Evaluation of Impacts of Proposed Well Pumping at the Villages of Vigneto Development, southwest of Benson, Arizona on Groundwater beneath the Saint David Cienega, in the Northern San Pedro River National Conservation Area

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Introduction

The Center for Biological Diversity (CBD) contacted Robert Prucha of Integrated Hydro Systems, LLC (IHS) and requested a review of available studies and evaluation of the potential impacts of proposed groundwater pumping wells associated with the Vigneto Development, southwest of Benson, Arizona at the base of the Whetstone Mountains (see Figure 1). CBD indicated that the Bureau of Land Management (BLM) has expressed concerns that the proposed groundwater development will adversely affect spring flow within the Saint David Cienega, located adjacent to the San Pedro River (see Figure 1), that discharges into the San Pedro. They believed the source of groundwater from these springs is from the deeper basin fill aquifer.

In addition, CBD also believe that groundwater flow conditions associated with the well-known Kartchner Caverns, located immediately southwest of the Vigneto Property boundary (see Figure 1) may also be negatively affected by proposed Vigneto groundwater pumping.

Specifically, CBD asked me to look at available data and relevant hydrological studies to date and give them an opinion on how the proposed Vigneto groundwater development may affect:

(1) Spring flows and groundwater associated with the Saint David Cienega, and

(2) groundwater conditions near the Kartchner Caverns.

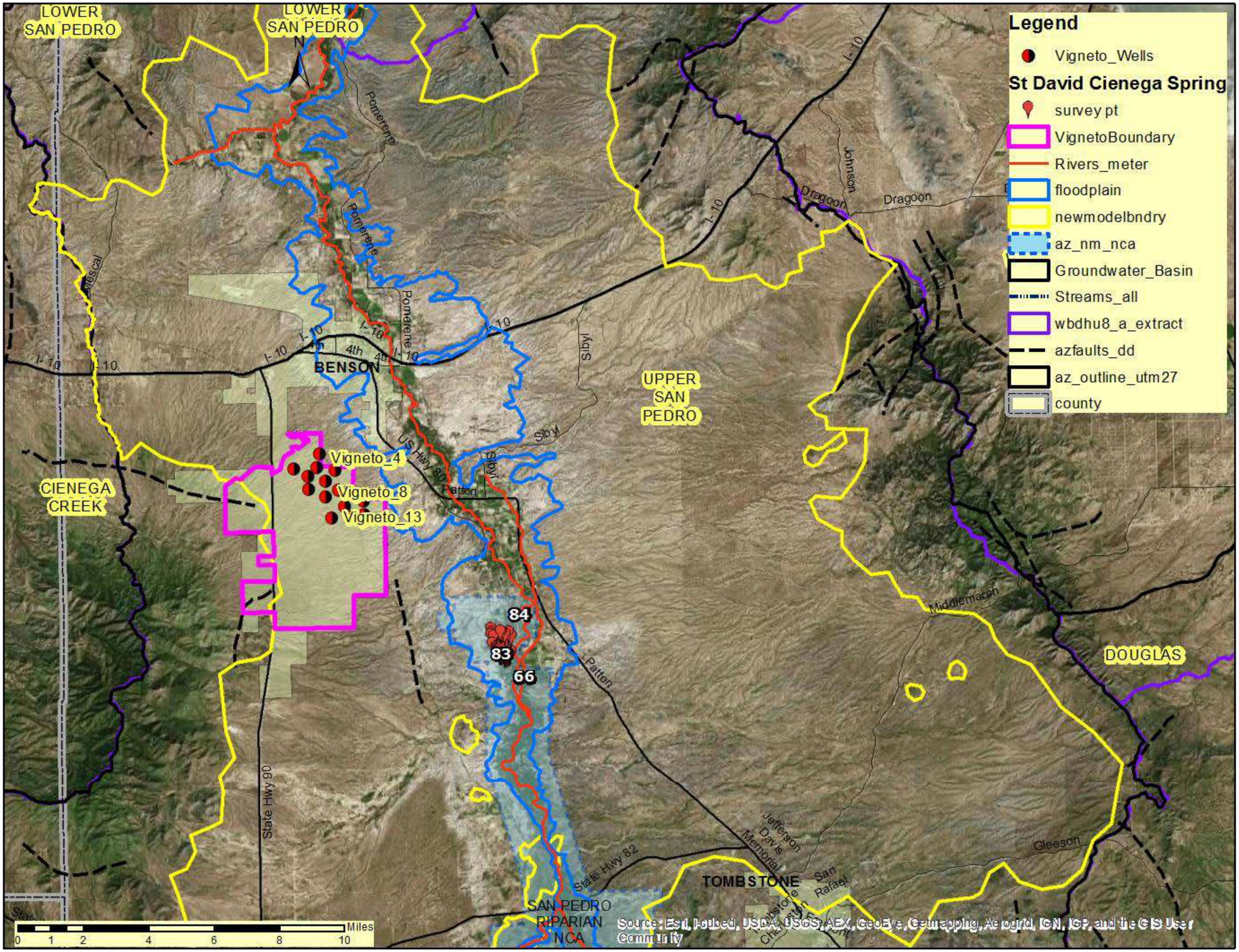

Figure 1. Site Overview. Magenta outline is proposed Vigneto Community Development. St. David Springs are located within San Pedro Riparian National Conservation Area just west of San Pedro River, southeast of Vigneto.

