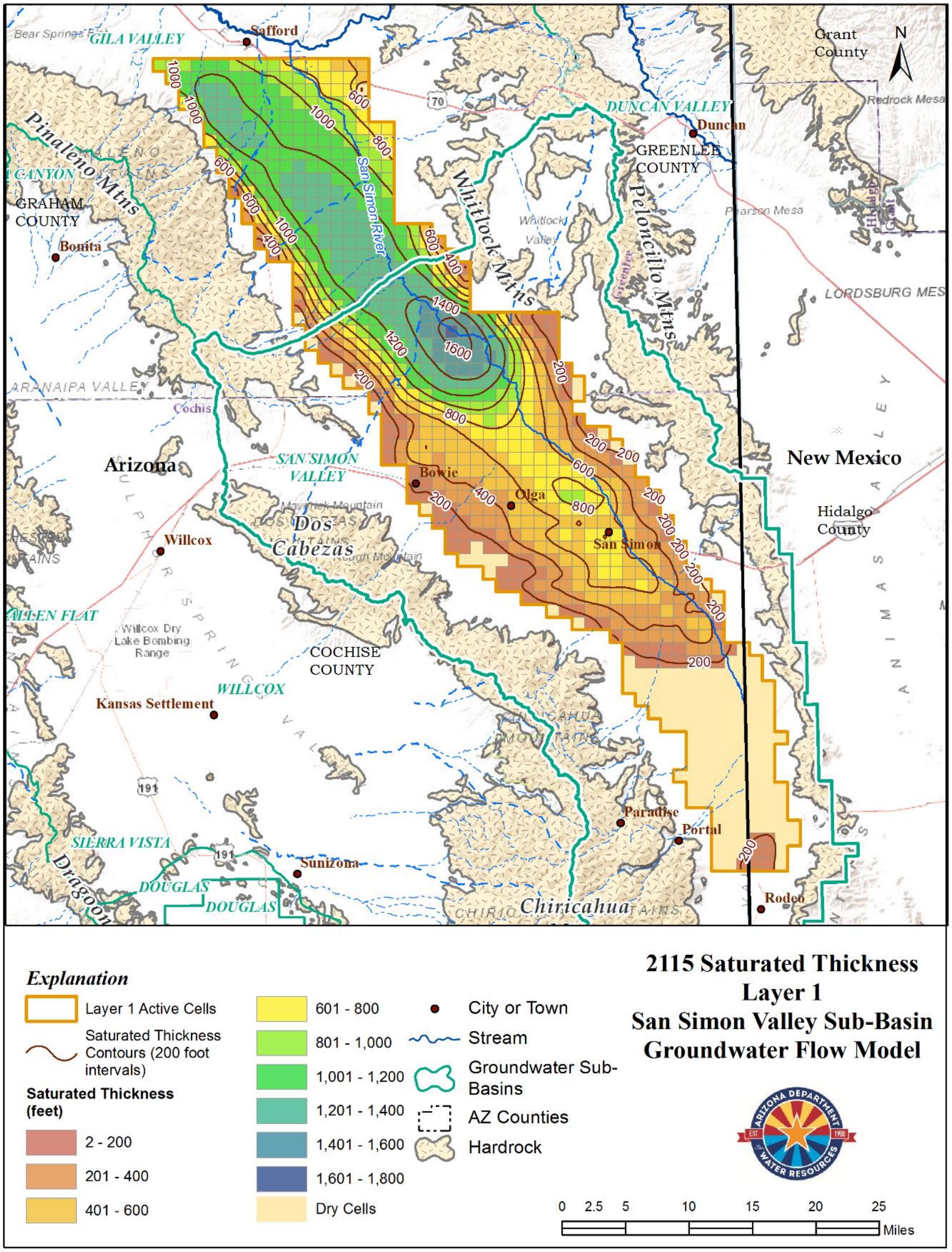


Figure 35 2115 Saturated Thickness Layer 1 San Simon Valley Groundwater Flow Model

