CLEAR CREEK ASSOCIATES

TECHNICAL MEMORANDUM

To: Mindi Cross and David Haag, Arizona Department of Environmental Quality

From: Paul Plato, R.G. and James Norris, R.G., Clear Creek Associates

Subject: Evaluation of Sulfate Migration in Response to Proposed Installation of Replacement Wells in the Naco Highway/Purdy Lane Area
Mitigation Order on Consent Docket No. P-121-07

Date: November 22, 2011

REGISTERED GEOLOGIST CERTIFICATE NO. 30842 JAMES R. NORRIS Date Signed 11/22/11 ARIZONA U.S.A. Expires 12/31/11

REGISTERED GEOLOGIST CERTIFICATE NO. 29376 PAUL R PLATO Date Signed November 22, 2011 ARIZONA, U.S.A. Expires September 30, 2013

1 INTRODUCTION

This memorandum presents the results of numerical groundwater flow and sulfate transport modeling to evaluate the installation of deep domestic water production wells as a mitigation measure in the Naco Highway/Purdy Lane area, north of Naco, Arizona (Figure 1). The purpose of modeling was to evaluate whether wells drilled deeper into the basin fill and bedrock would be adequately isolated from shallow groundwater containing sulfate at concentrations greater than 250 milligrams per liter (mg/l). Freeport-McMoRan Corporation Copper Queen Branch has proposed, as one mitigation measure and where feasible for certain well owners, to deepen wells in the Naco Highway/Purdy Lane area into the underlying bedrock which does not contain elevated sulfate concentrations at this location. To evaluate the influence of installing deeper wells on the future distribution of sulfate in groundwater, groundwater pumping and sulfate transport in the vicinity of the proposed replacement wells were simulated for a 100-year period using several different assumptions for hydraulic conductivity and pumping rate.

2 WELLS EVALUATED

Figure 2 illustrates the wells considered for replacement in the area. These wells are currently shallow wells completed in the upper portion of the basin fill aquifer. Table 1 lists the well construction and average sulfate concentrations for wells proposed for replacement. Average sulfate concentrations range from 362 to 909 mg/l.

Table 1 – Wells Proposed for Replacement

Well Name	East	North	Cadastral	Well Depth (feet)	Casing Depth (feet)	Casing Diameter (inches)	Elevation (feet-MSL)	Depth to Top of Screen (feet)	Depth to Bottom of Screen (feet)	Average Sulfate Since 2008 (mg/l)
ANDERSON	601135	3468816	D24024018AAA	236	110	8	4580.34	100	236	511
COOPER C	601350	3468913	D24024017BBB	220	220	6	4595.06	100	220	909
FRANCO	602850	3468836	D24024016BBB	200	200	6	4636.00	180	200	635
HOWARD	601282	3468769	D24024017BBC	600	4	6	4589.70	150	300	362
MCCONNELL 265	601463	3468840	D24024017BBB	216	216	8	4600.70	174	216	716
PIONKE	600936	3468837	D24024018AAA	300	300	6	4592.13	100	300	431
WEISKOPF	601155	3468659	D24024018AAD	200	200	6	4586.89	100	200	520

Elevations are feet above mean sea level. Depths are feet below land surface.

Figure 3 illustrates geologic Cross-Section C-C' (see Figure 1 for location of cross section) from the Aquifer Characterization Report (ACR) (Clear Creek Associates, 2010) overlain by a groundwater model cross-section showing the layers of the original numerical model. Layer 1 represents basin fill, Layers 2 and 3 are undifferentiated Bisbee Group bedrock, and Layer 4 is Glance Conglomerate bedrock. This section also shows wells in the Purdy Lane area. The domestic water supply wells are generally completed in the shallow portion of the basin fill aquifer (Layer 1).

Based on sampling data collected in 2001 and 2008, sulfate concentrations greater than 250 mg/l are limited to the upper portion of the basin fill aquifer. During 2001, a well at the Garner property was replaced with a deeper well (GARNER 635) drilled to bedrock. Samples collected from temporary wells during drilling of the GARNER 635 (GW-47 samples on Table 2) indicated that sulfate in excess of 250 mg/l did not extend below a depth of 350 feet below land surface, and that the lower basin fill and underlying bedrock contained sulfate concentrations in the range of 25 to 50 mg/l. GARNER 635 was constructed with approximately 100 feet of screen in the upper portion of the bedrock. After 10 years of continuous operation, the sulfate concentration at GARNER 635 remains in the 30 to 40 mg/l range (Clear Creek Associates, 2011); demonstrating that in the Naco Highway/Purdy Lane area well replacement in the bedrock aquifer is an effective mitigation option for obtaining drinking water with sulfate concentrations below 250 mg/l. In 2008, the installation of monitor well BMO-2008-4B provided depth specific sampling results indicating that the lower portion of the basin fill deeper than 450 feet below land surface had sulfate concentrations in the 10 to 20 mg/l range (Clear Creek Associates, 2010). Figure 4 is an east-west cross section along Purdy Lane illustrating the sulfate results for samples collected during drilling of the GARNER 635 and BMO-2008-4B wells and groundwater sampling at private wells.

Table 2 – Depth-Specific Sample Results from GARNER 635

Site ID	Depth Interval	Sample No.	Concentration (mg/l)	Type of Aquifer Material
GW-47	250-280	5	632	QTbf
GW-47	345-375	4	25.8	QTbf
GW-47	455-485	3	16.7	QTbf
GW-47	545-575	2	39.8	Km
GW-47	630-670	1	54.2	Km

These sampling results indicate that the lower portion of the basin fill (designated as QTbf on Figures 3 and 4) and the underlying bedrock (Km, Kml, Kmu, and Kc on Figures 3 and 4) in the Naco Highway/Purdy Lane area do not contain sulfate concentrations exceeding 250 mg/l. Concentrations are slightly higher in samples from the bedrock than in the deeper basin fill, but this is likely due to groundwater age and natural geochemical conditions, rather than transport from the shallow sulfate plume.

3 MODEL SIMULATION APPROACH

One consideration regarding the installation of deep wells beneath the sulfate plume is that the low hydraulic conductivity of the bedrock could result in significant well drawdowns during pumping, which may cause vertically downward hydraulic gradients and deeper migration of the shallow sulfate. To evaluate the potential to draw groundwater with elevated sulfate concentrations to the deepened wells, model simulations were executed using the groundwater flow and sulfate transport model developed to simulate the sulfate plume for the ACR (Clear Creek Associates, 2010). Using the Groundwater Vistas™ telescopic mesh refinement (TMR) feature, a sub-model focused on the area around the Naco Highway/Purdy Lane wells was constructed from the larger original calibrated model (Figure 5). The TMR utility uses the original model to setup a sub-model domain, setting boundary conditions based upon the original model. The TMR model boundaries were designated as constant heads, and were set to the values from the end of the model calibration (end of 2008) as calculated in the model simulation. The resulting model used uniform model cells approximately 141 feet by 157.5 feet in size[1]. Other stresses, such as recharge, are assigned to the TMR model based on specifications in the original model.

In addition to the horizontal refinement of the model domain using TMR, the model was divided into additional layers to allow for better definition of the groundwater zone containing sulfate in excess of 250 mg/l. The basin fill aquifer layer (original model layer 1) was divided into 5 TMR model layers, each approximately 98 feet thick with the exception of the uppermost TMR layer which was partially saturated and varied in thickness. Original model Layer 2 (bedrock) was also split into 2 layers, such that the undifferentiated Bisbee Group is represented by 3 TMR model layers (2 new layers, plus former Layer 3). Figure 6 displays a cross-section along model row 28 of the TMR model, illustrating several potential replacement wells extending into the uppermost bedrock.

Using the information from depth specific sampling, high sulfate concentrations were generally restricted to TMR model Layers 1 through 4, which were set to an initial concentration of 800 mg/l (Figure 6). Each constant head boundary cell for TMR Layers 3 and 4 was also set to a constant concentration of 800 mg/l (TMR Layers 1 and 2 are unsaturated at the boundaries). TMR Layer 5 representing the low-sulfate zone in the basin fill was set to 20 mg/l. Constant head cells for TMR Layers 6, 7, 8, and 9 representing bedrock were set to 40, 45, 30, and 20 mg/l, respectively.