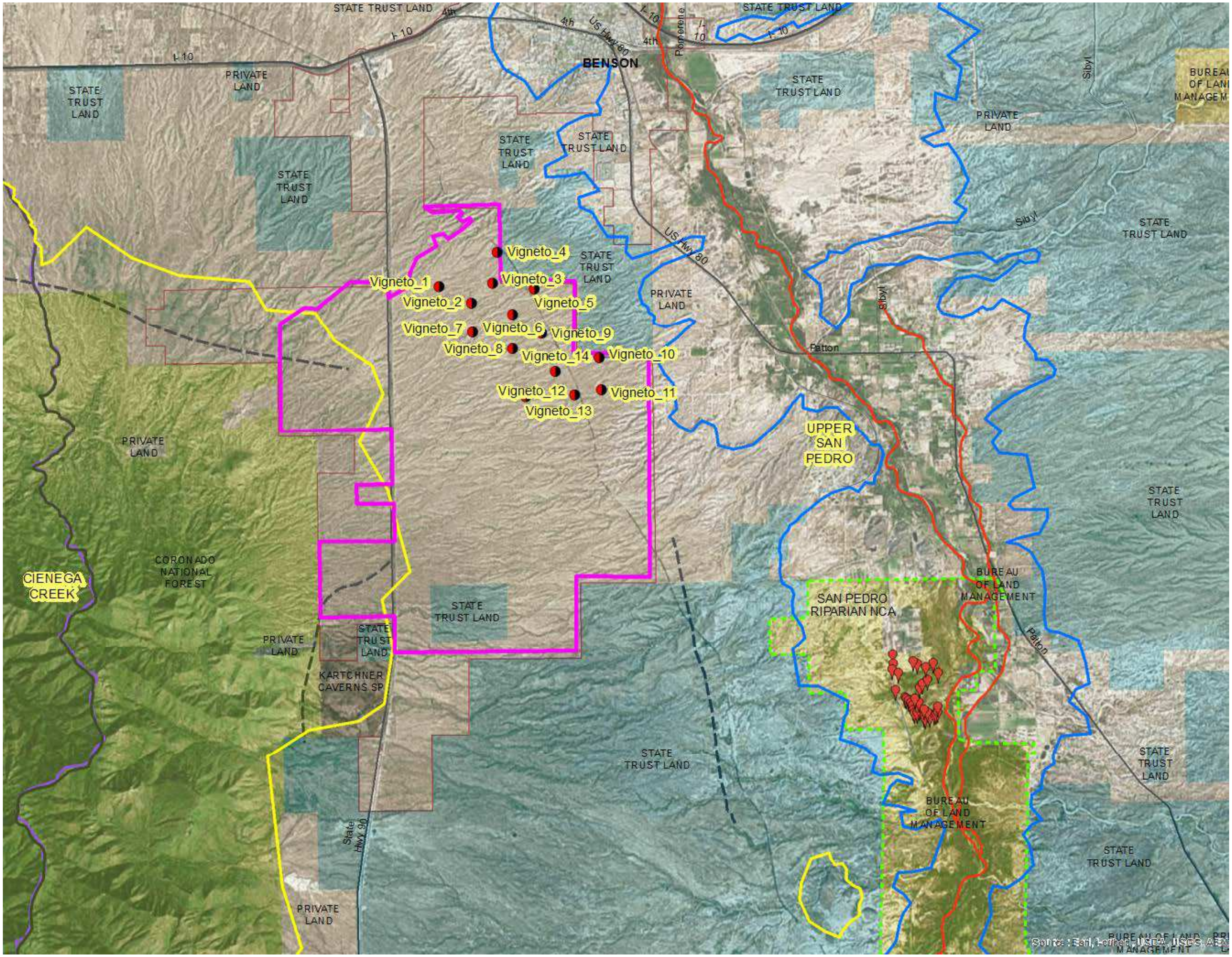

Figure 2. Location of Kartchner Caverns (immediately southwest of Vigneto Property Boundary. Springs are symbols in northern San Pedro Riparian NCA, immediately west of San Pedro River.