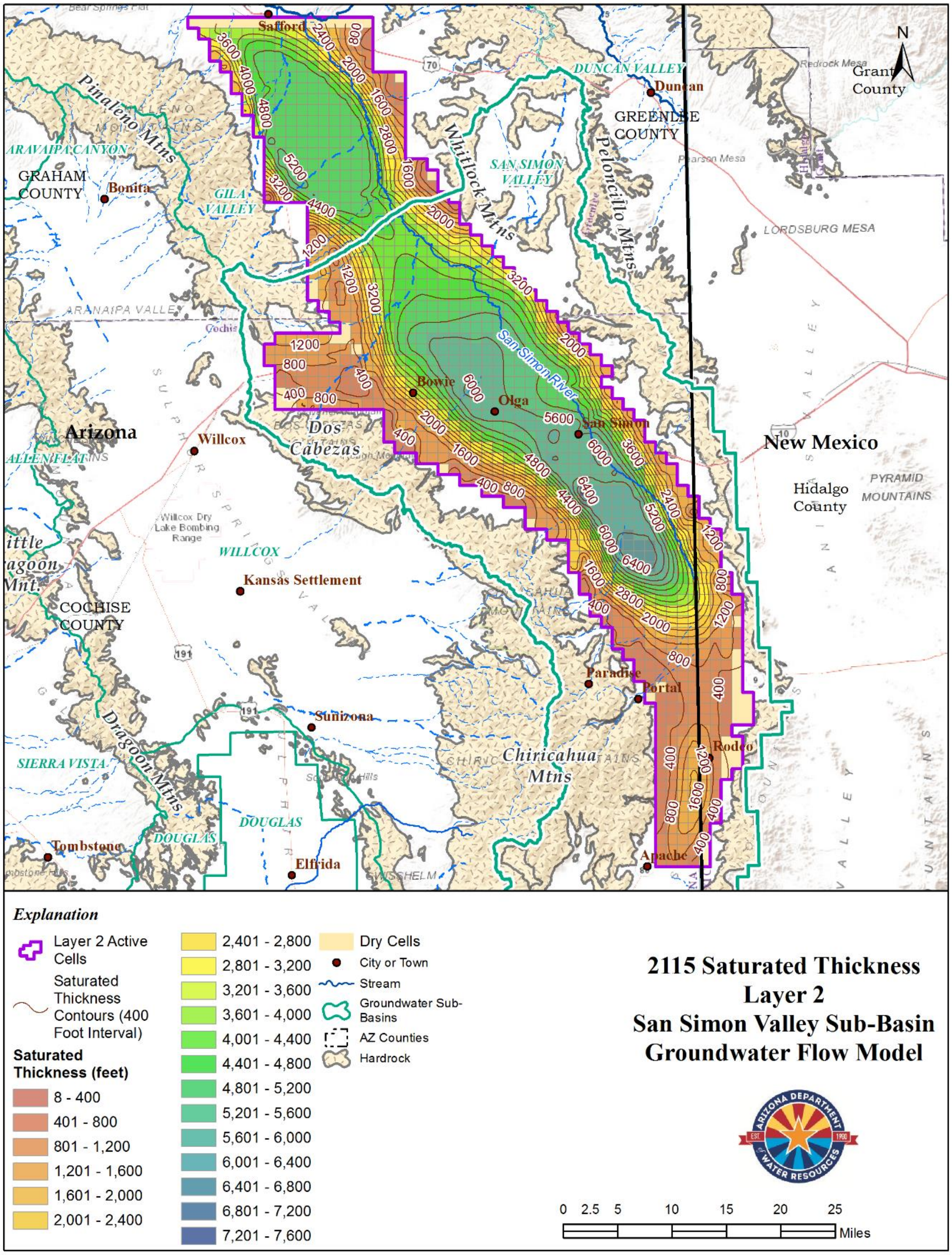


Figure 36 2115 Saturated Thickness Layer 2 San Simon Valley Groundwater Flow Model

Model Limitations

The regional scale model was calibrated to available target data, and the vast majority of data is located within the major pumping centers of Bowie, San Simon and Rodeo areas. Data are sparse in areas outside the valley center. Along the model edges the basin fill sediments become thin, and there is significant uncertainty regarding unit elevations and unit thicknesses in peripheral areas, where alluvial materials pinch-out (see cross-sections above). For example, the depth-to-bedrock contours that were used to develop the San Simon Valley Sub-basin model's bottom depth were based on original estimates that have approximate accuracies of +/- 30 percent (Oppenheimer and Sumner, 1981).

Inversion statistics indicate high parameter correlation exists between MFR, underflow and hydraulic conductivity (K). As previously noted, parameter correlation was reduced by the inclusion of flow target estimates and estimated a-priori K values. However, if assumptions about calibration target information including flow, and a-priori K assumptions, change in the future (i.e., new information about the magnitude and distribution of K for basin fill materials, or possibly assumptions about bedrock geometry), the resulting solution could alter the model simulation results. Areas along the model edges would, most likely, be sensitive to changes in the conceptual model and initial conditions.

The magnitude and distribution of estimated stresses (pumping and recharge) and boundary conditions (specified heads and fluxes) also impact the model results. Although these model inputs and features were tested and modified to minimize model residuals during the steady-state and transient model calibration periods, it is possible that new information could provide other combinations and distributions of stresses that would alter model results.

Although the final cumulative mass balance error was acceptable, the model may be susceptible to numerical instabilities especially along model edges where cell unit-thickness and/or saturated thicknesses become thin, or subject to dewatering. During model development, a few problematic cells were de-activated prior to the transient simulation, in order to reduce mass balances errors. However the "strength" of the model lies in representing regional-scale groundwater flow, especially in areas where the majority of head target data exist.