It should be noted that the simulation of an initial constant sulfate concentration of 800 mg/l in the shallow basin fill layers (TMR Layers 1 through 4) is a simplification of the system assumed to conveniently simulate the vertical extent of the sulfate plume. This assumption of a uniform, high sulfate concentration in the basin fill does not simulate the observed extent and concentration of the sulfate plume, which is less laterally extensive and has lower concentrations at the plume margin than was assumed for the TMR model (i.e., the TMR model does not represent the leading edge of the plume but, instead, assumes the plume is laterally continuous across the entire TMR model domain). Simulation of a more laterally continuous plume than the actual plume is conservative in that it overestimates the extent and, in places, the concentration of the plume; which allowed the simulations to focus on determining whether sulfate concentrations would spread vertically in response to pumping.

Each of the proposed replacement wells was initially simulated assuming continuous pumping at a rate of 0.35 gallons per minute (gpm) per well or 518 gallons per day (gpd). The replacement wells were simulated as being screened in TMR Layer 7 at the top of the bedrock. The initial simulation used the

[1] The TMR procedure allows interactive on-screen selection of a sub-model domain, which led to uniform model cells with odd dimensions.

same horizontal to vertical hydraulic conductivity ratios used in the calibrated model (approximately 8:1 in basin fill and 20:1 in bedrock). The horizontal to vertical hydraulic conductivity ratio was also tested in a simulation at 1:1 which allows the maximum opportunity for the vertical transport of sulfate.

3.1 Initial Model Simulation Results

Figure 7 displays the simulated sulfate concentrations in TMR model Layer 5, the lowermost basin fill layer, after 100 years (2109) of pumping from the proposed replacement well. The simulation results illustrate that sulfate concentrations are predicted to rise from the initial (2009) Layer 5 concentration of 20 mg/l to as much as 30 mg/l on the west side of the model domain in 2109. This indicates that vertical transport of sulfate is minimal over the 100 year period simulated and that bedrock would be unaffected by sulfate because concentrations in the overlying basin fill do not rise significantly.

Figure 8 shows the predicted concentrations in basin fill Layer 5 and bedrock Layers 6 and 7 (the proposed completion depth of replacement wells) at Observation Point 1 over the simulation. The proposed wells are simulated as pumping from Layer 7 (bedrock aquifer) at a rate of 0.36 gpm (518 gpd). The results indicate little change in the predicted sulfate concentrations in Layers 5, 6, and 7 over 100 years. The simulation results predict that pumping from the proposed bedrock replacement wells does not cause sulfate to migrate downward from the sulfate plume to the deeper basin fill or bedrock.

3.2 Vertical Hydraulic Conductivity

The initial simulation was run using the model horizontal to vertical hydraulic conductivity ratios from the calibrated model (approximately 8:1 in basin fill and 20:1 in bedrock). The ratio of horizontal to vertical hydraulic conductivity in the basin fill varies from approximately 9:1 to 7:1 in the model area. This ratio naturally limits the ability of contamination to migrate vertically in the basin fill to a deepened well because flow occurs more easily in the horizontal direction than the vertical direction. To test the sensitivity of the initial simulation to the assumed hydraulic conductivity ratios, the groundwater model was run with the hypothetical condition that the horizontal to vertical hydraulic conductivity are the same value, for both the bedrock and basin fill layers. A simulation of the horizontal to vertical hydraulic conductivity ratio set to 1:1 would tend to overestimate the vertical migration of sulfate compared to the initial simulation because it removes the naturally occurring resistance to vertical flow imparted by the lower vertical hydraulic conductivity. Figure 9 shows the results of the simulation with a 1:1 hydraulic conductivity ratio, which were nearly identical to the first simulation using the original ratios. Figure 10 shows that concentrations at Observation Point 2 in TMR model Layer 5 representing the lower basin fill are predicted to rise from the initial (2009) concentration of 20 mg/l to about 30 mg/l over the 100 year period. As in the initial simulation, the wells are pumping from TMR model Layer 7 at a rate of 0.36 gpm (518 gallons per day). Concentrations in TMR model Layer 7 are nearly constant over the course of the 100 year simulation.

3.3 Wells in Lower Basin Fill

As an additional test, a groundwater simulation was completed with the replacement wells moved to TMR model Layer 5, which is the layer of basin fill immediately below the zone of elevated sulfate in the shallow aquifer. This simulation used the same pumping rates as the previous two simulations and a 1:1 ratio of horizontal to vertical hydraulic conductivity. Figure 11 illustrates these results, with sulfate concentrations rising from 20 to 28 mg/l over the 100-year period in TMR model Layer 5 at Observation Point 2. Based on these results, sulfate is not predicted to migrate vertically downward to the lower basin fill in response to pumping 518 gallons per day (0.36 gpm) from each of the proposed replacement wells if they were located in the lower basin fill. The conclusion is that the hydraulic stresses from the proposed domestic wells are not adequate to cause significant changes in the existing groundwater flow and transport conditions.

3.4 Pumping Rates Raised to 10 GPM

To evaluate the possibility for sulfate migration under a scenario of relatively high pumping, a simulation was conducted in which each of the proposed replacement wells was pumped from TMR model Layer 7 (bedrock) steadily at 10 gpm (14,400 gpd) for the entire 100 year projection period. These results are nearly identical to those in the previous simulation (see Figure 11). Concentrations in TMR model Layer 5 are predicted rise from the initial (2009) concentration of 20 mg/l to 28 mg/l over the 100-year period.

4 CONCLUSION

The groundwater model reported here simulates flow and transport using porous media assumptions. These standard modeling assumptions should accurately simulate flow through an aquifer not dominated by preferential flow paths, such as conductive fractures or layers more discrete than the scale of the layers or model cells. The conclusion of these simulations is that pumping from the replacement wells proposed for construction in the bedrock is not predicted to result in sufficient drawdown to cause the plume to move downward into the bedrock under the simulation assumptions used. The lack of significant vertical migration of sulfate predicted for continuous groundwater pumping at 10 gpm at the seven proposed replacement wells indicates that no impact would be predicted for the installation of several additional replacement wells pumping at rates expected for domestic supply wells (i.e., approximately 0.36 gpm).

The proper placement of annular seals in the proposed wells will be a significant factor in preventing sulfate migration down the borehole. Figure 12 is a proposed conceptual design for the replacement wells. The depth of bedrock in the vicinity of Purdy Lane ranges from 535 feet at TM-19A to 636 feet at BMO-2008-4B. The conceptual design includes drilling 150 feet into the bedrock and installation of 100 feet of screen from the bottom of the borehole to approximately 50 feet below the basin fill. Filter pack would be placed in the well annulus from the bottom of the borehole to 10 feet over the top of the screen. A bentonite seal would be placed above the filter pack to approximately 20 feet below land surface, with the remainder of the annulus consisting of a cement surface seal. The well screen and casing would be 5-inch (nominal) Schedule 80 polyvinylchloride.

References

Clear Creek Associates, 2010. *Revision 1 Aquifer Characterization Report – Task 4 of the Aquifer Characterization Workplan – Mitigation Order on Consent Docket No. P-121-07, Cochise County, Arizona.* December 15, 2011.

