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Technical Memorandum

Prepared for:	Fluid Solutions
Project Title:	Groundwater Modeling in Support of Physical Availability Determination for the Pueblo del Sol Water Company
Project No:	140007

Technical Memorandum No. 2

Date:	January 13, 2012
To:	Erin Young, Project Manager
From:	Kathleen McHugh, Mark Nicholls
Subject:	Groundwater Modeling Approach and Results from Predictive Simulations

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Limitations:

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1. Groundwater Modeling Analysis

To assess the hydrologic impacts of future groundwater development by Pueblo del Sol Water Company (PDS) and the Bella Vista Water Company, a three-dimensional numerical groundwater flow model recently developed for the Sierra Vista Sub-watershed was modified for the purposes of assessing the adequacy of future groundwater supplies in the vicinity of the PDS service area. The modeling tasks and results documented in this technical memorandum are in support of a Physical Availability Determination (PAD) application and Analysis of Adequate Water Supply (AAWS) application to be submitted to the Arizona Department of Water Resources (ADWR) by Fluid Solutions on behalf of their client, Castle and Cooke Arizona, Inc. The Sierra Vista model (SV Model) was developed by Brown and Caldwell (BC) by updating the U.S. Geological Survey (USGS) model of the Lower San Pedro Watershed (BC, 2010; Pool and Dickinson, 2007). The primary purpose of this model update was to improve the ability of the model to evaluate effects of the City of Sierra Vista Water Reclamation Facility (WRF) on water levels in the regional aquifer and augmentation of flows in the San Pedro River. This improvement was accomplished by extending the calibrated USGS model simulation timeframe, and refining model parameters and layering in the vicinity of the WRF. Relative to the original USGS model, the SV Model has updated municipal pumping and recharge estimates, a refined geologic interpretation around the Sierra Vista WRF, a southern model boundary that terminates at the border with Mexico, an extended time frame through 2008 (from 2003), and improved calibration statistics . The SV model was chosen as the basis for performing PDS AWS simulations because it has previously been co-developed with and reviewed by ADWR staff, reviewed and accepted by the U.S. Bureau of Reclamation, and is the most current and up-to-date groundwater model for the Sierra Vista Sub-watershed.

Except where noted in this technical memorandum, the SV Model construction, parameterization, and groundwater inflows and outflows adhere to the information provided in the 2010 report *Sierra Vista Water Reclamation Facility Groundwater Modeling Study, Prepared for the City of Sierra Vista, Arizona* (BC, 2010). This BC (2010) model documentation was referenced for information regarding the regional hydrogeologic conceptualization for the PDS simulations.

2. Development of the Numerical Flow Model

A series of sequential, transient, groundwater simulations were developed to simulate past, current, and future groundwater conditions. All simulations were based upon the same numerical and hydrogeologic framework and have identical model grid construction and hydraulic parameterization. The simulations vary only in the length of timeframes and allocation of groundwater pumping.

The first simulation (base simulation) is based upon the original SV Model calibration simulation and simulates groundwater conditions from spring 1986 to summer 2008. Two modifications were made to the SV model to improve model calibration in the vicinity of the PDS service area: 1) hydraulic conductivity values were adjusted in the vicinity of PDS Well No. 2, and 2) the locations of natural (mountain front) recharge zones were shifted westward to more adequately reflect local hydrogeologic conditions. Additional information regarding the modifications made to the SV Model to produce the PDS simulations are presented in the following sections.

The second and third simulations comprise the full AWS 100-year simulation time period (Tribute simulation). Together these simulate estimated conditions from the winter of 2008 to the summer of 2110, and were only divided due to the computational limitations caused by the large size of the model output files. The total timeframe of both simulations includes the 100-year projection period required for the purposes of this AWS hydrology study. The first simulation ends in the summer of 2060, and the second simulation ends in 2110. Initial water level conditions were taken directly from the end of the last stress period for the calibrated, base simulation.

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Another set of simulations were run (the Non-Tribute simulation) which consists of the same two sequential models used for the Tribute simulation; however, the one difference between the simulations is the absence of Tribute pumping. This run was performed at the request of ADWR and will be used to assess the impact of PDS Tribute demand.

Table 2-1 presents the specifications of the PDS model. Specific details of the model construction including full inputs and water budget components can be found in Appendix Z (digital model files), as well as in the SV Model report (BC, 2010).

Table 2-1. Specifications of the PDS Groundwater Model

Model Characteristics	Specifications
Active Model Domain	~1,135 square miles, ~725,000 acres
Units	Time: Days Length: Meters (lateral and vertical)
Coordinate System	UTM NAD83, Zone 12N GIS: lateral units in meters, vertical units in meters
Model Grid	440 rows by 320 columns, 704,000 total cells, 81,160 active cells Origin X: 529,999.951 Y: 3,419,999.983 (No rotation)
Cell Size	250 meters by 250 meters (uniform) 820 feet x 820 feet 0.155 mile x 0.155 mile
Layering – 5 Layers	*Layer 1:* Pre and post-entrenchment stream alluvium, and the sand and gravel facies of the upper basin fill. LAYCON = 1 (Unconfined) *Layer 2:* Sand, gravel, silt and clay facies of the upper basin fill. LAYCON = 3 (Unconfined/Confined; T varies) *Layer 3:* Sand, gravel, siltstone, and mudstone facies of the lower basin fill. LAYCON = 3 (Unconfined/Confined; T Varies) *Layer 4:* Sand and gravel facies of the lower basin fill. LAYCON = 3 (Unconfined/Confined; T varies) *Layer 5:* sand and gravel facies on the perimeter of the alluvial basin of the lower basin fill; siltstone and conglomerate of the Pantano Formation, and consolidated rock. LAYCON = 3 (Unconfined/Confined; T varies)
Hydraulic Parameters	*Layer 1:* K = 4.0 m/d to 7.5 m/d; Sy = 0.3 ; SS = 0.000001 *Layer 2:* K = 0.02 to 5 m/d; Sy = 0.05 to 0.25 ; SS = 0.00002 *Layer 3:* K = 0.001 to 4 m/d; Sy = 0.05 to 0.1; SS = 0.000005 to 0.00001 *Layer 4:* K = 0.001 to 6.25 m/d; Sy = 0.05 to 0.25; SS = 0.000005 *Layer 5:* K = 0.000125 to 0.625 m/d; Sy = 0.001 to 0.2; SS = 0.000001
MODFLOW Packages	MODFLOW 2000, Drain, Well, Stream, ET, Recharge, BAS, DIS, LPF, CHD
Stress Periods and Simulation Time	Base Model: 45 Seasonal Stress Periods, 10 time steps each, 1.5 multiplier Begins on March 12, 1986 and continues to October 15, 2008. Predictive Model No. 1: 104 Seasonal Stress Periods, 10 time steps each, 1.5 multiplier Begins on October 16, 2008 and continues until October 15, 2060 Predictive Model No. 2: 100 Seasonal Stress Periods, 10 time steps each, 1.5 multiplier Begins on October 16, 2060 and continues until October 15, 2110
Recharge	Cell inputs range from 0.001 ft/yr to 28.5 ft/yr
Wells	Imported as prescribed flux analytical element wells. (Note: These wells sum to a total pumping value for each model node. They include both pumping and recharge wells.)
Boundary Conditions	Constant Heads at the North end of the model to represent underflow to the remaining portion of the Upper San Pedro Basin; Constant Heads along the Mexican Boundary to represent underflow from the Mexico portion of the Basin
Initial Conditions	Resulting heads from the immediately previous transient USGS model
Solution Methods	Geometric Multi-Grid (GMG)