References

ADWR, 2015. ADWR GWSI water level data for the San Simon Valley Sub-Basin. Download spreadsheet at: http://www.azwater.gov/azdwr/SanSimonValley.htm

Anning, D.W., and Duet, N.R., 1994. Summary of Ground-Water Conditions in Arizona, 1987 - 90. U.S. Geological Survey Open-File report 94-476

Arizona Crop and Reporting Service, 1974. Cropland Map of Arizona.

Barnes, R.L., 1991. Maps showing groundwater conditions in the San Simon Sub-basin of the Safford Basin Graham and Cochise Counties, Arizona Hidalgo County, New Mexico – 1987.

Freethey, G.W., and Anderson, T.W. 1986. Predevelopment Hydrologic Conditions in the Alluvial Basins of Arizona and Adjacent Parts of California and New Mexico. U.S. Geological Survey Hydrologic Investigations Atlas HA-664.

Gootee, B.F., 2012. Geologic evaluation of the safford basin for carbon dioxide sequestration potential: Arizona geological survey Open File Report 12-01.

Harbaugh, A.W., and others, 2000. MODFLOW – 2000, the U.S. Geological Survey Modular Ground-Water Model—User guide to modularization concepts and the Ground-Water flow Process: U.S. Geological Survey Open-File Report 00-92.

Hill, M. (1998). Methods and Guidelines for Effective Model Calibration. U.S. Geological Survey Water Resources Investigation Report 98-4005.

Oppenheimer, J.M., and sumner, J.S., 1981. Depth-to-Bedrok Map, basin and Range Province, Arizona. Laboratory of Geophysics, University of Arizona, Tucson, Arizona.

Schwennesen, A.T., and Forbes, R.H., 1917. Groundwater in the San Simon Valley, Arizona and New Mexico, with a section on Agriculture. U.S. Geological Survey Water Supply Paper 24-A.

University of Arizona, 1974. Cropland Atlas of Arizona, University of Arizona, Collage of Agricultural in cooperation with the U. S. Department of Agriculture Statistical Reporting Service.

USGS, 2015. USGS Crop Survey and related data for San Simon Valley Sub-basin Basin. Data from Saeid Tadayon USGS Tucson.

Waterloo Hydrogeologic, 2015. Visual MODFLOW Flex. http://www.novametrixgm.com/groundwater-software/groundwater-modeling-software

White, N.D., 1963. Analysis and Evaluation of Available Hydrologic Data for San Simon Basin, Cochise and graham Counties, Arizona. U.S. Geological survey Water Supply Paper 1619-DD.

WinPEST, 2003. Users Manual for WinPEST. Watermark Numerical Computing & Waterloo Hydrogeologic, Inc.

Appendix A - Parameter Sensitivity Data

Excerpt of PEST Record File and Summary of Parameter Sensitivities

```
                   OPTIMISATION RESULTS
Adjustable parameters ----->
Parameter        Estimated          95% percent confidence limits
                 value              lower limit        upper limit
 kx_10          0.708424           4.548951E-02        11.0325
 kx_11           15.4850            7.50806            31.9369
 kz_11          4.874537E-05       1.233694E-05       1.926014E-04
 kx__1           22.9292            12.5532            41.8815
 kx__2           1.73063            1.20577            2.48395
 kx__3          0.859125           0.133978            5.50907
 kx__6           3.60111            2.87250            4.51453
 par003         0.143631           0.113216           0.182217
 par004         9.692059E-02       8.304360E-02       0.113116

Note: confidence limits provide only an indication of parameter uncertainty.
      They rely on a linearity assumption which may not extend as far in
      parameter space as the confidence limits themselves - see PEST manual.

Tied parameters ----->
Parameter      Estimated value
 kx_10          0.708424
 kz_10          7.084243E-02
 ky_11           15.4850
 ky__1           22.9292
 kz__1           2.29292
 ky__2           1.73063
 kz__2          1.429314E-04
 ky__3          0.859136
 kz__3          8.591359E-02
 ky__6           3.60111
 kz__6           1.09097
 kx__7           3.60111
 ky__7           3.60111
 kz__7           1.09097
 kx__9           3.60111
 ky__9           3.60111
 kz__9           1.09097
 par001          5.20942
 par002          5.20942
See file C:\SAN_SIMON_MODEL\AA_05302015\SANSIM_SS_0530A.SEN for parameter
sensitivities.
```