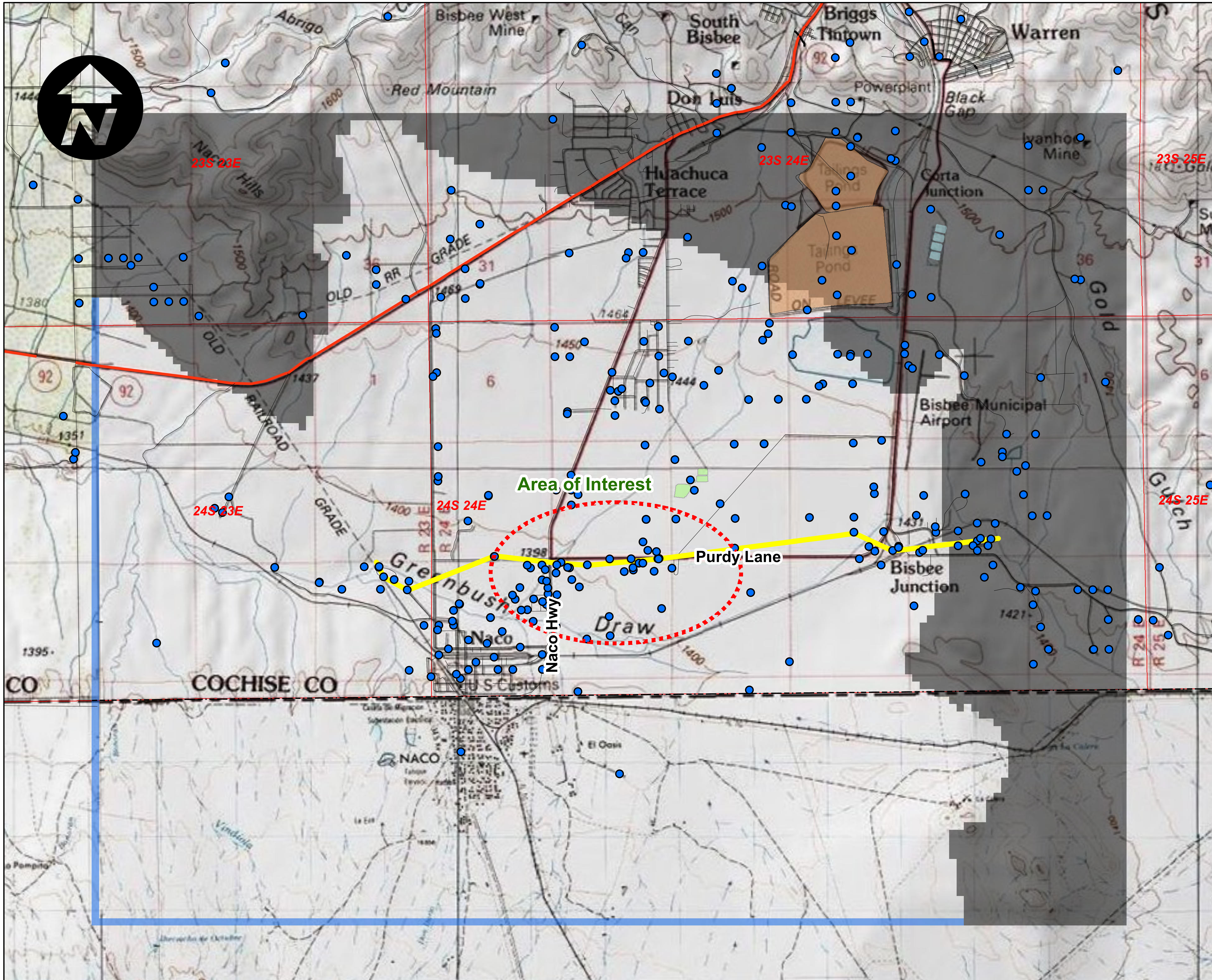
Clear Creek Associates, 2011. *Third Quarter 2011 Groundwater Monitoring Report.* October 7, 2011.

Environmental Simulations, Inc., 2010. Groundwater Vistas™ software, version 5.

Attachments

- Figure 1 – Mitigation Order Model Area
- Figure 2 – Wells Considered for Replacement
- Figure 3 – Model Cross Section in Purdy Lane Area
- Figure 4 – Depth Specific Sampling for Sulfate, Garner 635 and BMO-2008-4 Wells
- Figure 5 – TMR Model Domain
- Figure 6 - TMR Model Cross-Section Along Row 28
- Figure 7 – TMR Model Layer 5 Sulfate Concentrations in 2109 (Kv:Kh ratio from original model)
- Figure 8 – Projected Sulfate Concentration by TMR Model Layer, Observation Point 1 - 2009 to 2109
- Figure 9 – TMR Model Layer 5 Sulfate Concentrations in 2109 (Kv:Kh ratio 1:1)
- Figure 10 – Projected Sulfate Concentration by TMR Model Layer, Observation Point 2 - 2009 to 2109
- Figure 11 – Projected Sulfate Concentration by TMR Model Layer, Observation Point 2 - 2009 to 2109
- Figure 12 – Conceptual Design for Replacement Wells

- Table 1 – Wells to be Deepened (**in text**)
- Table 2 – Depth-Specific Sample Results from GARNER 635 (**in text**)



Legend

- Wells in Database
- Figure 3 Cross Section Location
- US/Mexico Border
- San Jose WWTP
- Warren WWTP
- Tailings

Boundary Conditions

Layer 1

- Constant Heads
- No Flow

0 0.25 0.5 1 1.5 Miles

Figure 1

Mitigation Order Model Area

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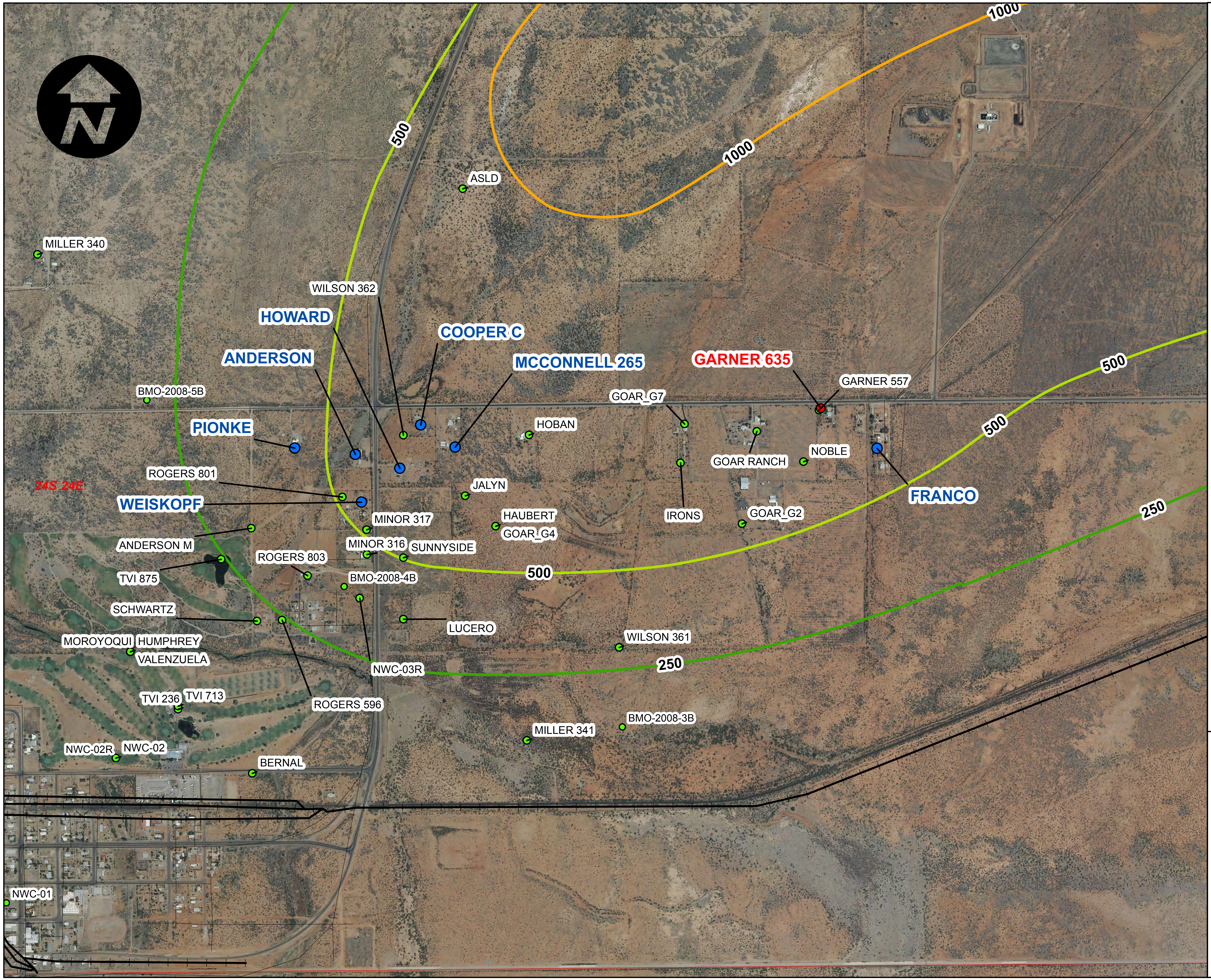

Legend

Wells Along Purdy Lane

Well Type

- Potential Well to be Replaced
- Garner Well (previously replaced)
- Other Wells

3rd Quarter 2011 SO4 Contours

Sulfate Concentration Contour (mg/l)