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2.1 Model Grid

The model grid was georeferenced within the Universal Transverse Mercator (UTM) coordinate system, North American Datum 1983, Zone 12N and has a uniform grid spacing of 250 meters by 250 meters. The full extent of the model domain and locations of PDS wells are shown on Figure 1. The extent and spacing of the active model cells for each layer are identical to those of the SV Model (BC, 2010).

2.2 Layering

General layer information is presented above in Table 2-1 and provided digitally in Appendix Z. Elevations for layer tops and bottoms are identical to those estimated by the USGS and BC for the SV Model and were not modified for the PDS model.

2.3 Aquifer Parameters

The majority of horizontal and vertical hydraulic conductivity values and storage parameters are identical to those estimated by the USGS and BC for the SV Model. However, a small hydraulic conductivity zone in layer 4 within a portion of the PDS service area was modified based on observed well performance to improve water level calibration. This new hydraulic conductivity zone was added to the model in the vicinity of PDS Well No. 2. The original hydraulic conductivity value for this area was 0.01625 meters per day (m/day) (~.05 feet per day [ft/d]) and was changed to 0.3125 m/day (~1.0 ft/d) to more accurately simulate local water levels and observed well performance.

2.4 Boundary Conditions

Transient proscribed head cells were used as boundary conditions for the northern and southern boundaries of the model domain. No changes were made to the boundary conditions applied to the PDS Model.

2.5 Wells

For the base simulation, all non-PDS pumping wells were simulated at the same locations, layers, and magnitudes as those in the SV Model. Pumping volumes for the PDS wells identified below were updated to recorded volumes as presented below in Table 2-2.

Table 2-2. PDS Pumping

Year	Well No. 2 (Acre-feet)	Well No. 3 (Acre-feet)	Well No. 4 (Acre-feet)	Well No. 5 (Acre-feet)	Total (Acre-feet)
1986	98	102	119	0	320
1987	114	118	138	0	370
1988	132	137	160	0	430
1989	151	156	183	0	490
1990	169	176	205	0	550
1991	188	195	228	0	610
1992	206	214	250	0	670
1993	225	233	272	0	730
1994	243	252	295	0	790

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Table 2-2. PDS Pumping					
Year	Well No. 2 (Acre-feet)	Well No. 3 (Acre-feet)	Well No. 4 (Acre-feet)	Well No. 5 (Acre-feet)	Total (Acre-feet)
1995	263	273	319	0	855
1996	283	294	344	0	921
1997	322	334	390	0	1,046
1998	321	333	389	0	1,042
1999	350	363	424	0	1,137
2000	365	379	443	0	1,187
2001	292	518	362	0	1,172
2002	437	417	501	0	1,355
2003	502	343	630	0	1,475
2004	258	255	297	557	1,367
2005	202	276	328	654	1,460
2006	312	264	419	475	1,470
2007	257	247	387	562	1,453
2008	145	269	357	644	1,414
2009	229	267	404	602	1,502
2010	94	188	355	362	1,431

For the AWS simulations, a total of 9,226 pumping well locations were included in the model domain as grid-independent analytical element wells, which are compiled as layer-specific standard flux cells during model runs. Pumping values from the final two seasonal stress periods of the base model were carried forward for the entire simulation. Although existing groundwater demands were already included in the SV Model by USGS and BC, additional pumping was added to reflect all current and committed demands, as provided by ADWR's Office of Assured and Adequate Water Supply, that were not included in the USGS and BC models. Application demands were also included that reflect planned future growth within the PDS service area and The Oaks subdivision to be served by Bella Vista Water Company. Additional information regarding the calculation and determination of demands for the AWS simulations is included in the AAWS application documentation developed by Fluid Solutions.

2.6 Recharge and Evapotranspiration

For the base simulation, the magnitude and distribution of recharge and evapotranspiration are identical to the SV Model for the majority of the model domain. However, in the vicinity of PDS Well No. 2, a zone of natural recharge was moved westward into the exposure of model layer 5, towards the mountain front, removing the localized occurrence of recharge from the exposure of model layer 4. This shift in recharge improved model calibration by allowing simulated water levels to decline and served to refine the conceptualization of the extent of mountain front recharge and location of the steep groundwater gradient simulated in the vicinity of the PDS well field.

For the AWS simulations, the magnitude and distribution of recharge and evapotranspiration for the final two seasonal stress periods of the calibrated simulations were carried forward for the full predictive time period. Additionally, 4 million gallons per day of permitted recharge by the Sierra Vista WRF, previously included in predictive simulations with the SV Model, was also included in the AWS Simulations.

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2.7 Stress Periods and Initial Conditions

For the base simulation, 45 seasonal stress periods with 10 time steps each were used to simulate the time period from 1986 to 2008, identical to the SV Model. The 100-year AWS simulation time period was split into two separate simulations due to extremely large output file sizes and extensive run time. The first AWS simulation consists of 104 seasonal stress periods with 10 time steps each, simulating the timeframe from fall 2008 to summer 2060. The second simulation consists of 100 stress periods with 10 time steps each, simulating from fall 2060 to summer 2110. Initial conditions for the first portion of the AWS run were the final, calibrated heads from the base model. Likewise, heads from the summer of 2060 (final output of the first AWS simulation) were imported into the second portion of the AWS simulation as initial conditions for both the Tribute and Non-Tribute simulations.

2.8 Calibration

The base simulation and early stress periods of the AWS simulations were calibrated by importing observed water levels at the PDS site into the target file already developed for the SV Model. The calibration process necessitated adjustment of localized hydraulic conductivity and recharge estimates near PDS Well No. 2 (Sections 2.3 and 2.6).

During calibration, residuals were calculated to assess the "fit" of the model-calculated (or simulated) heads to those actually observed. A residual is defined as the observed (or field-measured) water level minus the simulated water level at the same location. Positive residuals represent a model-calculated head value that is lower than the observed head value, and negative residuals represent a model-calculated head value that is higher than the observed value. Calibration statistics based on the residual values are used as a quantitative measure of the overall ability of the model to match observed conditions. Calibration statistics that were calculated to quantify the average model error included:

- Absolute Residual Mean (ARM), the arithmetic average of the absolute value of the residuals;
- Residual Mean (RM), the arithmetic average of the residuals; and
- Residual Standard Deviation (RSD), the standard deviation of the residuals.