Composite Sensitivity of Fundamental Model Parameters			
Parameter	Steady with Flow & a-priori	Steady without Flow & a-priori	Transient 101 years
Kx10	0.134	0.061	0.023
Kx11	0.142	0.071	0.047
Kz11	0.056	0.028	0.018
Kx1	0.75	0.37	0.058
Kx2	1.34	1.13	0.0404
Kx3	0.071	0.067	0.045
Kx6	0.73	0.74	0.043
Natural Recharge	3.1	2.29	0.065
UnderFlow *to* North*	5.4	4.37	0.038
AG RCH Bowie	N/A	N/A	0.006
AG RCH San Simon	N/A	N/A	0.02
AG RCH South	N/A	N/A	0.004
Underflow *from* South**	N/A	N/A	0.009
Ss (combined L2)	N/A	N/A	0.12
Sy (layer 1)	N/A	N/A	0.053
Sy (combined Layer 2)	N/A	N/A	0.026
Standard error of regressions for 1) steady state with flow and a-priori weighting: 0.90; 2) steady state without flow or a-priori weighting: 0.85; and 3) transient state: 1.14. *Applied specified flux to represent underflow to the north, which provided greater parameter sensitivities than the application of head-dependent boundaries (i.e., CHB). **Converted CHB to specified flux for transient simulation. During transient-based PEST simulations, analysis of parameter upgrades/directions (i.e., process of minimizing objective function) inferred the following with respect to transient simulated rates : 1) slightly higher rates of underflow simulated out of the model to the north, with respect to steady state flow rates; 2) higher rates of AG recharge in the Bowie area; 3) lower rates of AG recharge in the San Simon area; 4) higher rates of AG recharge in the southern and Rodeo areas; 5) higher rates of underflow from the south; 6) slightly lower rates of natural MFR.			

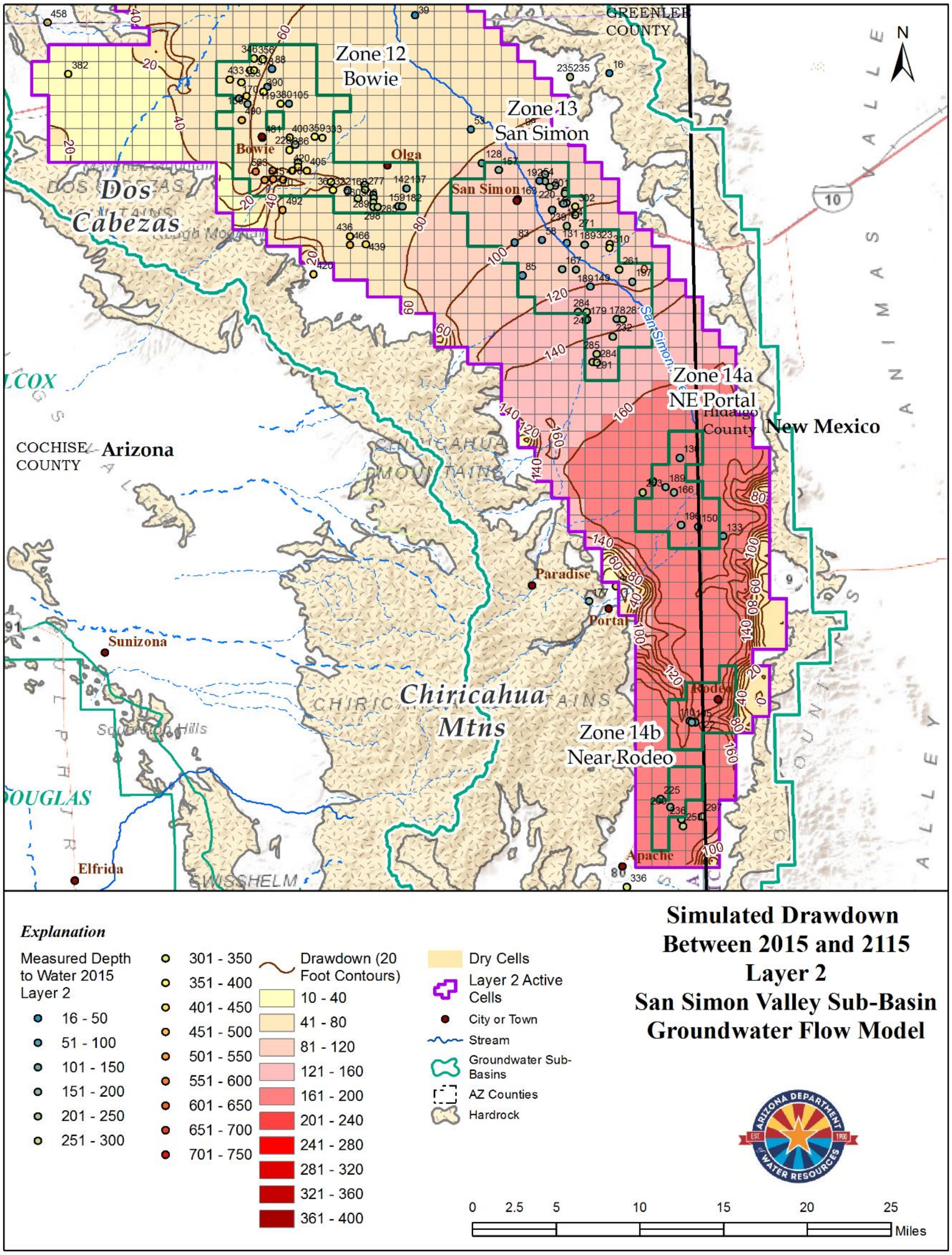
Appendix B - Summary of Simulated Water Budgets for San Simon Valley Sub-basin Model From MODFLOW (LST) Files