- 250
- 500
- 1000
- 1500

Railroads

- Railroad

0 250 500 1,000 1,500 2,000
Feet

Figure 2

Wells Considered for Replacement

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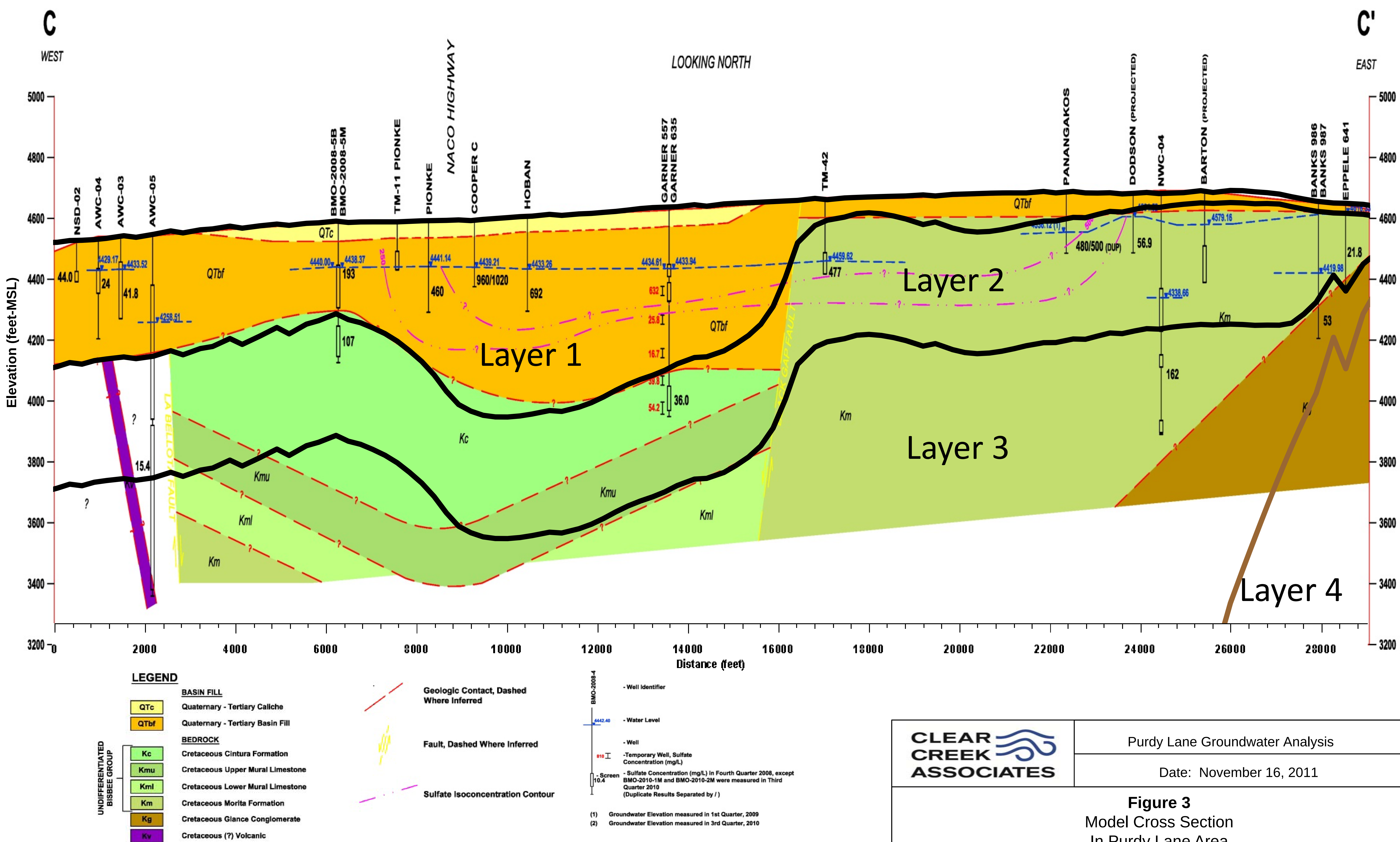

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Purdy Lane Groundwater Analysis

Date: November 16, 2011

Figure 3
Model Cross Section
In Purdy Lane Area

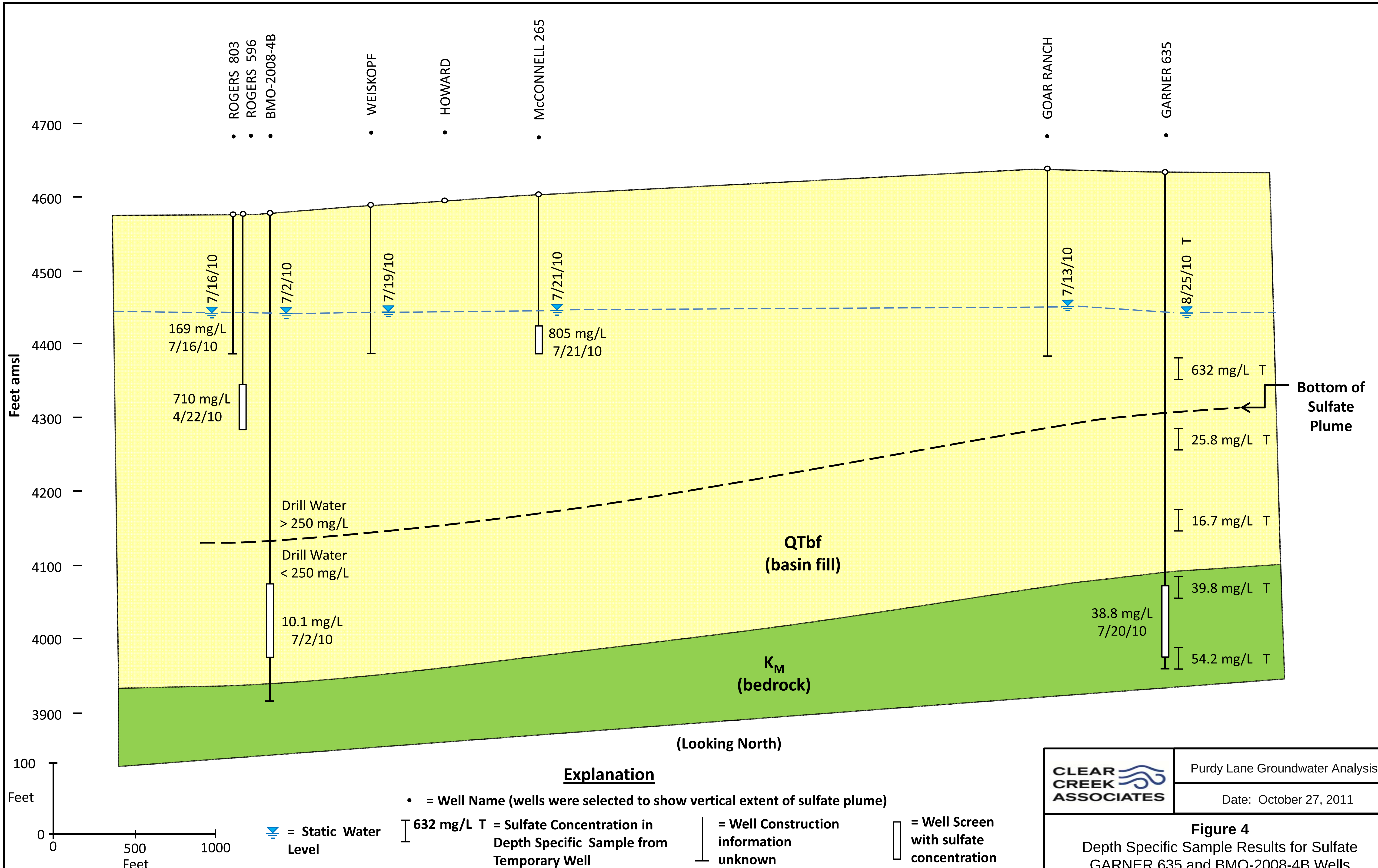
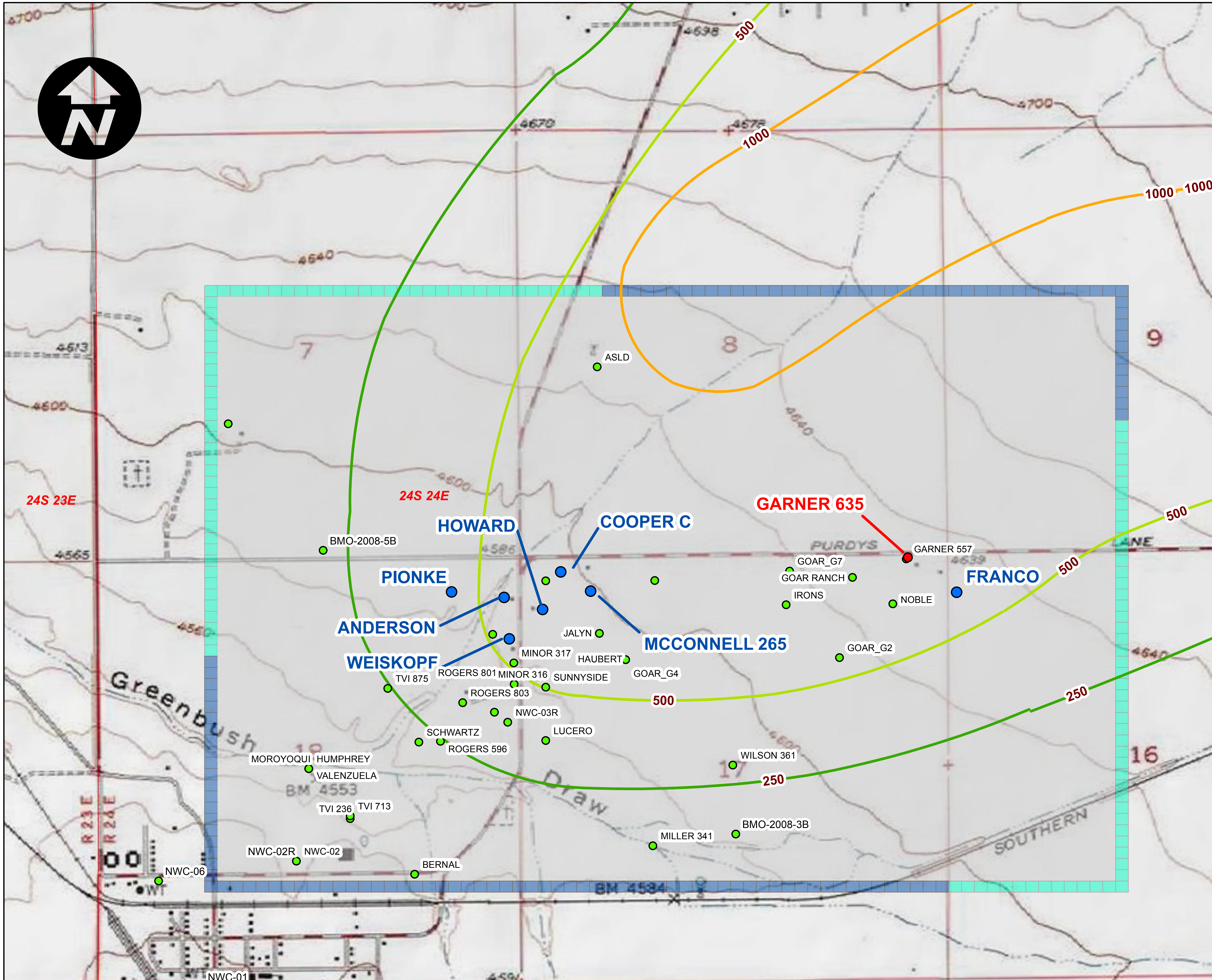