When the ratio of the ARM to the range of observed head values in the system is small, discrepancies between simulated and observed values comprise only a small part of the overall model response (Anderson and Woessner, 1992). One of the goals of the quantitative calibration process was for the ratio of the ARM to the range in observed heads to be less than five percent for the full and final calibration time periods. Total interpreted head change across the SV Model domain is approximately 483 feet based on the range of observed heads over the full 22-year model simulation time period; therefore, the ARM should be less than 24 feet to meet this goal. A listing of the key regional calibration metrics for the PDS Model is presented in Table 2-3. All calibration statistics and metrics are reflective of the water level target values for the entire simulation time period of 1986 through the end of 2008. The ARM is approximately 9.5 feet, producing a ratio of ARM to observed head range of two percent, well below the calibration goal. The ratio of RSD to range in observed head values is also significantly less than 10 percent, a secondary calibration goal. Overall, the model calibration metrics are well within industry standard guidelines for successful model calibration.

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Table 2-3. Base Model Regional Calibration Statistics

	Residual Mean (RM) (feet)	Absolute Residual Mean (ARM) (feet)	Residual Standard Deviation (RSD) (feet)	Simulated Range of Head Values (Range) (feet)	RM/Range (%)	ARM/Range (%)	RSD/Range (%)
1986 to 2008	-1.09	9.56	23.47	483	0.22	2	4.9
2007 to 2008 (365 days)	-0.9	2.81	5.07	82	1	3.4	6.2

In addition to the calibration statistics for the full model domain, simulated residuals at the PDS wells were also checked for the year 2008 to verify calibration at the project (local) scale. Resulting model residuals for these wells are presented below in Table 2-4. All simulated residual values at PDS well locations are at or within 15 feet after the full calibration time period, which demonstrates an acceptable local scale calibration for the base simulation.

Resultant water levels for 2008 are shown on Figure 1. A water level comparison map (Figure 2) was also produced and evaluated. Water level data in the vicinity of PDS was gathered from January 2000 to the end of 2008. The most recent water level at each individual well was then used for contouring an observed water level map. Figure 1 shows these contours along with model-simulated water levels from the end of the base model illustrating a good agreement. Both the mountain front recharge areas with high gradients as well as the overall gradient around PDS match well.

Table 2-4. Local Scale Residuals in 2008

Well ID	Observed Water Level (feet amsl)	Simulated Water Level (feet amsl)	Residual (feet)
Well #2	4334.7	4342.113	-7
Well #3	4181.3	4185.781	-4
Well #4	4174.4	4186.766	-12
Well #5	4200	4184.994	15

amsl = above mean sea level

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3. Model Results

Detailed model simulation results are provided in digital MODFLOW and GIS formats in Appendix Z.

3.1 Water Level Altitudes

Figure 3 presents model predicted groundwater altitudes in 2110 in the vicinity of PDS from the Tribute Simulation. Groundwater elevations range from approximately 4,050 feet above mean sea level (amsl) to over 4,400 feet amsl in the vicinity of the PDS service area, with the higher water levels being associated with higher land surface elevations and mountain front recharge zones to the west. Regionally, flow generally proceeds radially from the west, south and east towards PDS Wells Nos. 3 and 5.

Figure 4 shows model predicted groundwater altitudes in 2110 for the Non-Tribute simulations. Groundwater elevations range from approximately 4,100 feet amsl to over 4,400 feet amsl in the vicinity of the PDS service area.

An extremely low water level elevation is also simulated for a well operated by the East Slope Water Company to the southeast of PDS Well No. 2 in both the Tribute and the Non-Tribute simulations. The steep cone of depression around this well was determined to be due to the low estimate of hydraulic conductivity for the aquifer zone from which it pumps and has no relationship with PDS or other neighboring pumping. The impact of this simulated steep pumping cone extends less than 3,000 feet, is not spatially extensive, and does not significantly impact future estimated water levels at PDS well locations.

3.2 Depth to Water

Figure 5 shows model simulated depths to water in 2111 in the vicinity of PDS for the Tribute simulation. Depths to water in the area around PDS generally range from 160 feet to approximately 600 feet, reaching a maximum simulated value of 613 feet near PDS Well No. 5.

Figure 6 shows model simulated depths to water in 2111 for the Non-Tribute simulation. Depths to water in the area around PDS generally range from 190 feet to approximately 550 feet, reaching a maximum simulated value of 565 feet near PDS Well No. 5. All simulated depths to water in both simulations that are influenced by pumping by PDS are well above the AWS depth to water criteria of 1,200 feet.

3.3 Drawdown

For the purposes of this study, drawdown was calculated as the difference between the model-simulated water levels in 2111 and 2008. Figure 7 shows model simulated drawdown in 2111 in the vicinity of PDS for the Tribute simulation. Drawdown in the area of PDS generally ranged from approximately 100 feet (near PDS Well No. 6) to 170 feet (near PDS Well No. 2).

Figure 8 shows model simulated drawdown in 2111 in the vicinity of PDS for the Non-Tribute simulation. Drawdown in the area of PDS generally ranged from approximately 70 feet (near PDS Well No. 6) to 150 feet (near PDS Well No. 2).

The maximum difference between drawdown in the Tribute simulation and the Non-Tribute simulation is approximately 70 feet and occurs near PDS Well No. 5.

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4. Conclusions

To assess the hydrologic impacts of future groundwater development by PDS, the Sierra Vista Model, a three-dimensional numerical groundwater flow model was used to simulate water level changes in response to the current, committed and projected groundwater demands within the groundwater basin. Estimated maximum depths to water from the predictive AWS simulations in the area of the basin under the influence of PDS pumping do not exceed 650 feet below land surface. Therefore, projected depths to water meet the requirement for AWS analyses in that they are not estimated to exceed 1,200 feet from ground surface over the next 100 years. In fact, simulated depths to water after 100 years of the full allotment of regulatory pumping barely exceed half of the regulatory criteria.