Model Simulated Water Budgets SS, Transient 1915 - 2015, Projection 2016-2115

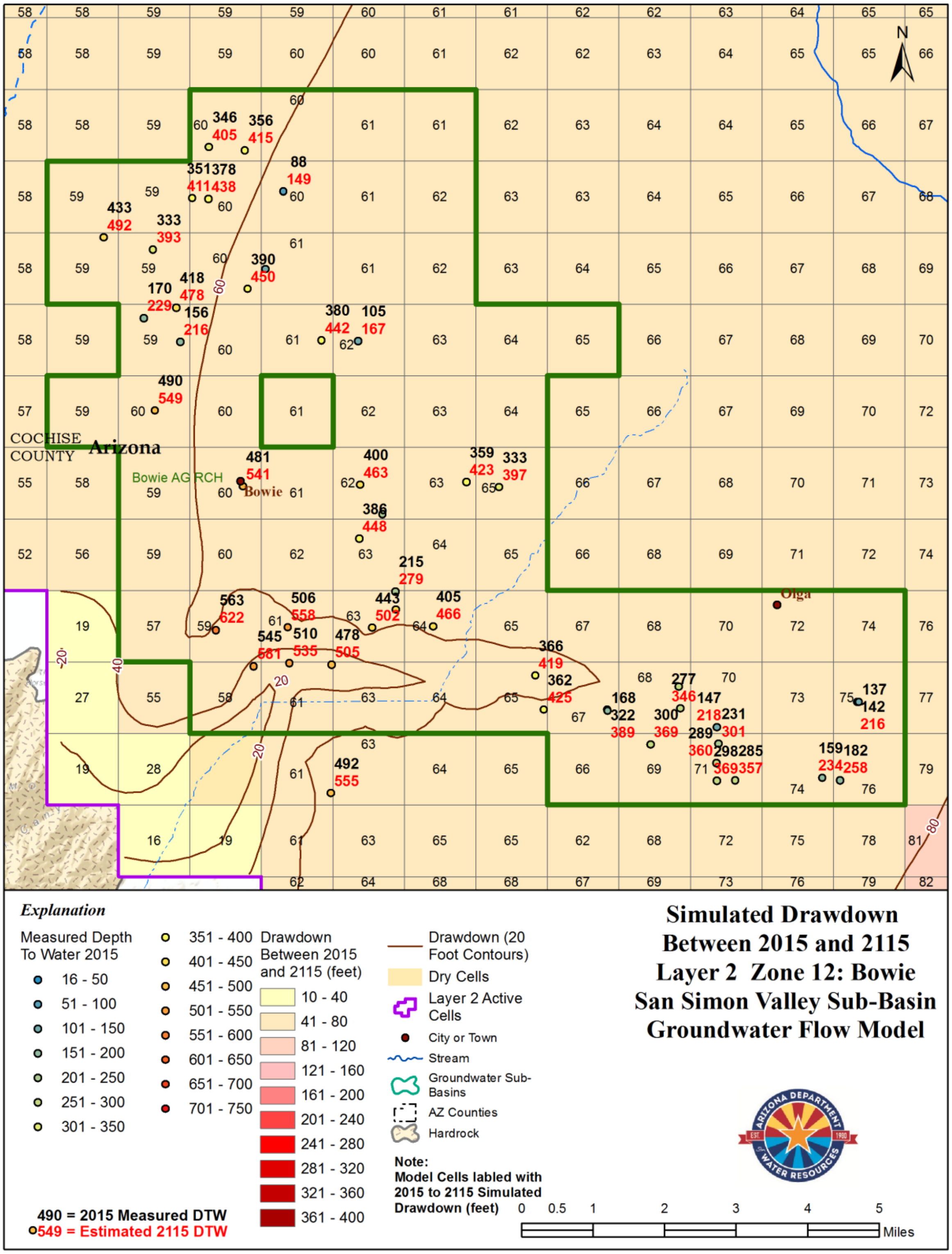
Budget Component	Steady State (circa Pre-1915) (One Year)		Transient (1915-2015) (101 Years)		Projection (2016-2115) (100 years)		Difference (2115 - 2015) (100 years)
	Cumulative	Average	Cumulative	Average	Cumulative	Average	Cumulative
	AF	AF/yr	AF	AF/Yr	AF	AF/Yr	AF
IN							
Storage	0	0	4,187,995	41,465	8,337,493	41,495	4,149,497
Constant Head	3,031	3,031	0	0	0	0	0
Recharge	31,240	31,240	4,474,617	44,303	8,386,499	39,119	3,911,882
Total In	34,271	34,271	8,662,612	85,768	16,723,991	80,614	8,061,379
OUT							
Storage	0	0	655,230	6,487	675,190	200	19,960
Constant Head	0	0	0	0	0	0	0
ET	4,838	4,838	230,702	2,284	230,702	0	0
Wells	0	0	4,688,005	46,416	9,660,612	49,726	4,972,607
Recharge	29,433	29,433	3,067,174	30,368	6,103,974	30,368	3,036,801
Total Out	34,271	34,271	8,641,111	85,556	16,670,478	80,094	8,009,407
In - Out	0		676,731		728,703		
Percent Discrepancy	0.00		0.25		0.32		
Change In Storage	0	0	-3,532,765	-34,978	-7,662,303	-41,295	-4,129,538