Figure 4
Depth Specific Sample Results for Sulfate
GARNER 635 and BMO-2008-4B Wells



Legend

Domestic Wells Along Purdy Lane

Well Type

- Potential Domestic Well to be Deepened
- Garner Well (previously deepened)
- Other Wells

3rd Quarter 2011 SO4 Contours for Basin Fill Aquifer

Contour (mg/l)

- 250
- 500
- 1000
- 1500

TMR Model Domain

Layers and Cells

- Active Model Cell: All Layers
- Constant Head: Layers 3-9
- Constant Head: Layers 4-9

NOTES:
Layers 1 and 2 are not saturated at the boundaries, so constant heads were not assigned.

0 250 500 1,000 1,500 2,000 2,500 3,000 Feet

Figure 5

TMR Model Domain

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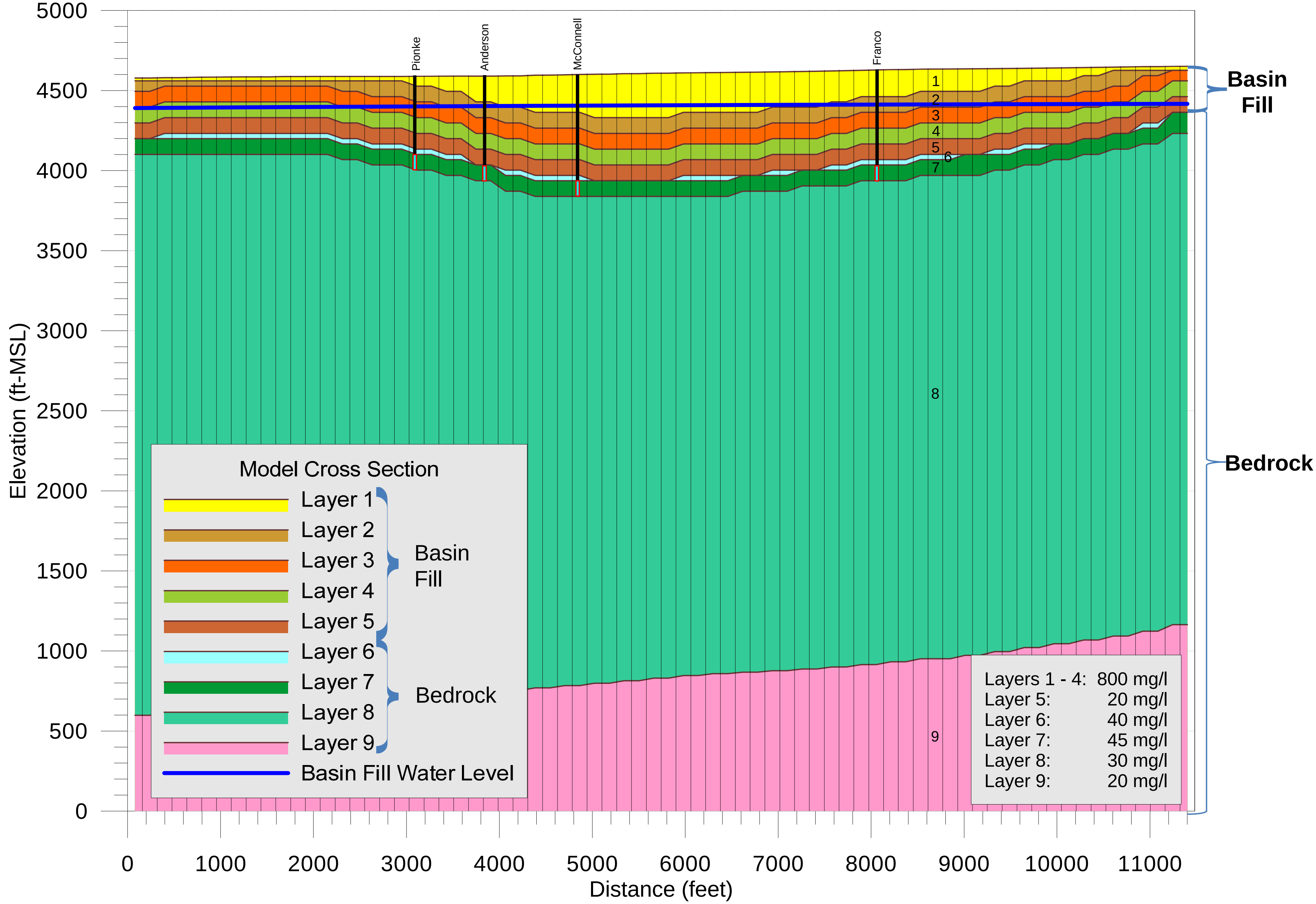