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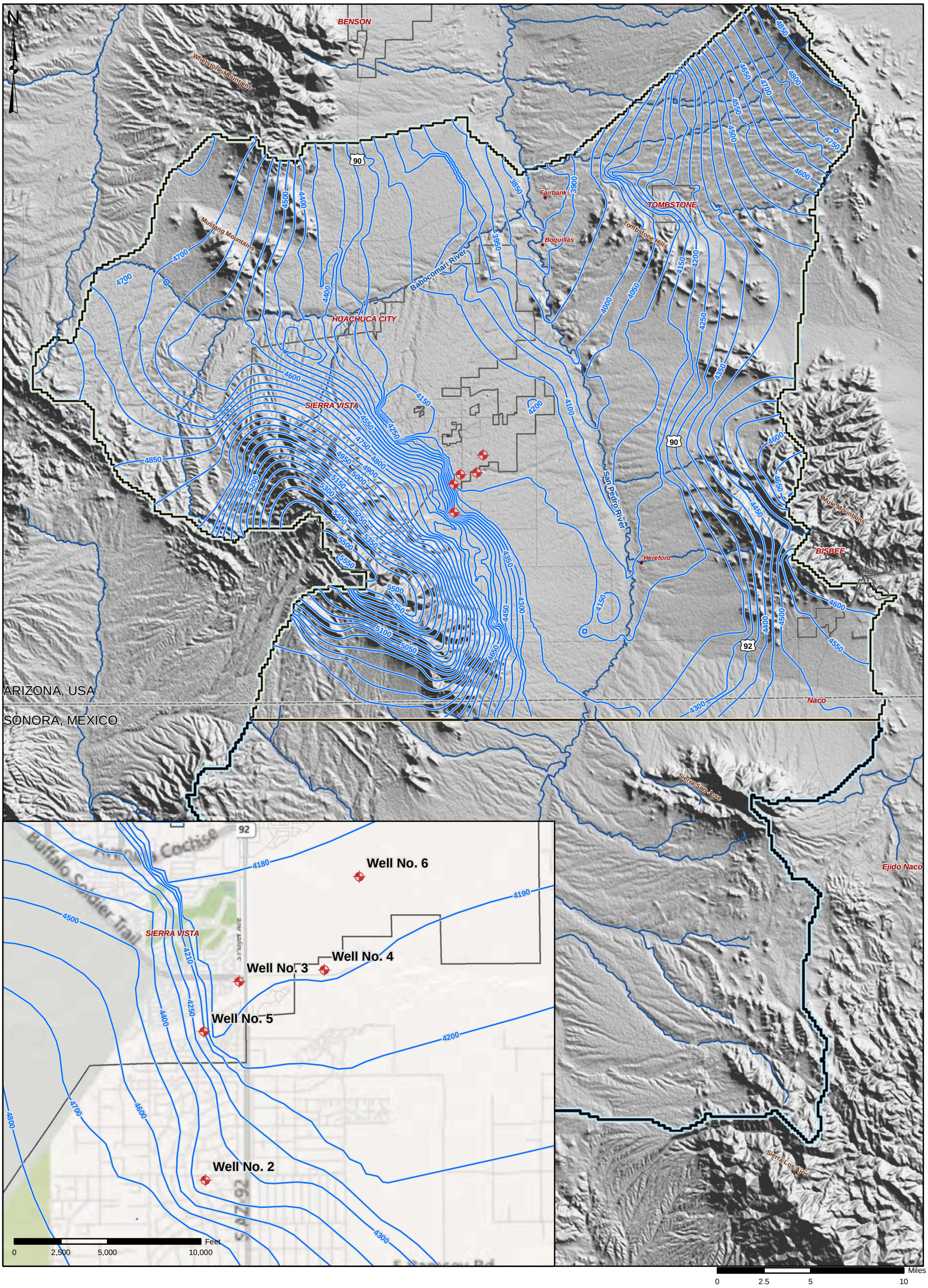

EXPLANATION

- PDS Production Wells
- 2008 Simulated Water Elevation (ft amsl)
- USGS Active Model Domain
- Sierra Vista Active Model Domain

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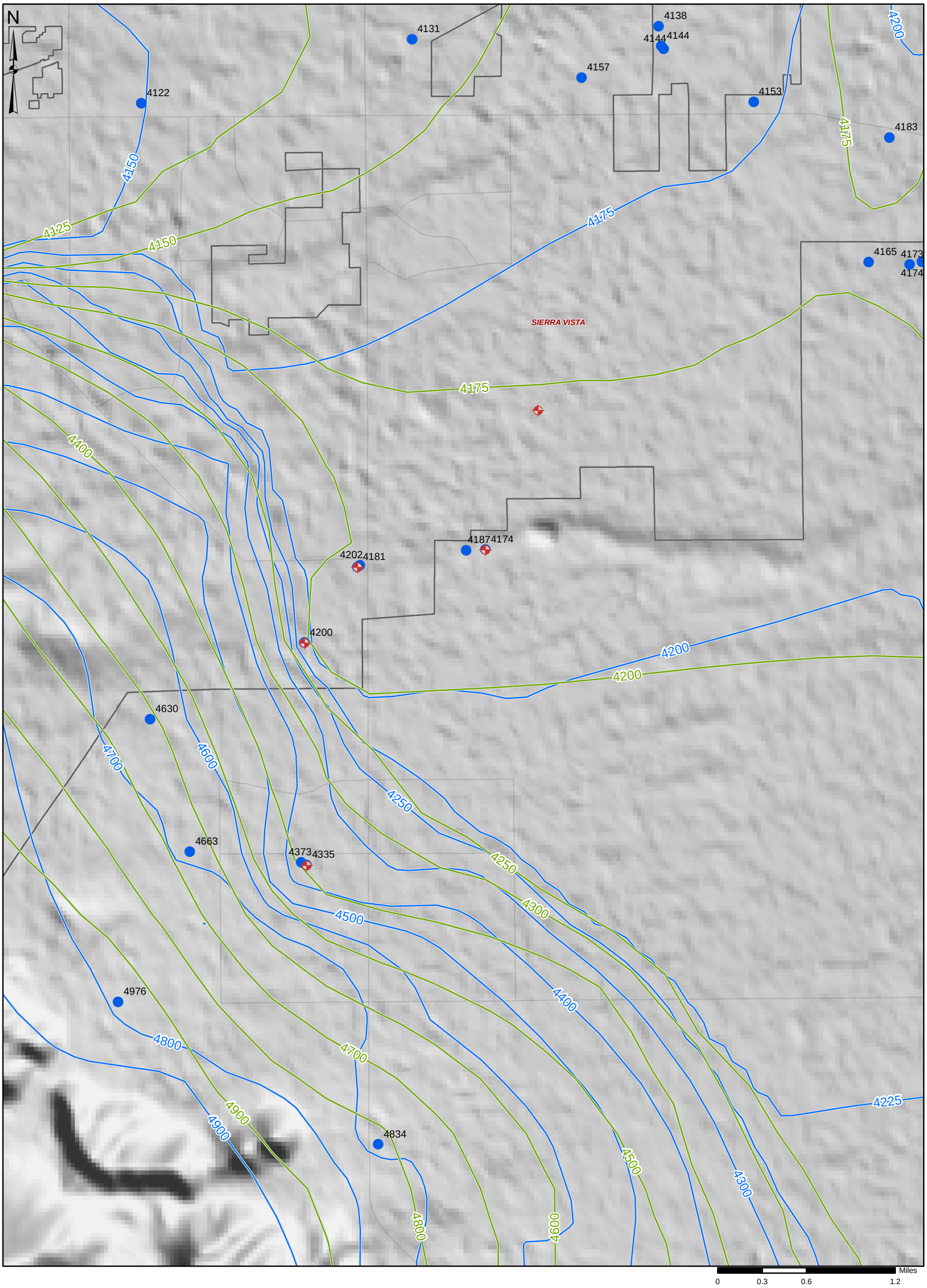
Figure 1
PDS MODEL DOMAIN AND
RESULTING 2008 SIMULATED HEADS
PUEBLO DEL SOL ADEQUATE WATER SUPPLY