- Some values presented in this table may differ slightly values listed in Tables 4, 5 and 6 which were based on optimized PEST solutions.

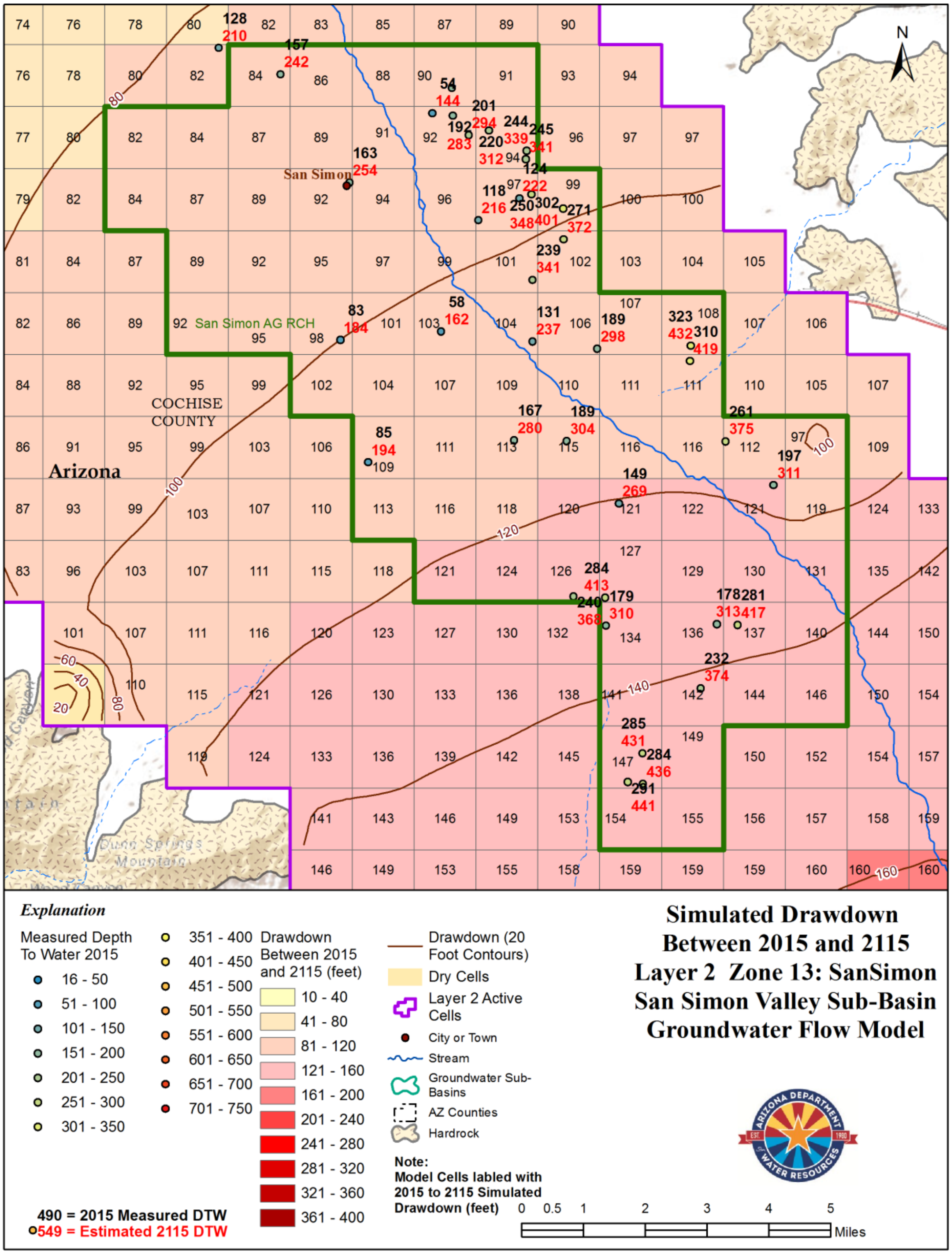
Appendix C - Projected Depth to Water In 2115 for Agricultural Areas of the San Simon Valley Sub-basin