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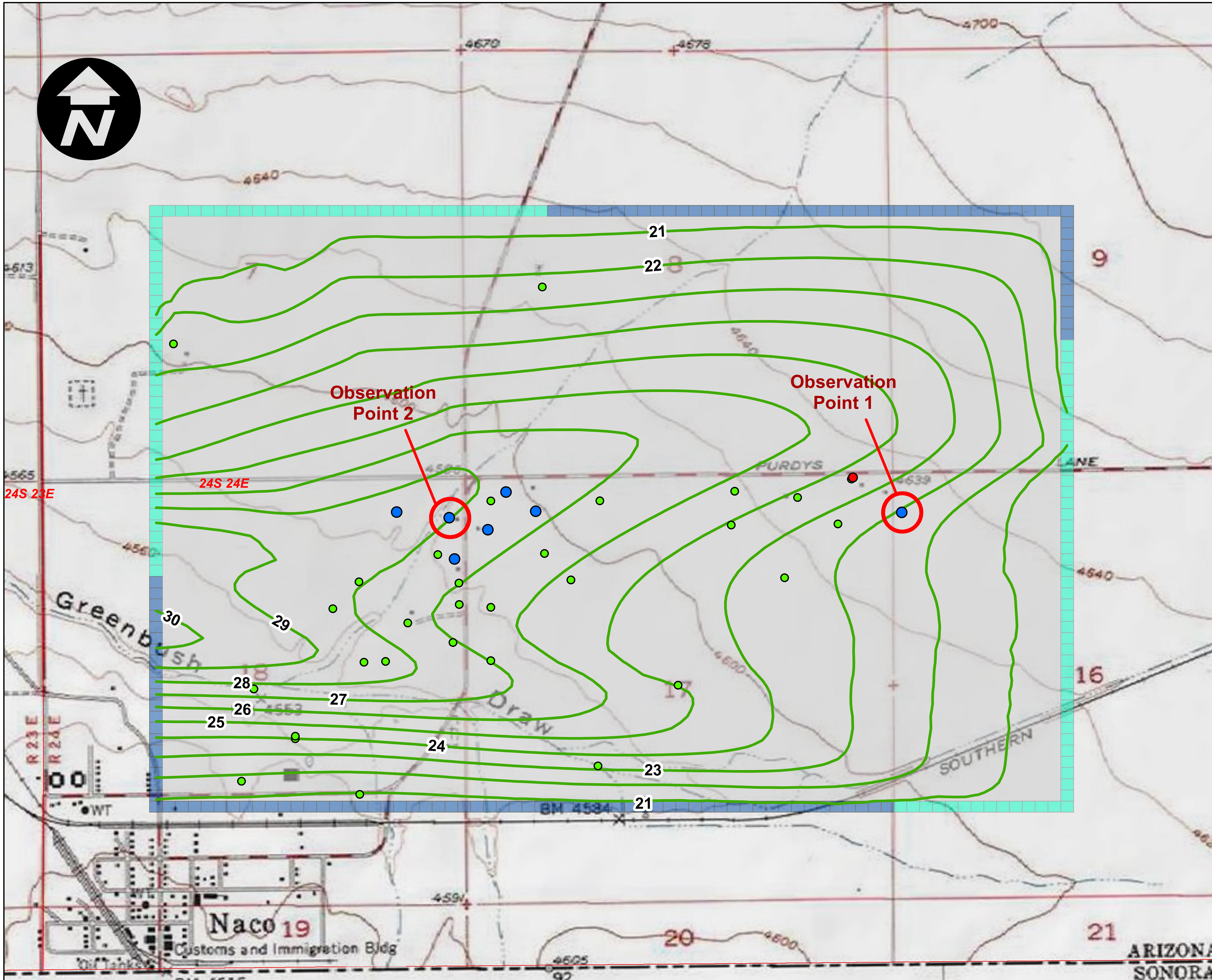
October 20, 2011

Model Cross-Section along Row 28
TMR Model

Figure 6



Legend

Wells Along Purdy Lane

Well Type

- PotentialWell to be Replaced
- Garner Well (previously deepened)
- Other Wells
- 2109 Sulfate Concentraions in Layer 5

TMR Model Domain

Layers and Cells

- Active Model Cell: All Layers
- Constant Head: Layers 3-9
- Constant Head: Layers 4-9

0 250 500 1,000 1,500 2,000 2,500 Feet

Figure 7

TMR Model Layer 5
2109 Sulfate Concentrations

(Kv:Kh Ratio from Original Model)

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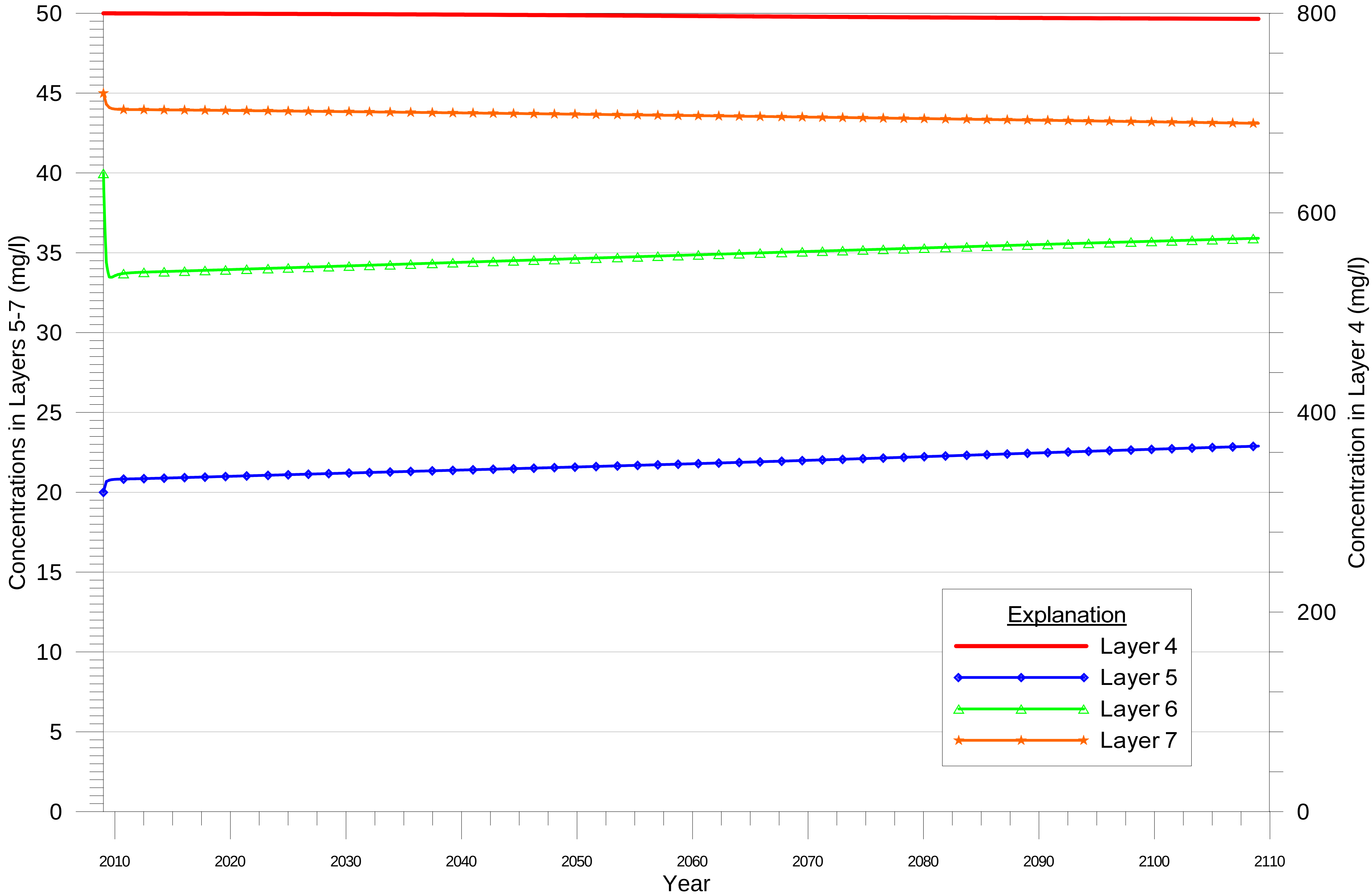

Note: Pumping Rate at each well = 0.36 gpm or 518 gpd; K_V/K_H = Same as Original Model