[BCSAC-NAS01]: K:\BC_PHX\140007_CastleCookeAWSModeling\GIS\ArcMaps\FIGURES\ADWR Response\Fig1-2008SimWL.mxd



EXPLANATION

- Model Calibration Targets
- PDS Production Wells
- Observed Water Level Elevation (ft amsl)
- Simulated Water Level Elevation (ft amsl)

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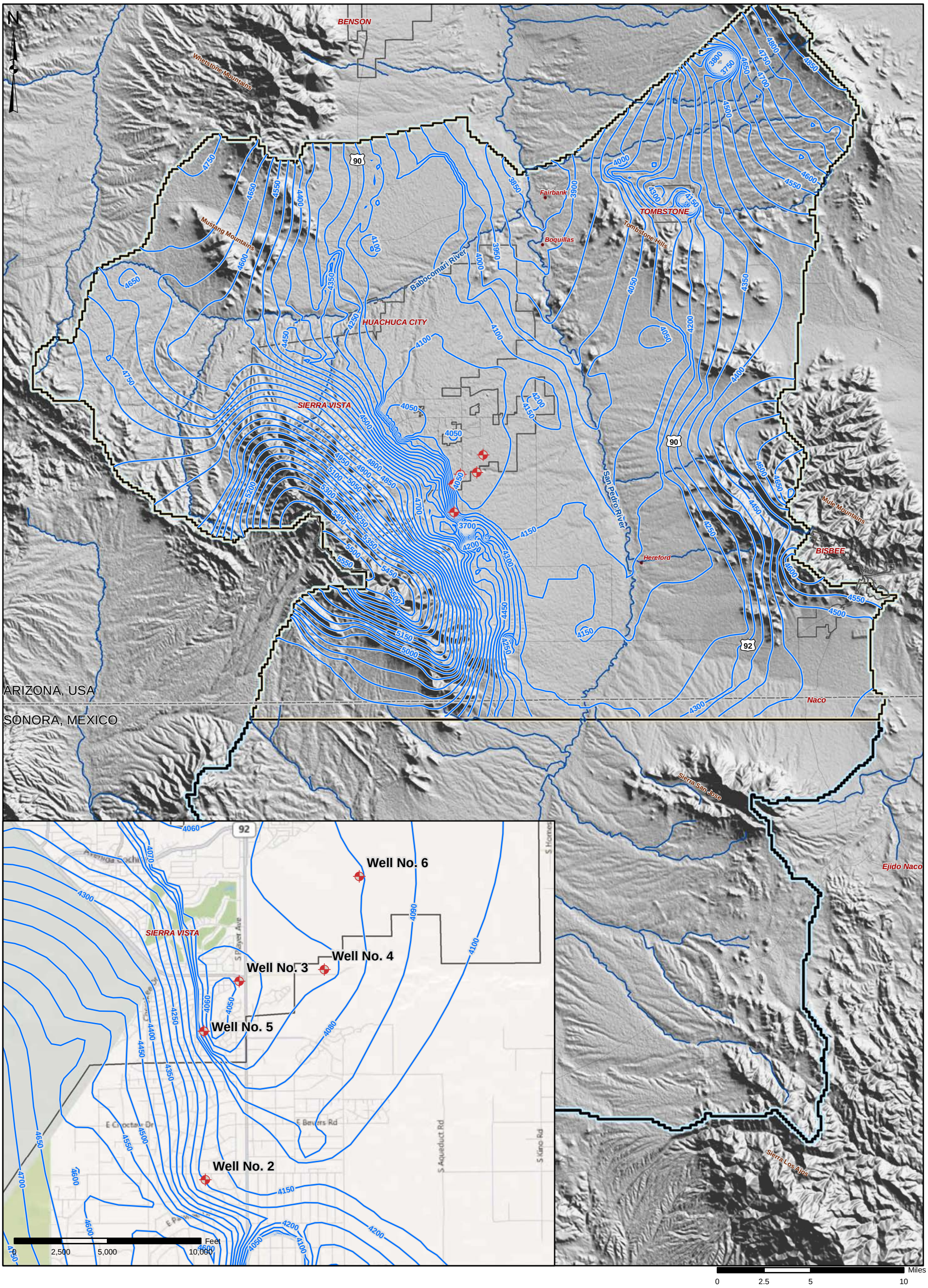
Figure 2
OBSERVED VS. MODEL-SIMULATED WATER LEVELS (2008)
PUEBLO DEL SOL ADEQUATE WATER SUPPLY

[BCSAC-NAS01]: K:\BC_PHX\140007_CastleCookeAWSModeling\GIS\ArcMaps\FIGURES\ADWR Response\Fig2-WLCompare.mxd



EXPLANATION

- PDS Production Wells
- 2111 Simulated Water Level Elevation (ft amsl)
- USGS Active Model Domain
- Sierra Vista Active Model Domain