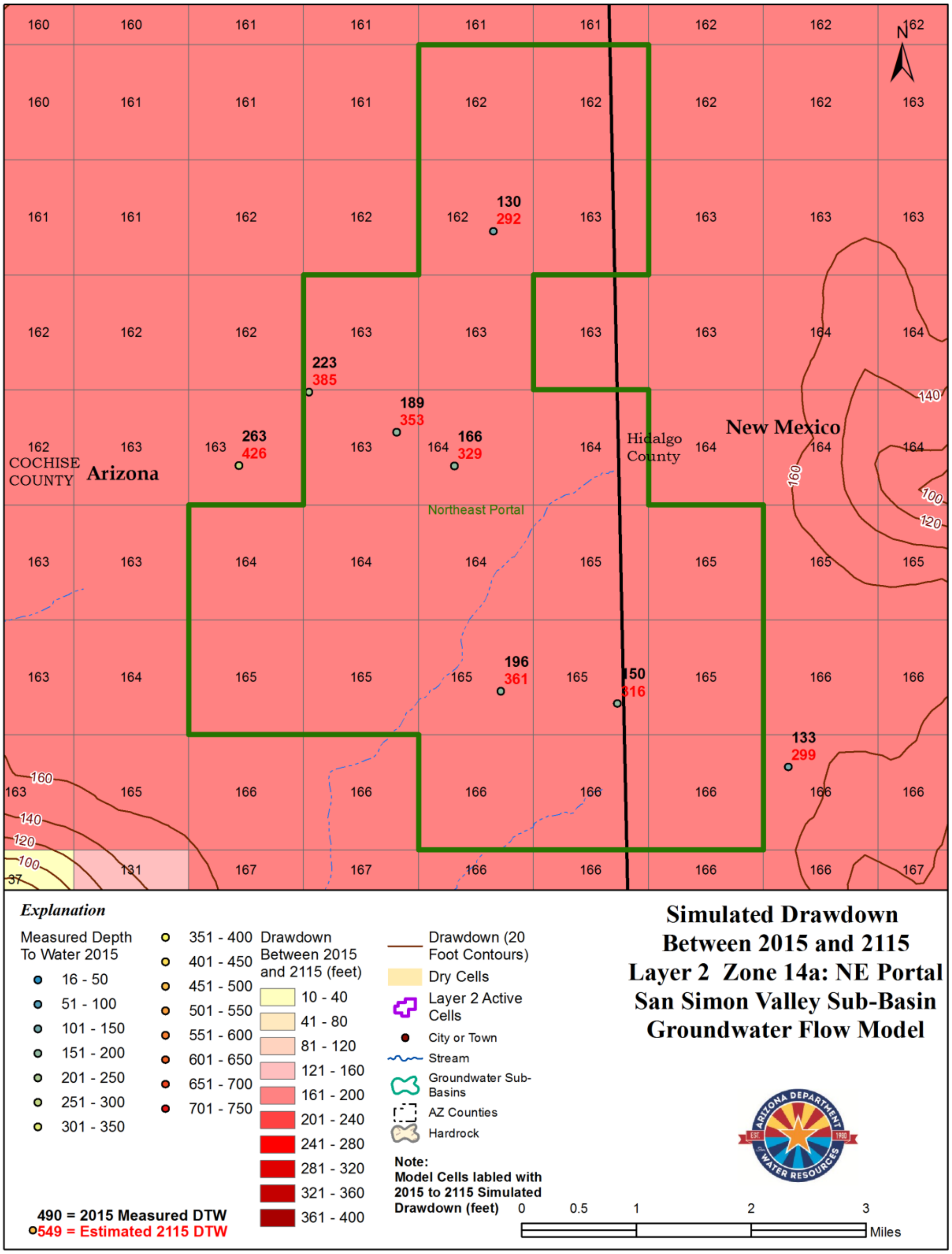
Simulated Drawdown Between 2015 and 2115 Layer 2
San Simon Valley Sub-basin Groundwater flow Model