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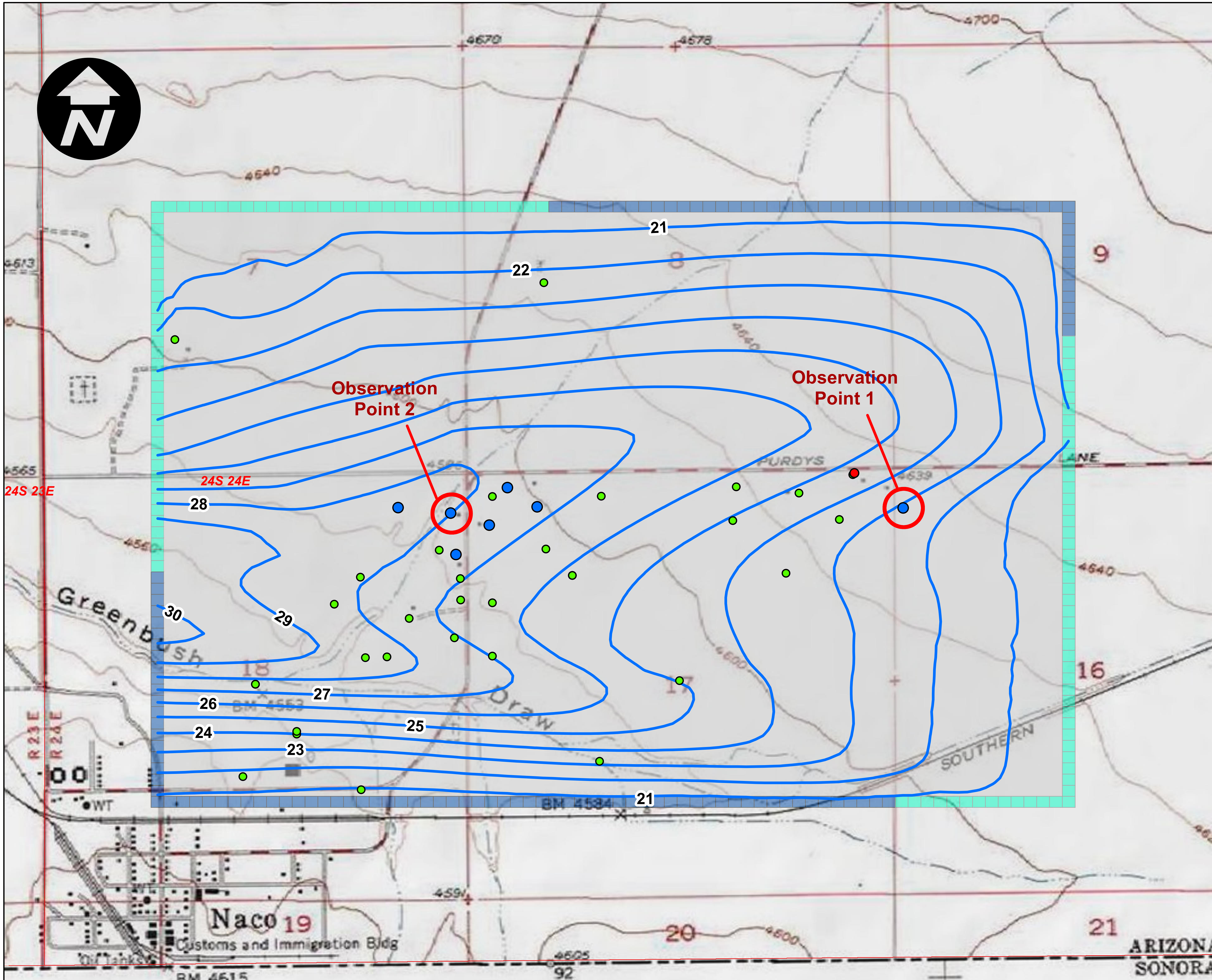
Projected Sulfate Concentration
TMR Model Layers
Observation Point 1 - 2009 to 2109

Figure 8



Legend

Wells Along Purdy Lane

Well Type

- Potential Well to be Replaced
- Garner Well (previously deepened)
- Other Wells
- 2109 Sulfate Concentraions in Layer 5

TMR Model Domain

Layers and Cells

- Active Model Cell: All Layers
- Constant Head: Layers 3-9
- Constant Head: Layers 4-9

0 250 500 1,000 1,500 2,000 2,500 Feet

Figure 9

TMR Model Layer 5
2109 Sulfate Concentrations

(Kv:Kh Ratio set to 1:1)

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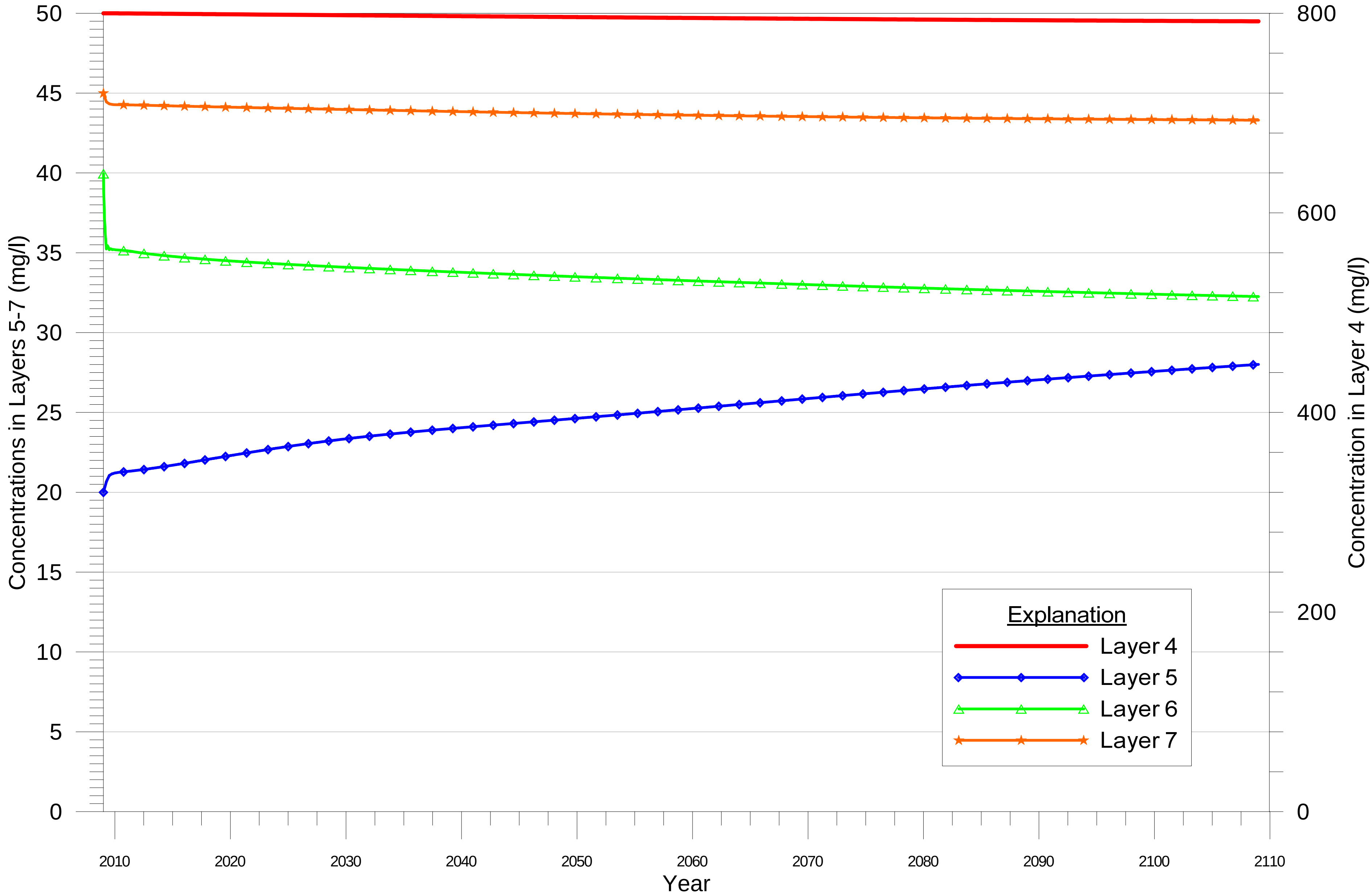
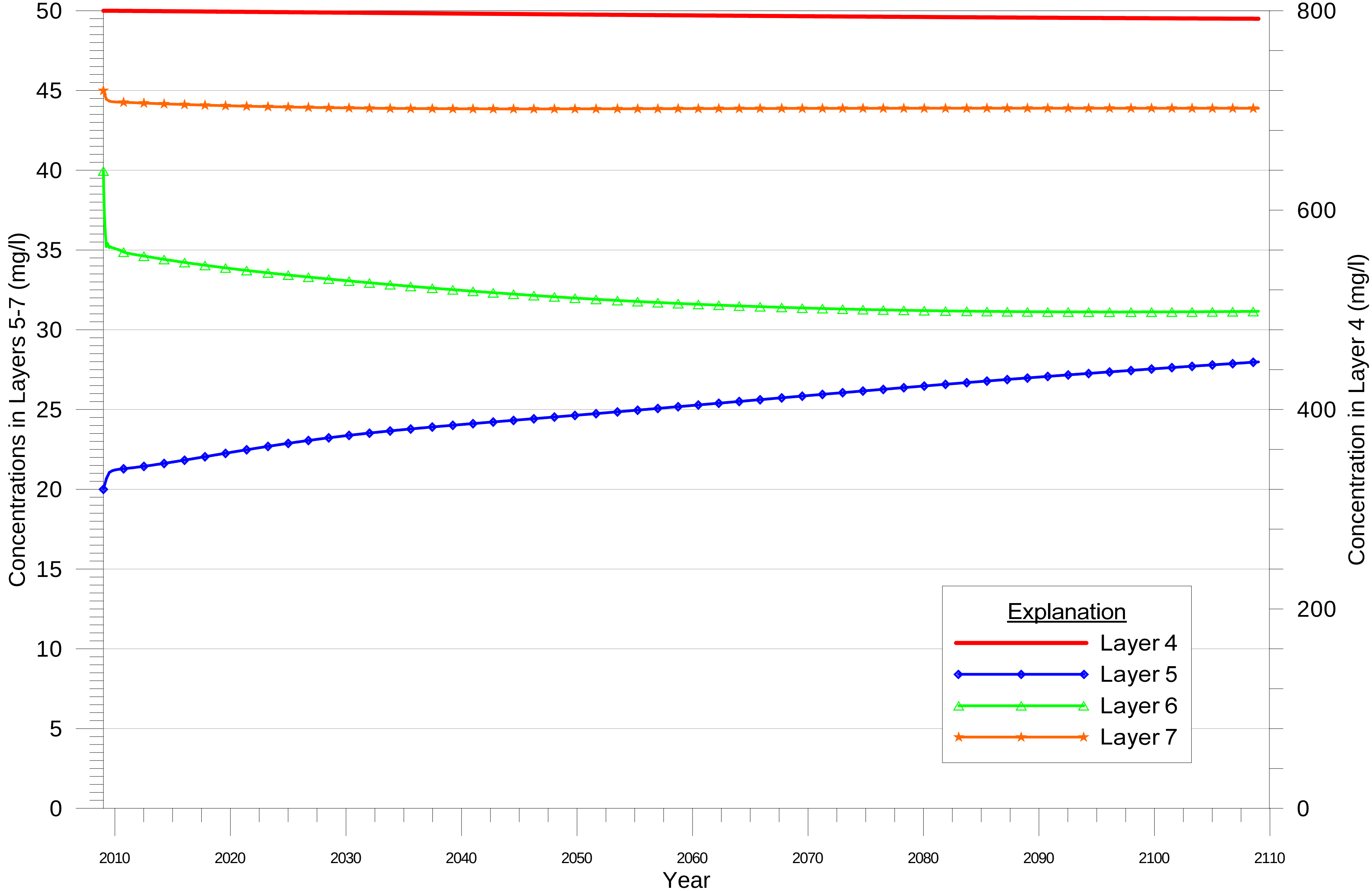