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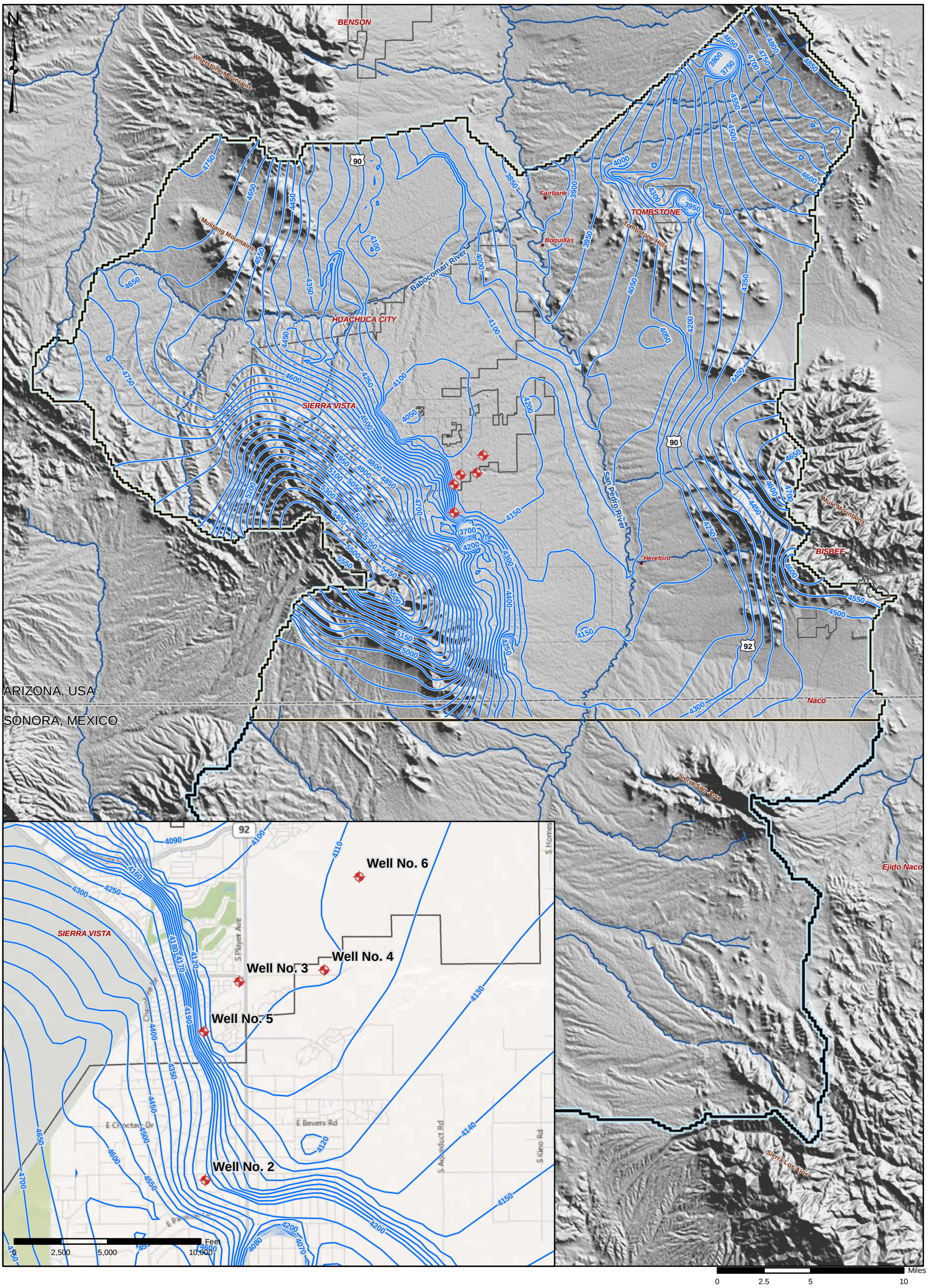
Figure 3
2111 SIMULATED HEADS - TRIBUTE SIMULATION
PUEBLO DEL SOL ADEQUATE WATER SUPPLY

[BCSAC-NAS01]: K:\BC_PHX\140007_CastleCookeAWSModeling\GIS\ArcMaps\FIGURES\ADWR Response\Fig3-2111SimWL_Tribute.mxd



EXPLANATION

- PDS Production Wells
- 2111 Simulated Water Level Elevation (ft amsl)
- USGS Active Model Domain
- Sierra Vista Active Model Domain

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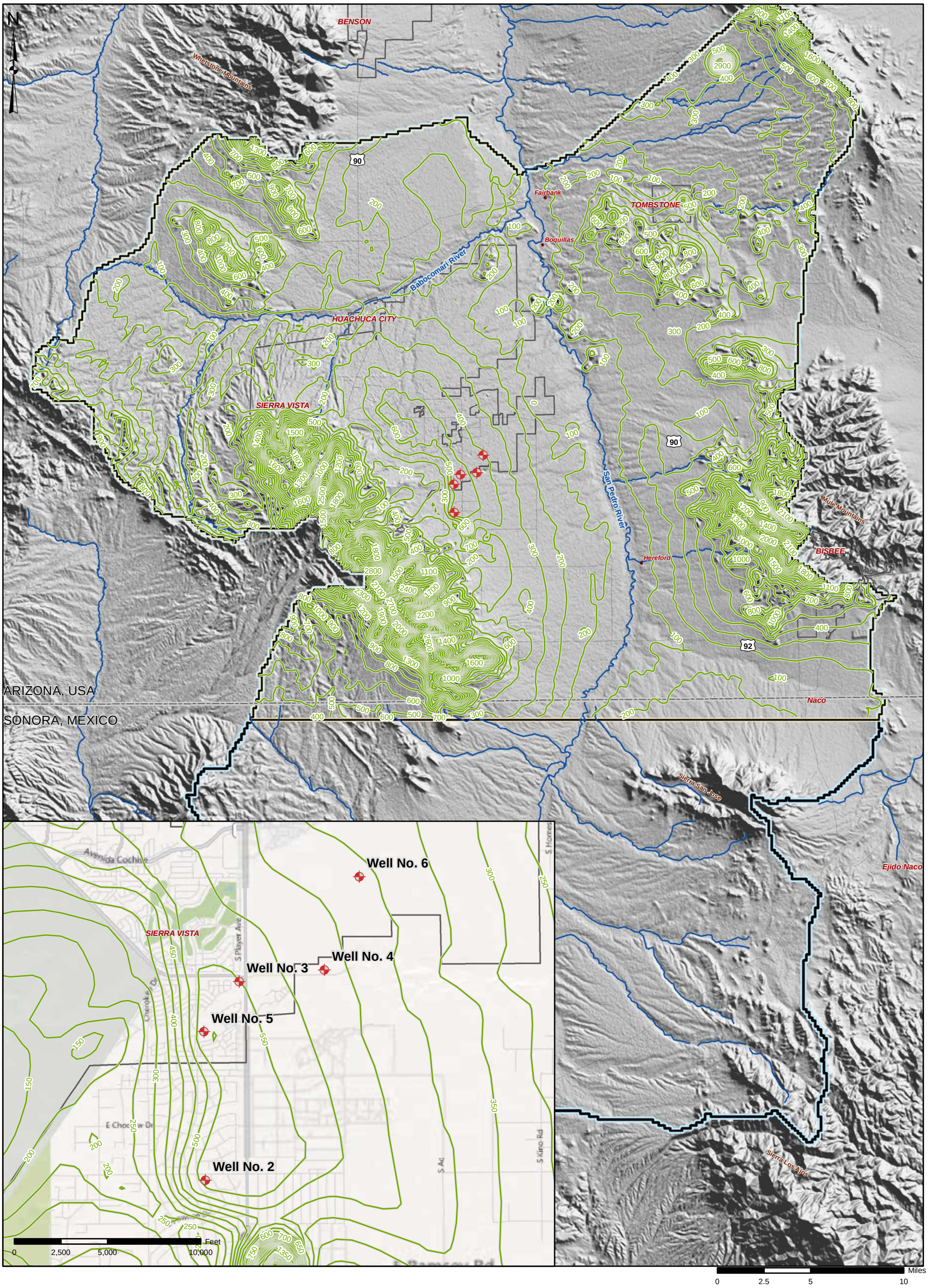
Figure 4
2111 SIMULATED HEADS - NON TRIBUTE SIMULATION
PUEBLO DEL SOL ADEQUATE WATER SUPPLY