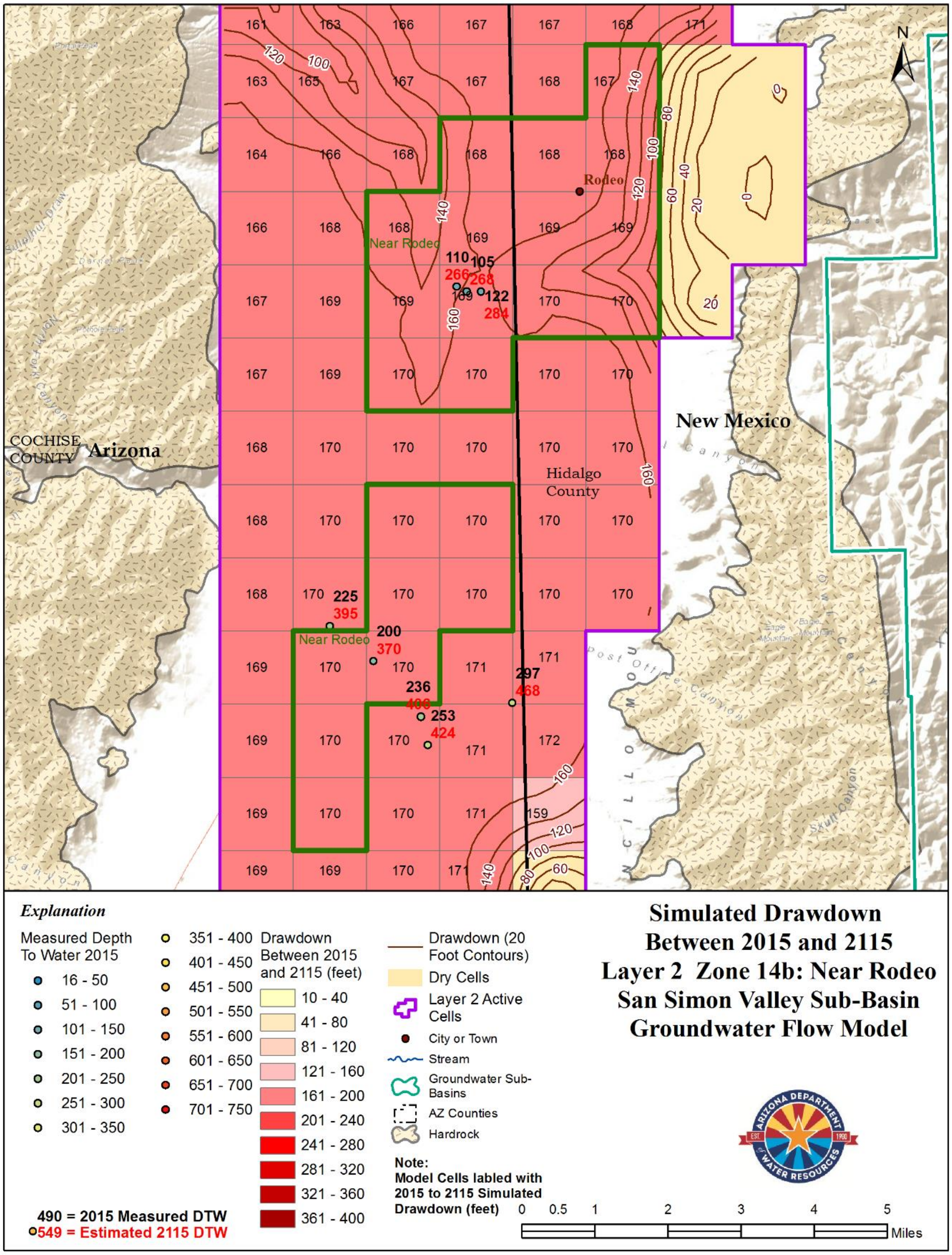
Simulated Drawdown Between 2015 and 2115 Layer 2 Zone 12: Bowie
San Simon Valley Sub-basin Groundwater flow Model



Simulated Drawdown Between 2015 and 2115 Layer 2 Zone 13: San Simon San Simon Valley Sub-basin Groundwater Flow Model



Simulated Drawdown Between 2015 and 2115 Layer 2 Zone 14a: NE Portal
San Simon Valley Sub-basin Groundwater Flow Model



Simulated drawdown Between 2015 and 2115 Layer 2 Zone 14b: Near Rodeo San Simon Valley Sub-basin Groundwater Flow Model

Projected Depth to Water for Deep Agricultural Wells in the San Simon Valley Sub-basin in 2115

	Zone 12 Bowie Area (Feet BLS)	Zone 13 San Simon Area (Feet BLS)	Zone 14a NE of Portal (Feet BLS)	Zone 14b Near Rodeo (Feet BLS)
Deep Ag Well Count	44	36	6	4
Minimum Depth	149	144	292	266
Maximum Depth	622	441	385	370
Mean Depth	388	316	339	297
Median Depth	408	312	341	276

- Statistics Are For Deep Agricultural Wells That Were Measured in 2015. (Well Depth >= 400 feet Below Land Surface (BLS))
- Projected Depth-to-Water in 2115 = (2015 Measured Depth-to-Water) + 2015-2115 Model Layer 2 Projected Drawdown