Note: Pumping Rate at each well = 0.36 gpm or 518 gpd; $K_V/K_H = 1$

CLEAR CREEK ASSOCIATES	6155 E Indian School Road Suite 200 Scottsdale, Arizona 85251 (480) 659-7131	**Projected Sulfate Concentration** **TMR Model Layers** **Observation Point 2 - 2009 to 2109**	**Figure** **10**



Note: Pumping Rate at each well = 10 gpm or 14400 gpd; K_V/K_H = 1

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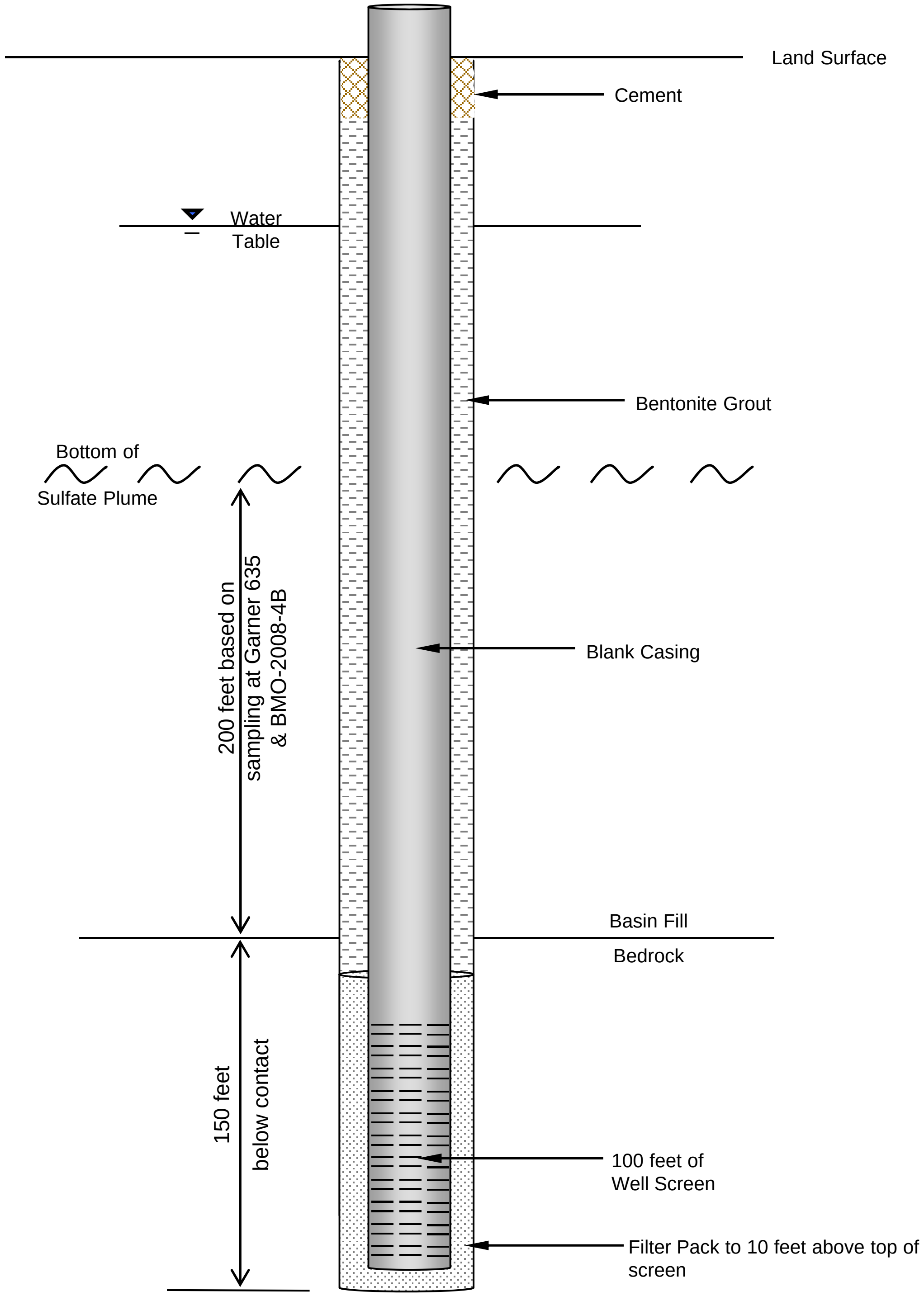
Projected Sulfate Concentration
TMR Model Layers
Observation Point 2 - 2009 to 2109

Figure
11



Not To Scale

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Purdy Lane Groundwater Analysis

Date: October 27, 2011

Figure 12
Conceptual Well Design for
Replacement Wells