[BCSAC-NAS01]: K:\BC_PHX\140007_CastleCookeAWSModeling\GIS\ArcMaps\FIGURES\ADWR Response\Fig4-2111SimWL_NoTribute.mxd



EXPLANATION

- PDS Production Wells
- 2111 Depth to Water (ft)
- USGS Active Model Domain
- Sierra Vista Active Model Domain

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Figure 5
2111 DEPTH TO WATER - TRIBUTE SIMULATION
PUEBLO DEL SOL ADEQUATE WATER SUPPLY

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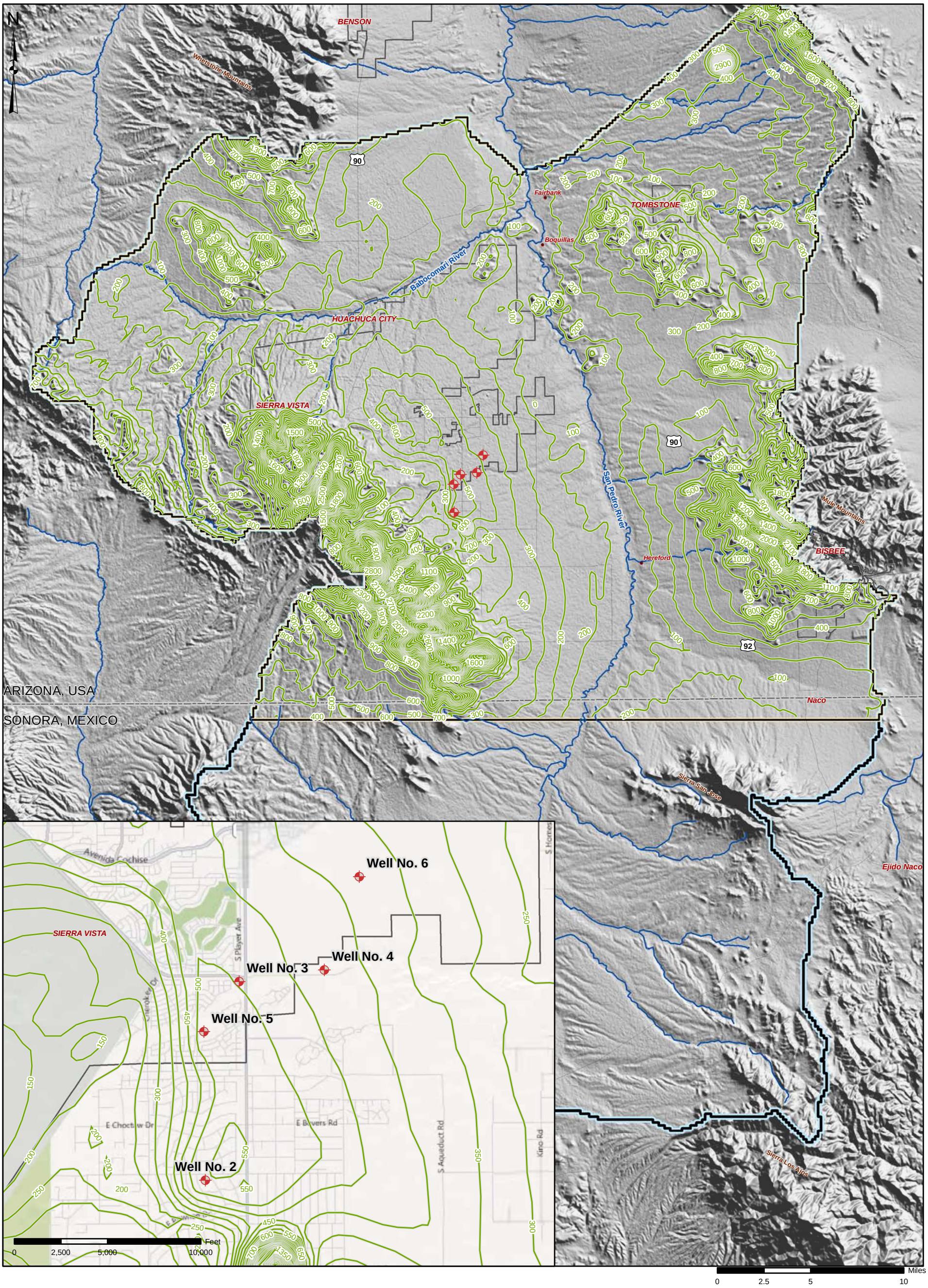

EXPLANATION

- PDS Production Wells
- 2111 Depth to Water (ft)
- USGS Active Model Domain
- Sierra Vista Active Model Domain

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Figure 6
2111 DEPTH TO WATER - NON TRIBUTE SIMULATION
PUEBLO DEL SOL ADEQUATE WATER SUPPLY

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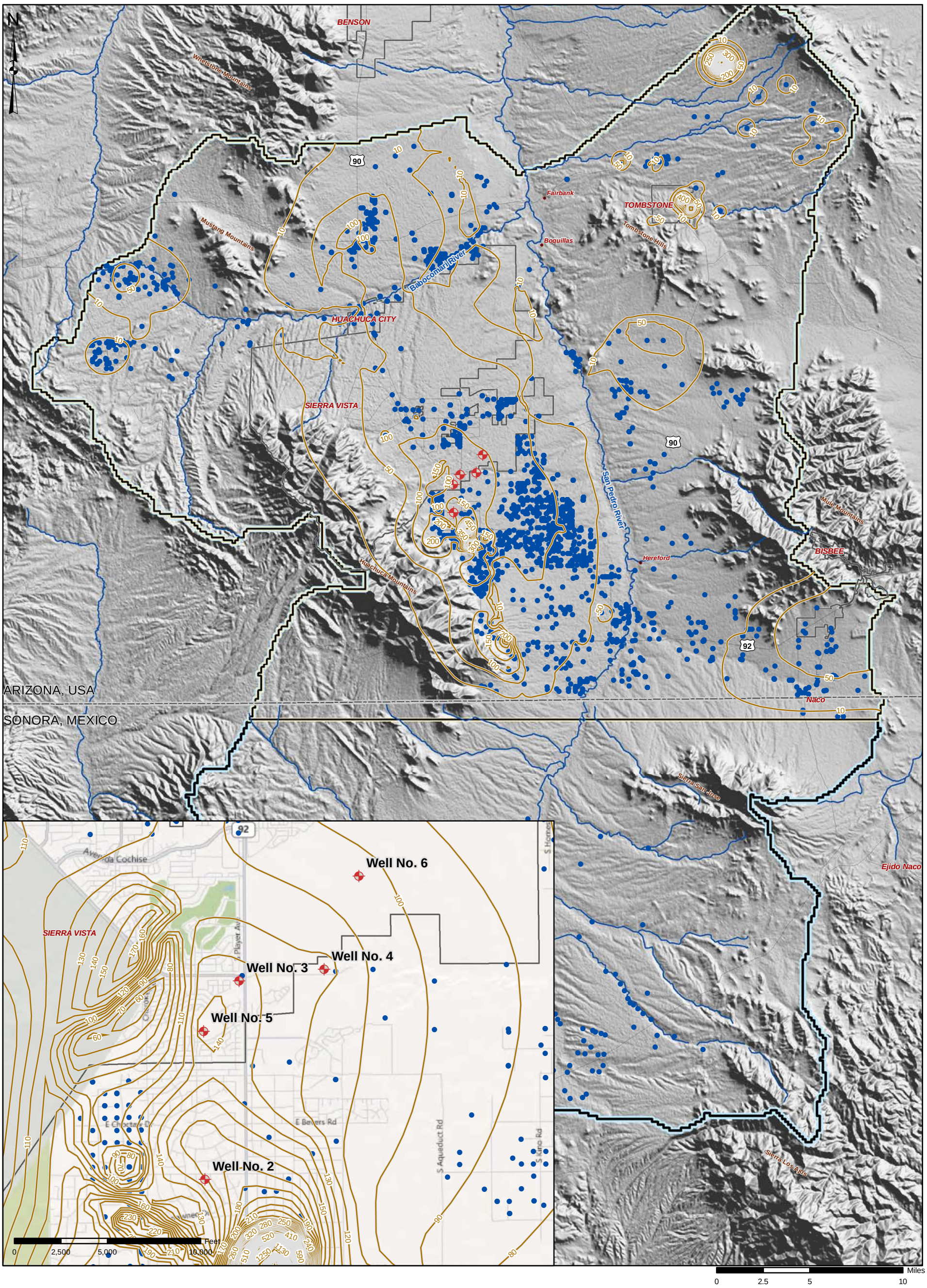

EXPLANATION

- PDS Production Wells
- Pumping Locations in 2111
- 2111 Drawdown (ft)
- USGS Active Model Domain
- Sierra Vista Active Model Domain

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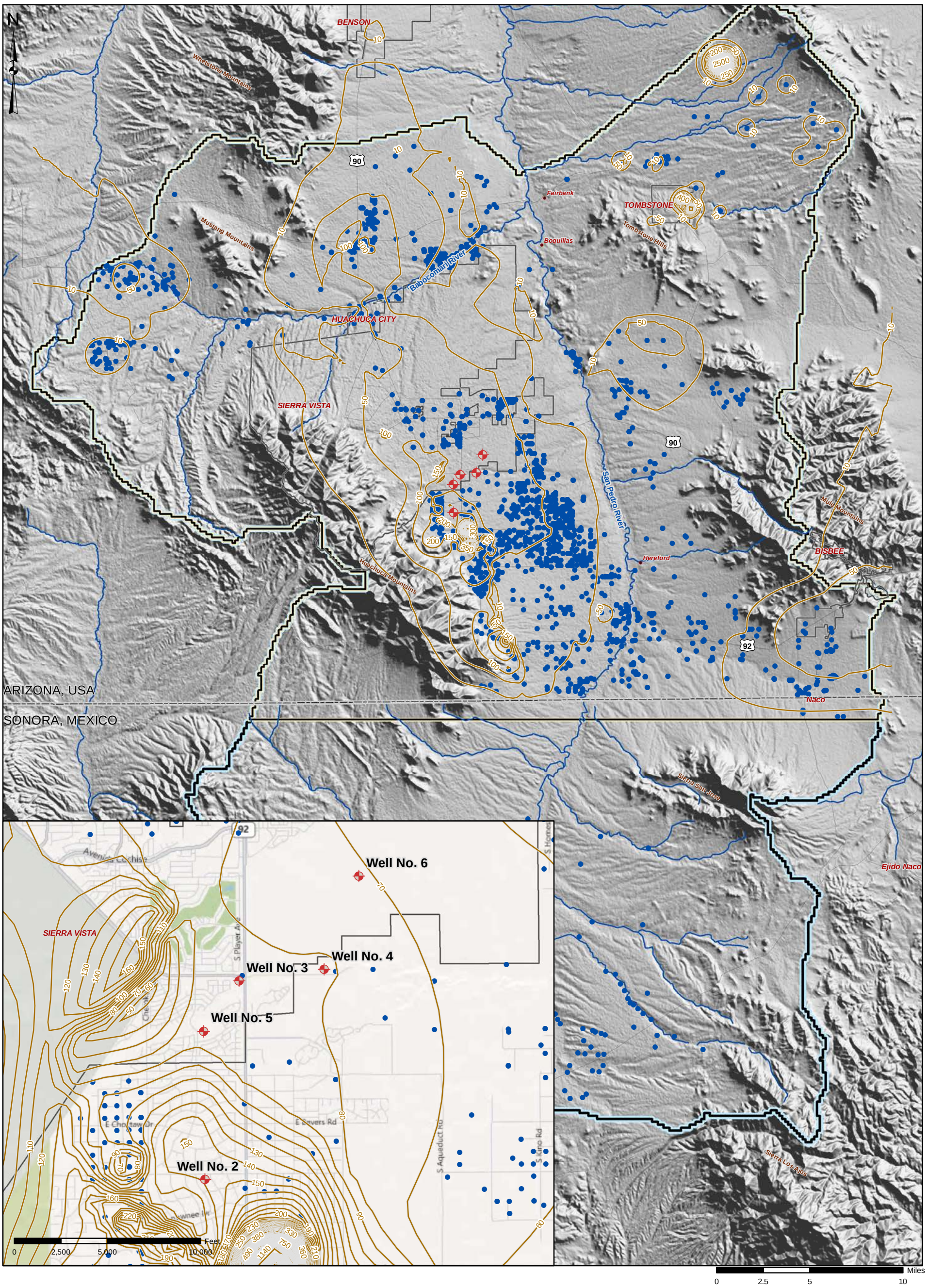
Figure 7
2111 DRAWDOWN - TRIBUTE SIMULATION
PUEBLO DEL SOL ADEQUATE WATER SUPPLY

[BCSAC-NAS01]: K:\BC_PHX\140007_CastleCookeAWSModeling\GIS\ArcMaps\FIGURES\ADWR Response\Fig7-2111DDN_Tribute.mxd



EXPLANATION

- PDS Production Wells
- Pumping Locations in 2111
- 2111 Drawdown (ft)
- USGS Active Model Domain
- Sierra Vista Active Model Domain

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Figure 8
2111 DRAWDOWN - NON-TRIBUTE SIMULATION
PUEBLO DEL SOL ADEQUATE WATER SUPPLY

[BCSAC-NAS01]: K:\BC_PHX\140007_CastleCookeAWSModeling\GIS\ArcMaps\FIGURES\ADWR Response\Fig8-2111DDN_NoTribute.mxd