General Approach/Methodologies

1) Develop GIS database of system (upper/middle San Pedro) including:
2) Review available data and reports:
    a. M&A hydrology reports
    b. Vigneto development reports
    c. USGS Reports:
        i. Hopkins et al, 2014
        ii. Dickinson et al, 2010
        iii. Cordova et al, 2013
3) Develop a conceptual flow model in vicinity of Vigneto property, Saint David Cienega and Kartchner Caverns.
4) Utilize the finite element code to develop a groundwater model of the area surrounding Vigneto, Saint David Cienega and Kartchner Caverns, and then simulate effects of proposed Vigneto pumping.
5) Evaluate the results.

Organization of this evaluation

1. Document review
2. Data review/GIS preparation
3. Revised groundwater model evaluation
4. Results/Conclusions

Document Review

I reviewed the following documents as part of this evaluation:

Goode, T.C., and Maddock, T.I., 2000, Simulation of groundwater conditions in the Upper San Pedro Basin for the evaluation of alternative futures: University of Arizona, Department of Hydrology and Water Resources, catalog no. 2000-030, 113 p.

Cordova, J.T., Dickinson, J.E., Beisner, K.R., Hopkins, C.B., Kennedy, J.R., Pool, D.R., Glenn, E.P., Nagler, P.L., and Thomas, B.E., 2015, Hydrology of the middle San Pedro Watershed, southeastern Arizona: U.S. Geological Survey Scientific Investigations Report 2013–5040, 77 p., http://dx.doi.org/10.3133/sir20135040.

Dickinson, J.E., Kennedy, J.R., Pool, D.R., Cordova, J.T., Parker, J.T.C., Macy, J.P., and Thomas, B.E., 2010a, Hydrogeologic framework of the middle San Pedro Watershed, southeastern Arizona: U.S. Geological Survey Scientific Investigations Report 2010–5126, 36 p.

Errol L. Montgomery & Associates, Inc. 2005. Hydrologic Study for San Pedro Partners Master Planned Community in Support of an Application for an Analysis of Water Adequacy Cochise County, Arizona. Prepared for San Pedro Partners, LLC.

Graf, Charlies. 1999. Hydrogeology Of Kartchner Caverns State Park, Arizona. Journal of Cave and Karst Studies 61(2): 59-67.

Hopkins, C., McIntosh, J., Eastoe, C., Dickinson, J.E., and Meixner, T., 2014, Evaluation of the importance of clay confining units on groundwater flow in alluvial basins using solute and isotope tracers: the case of Middle San Pedro Basin in southeastern Arizona (USA): Hydrogeology Journal, p. 1-21.

Makings, Elizabeth. 2013. Flora and Vegetation of the Saint David and Lewis Springs Cienegas, Cochise County, Arizona. USDA Forest Service Proceedings RMRS-P-67. 2013.

The Nature Conservancy, 2015. San Pedro River Surface Water Extent June 2015 (see www.azconservation.org)

The Nature Conservancy, 2014. San Pedro River Surface Water Extent June 2014 (see www.azconservation.org)

The Nature Conservancy, 2013. San Pedro River Surface Water Extent June 2013 (see www.azconservation.org)

El Dorado Benson, LLC. 2015 Final Community Master Plan and Development Plan for The Villages at Vigneto. September 8, 2015

GIS Database Preparation/Data Review

GIS Database Preparation

I prepared a Geographic Information System (GIS) database using ESRI's ArcGIS 10.1 to facilitate review and evaluation of various geospatial datasets I obtained via the internet. Specific datasets included in my review are:

- Groundwater
  - ADWR Data (Wells 55 Registry and Arizona Groundwater Site Inventory (GWSI) (http://www.azwater.gov/azdwr/gis/)
  - USGS NWIS Data (http://waterdata.usgs.gov/az/nwis/gw)
- Springs
  - Univ. of Arizona (http://libguides.library.arizona.edu/GIS)
  - Saint David Cienega Survey Locations – Ben Lomeli, BLM
- Surface Geology USGS - https://mrdata.usgs.gov/geology/state/state.php?state=AZ
- Isopachs (thickness) and Top/Bottom of Fine and Medium-Grained Units – Jesse Dickinson, USGS, Tucson, AZ.
- Stream and National Hydrographic Dataset (surface watershed HUC boundaries) – USDA (https://gdg.sc.egov.usda.gov/).
- Groundwater basins (ADWR - http://gisdata.azwater.opendata.arcgis.com/).
- Upper/Middle San Pedro Groundwater Modeling Dataset (Thomas Maddock), included various datasets supporting the Goode and Maddock, 2000 groundwater model.
- Surface topography – USDA gateway. Utilized a 10-m topographic dataset, which was used to define the upper model surface, rather than the former Goode and Maddock, 2000 topographic dataset.
- Georeferenced Vigneto property boundary and proposed well locations (from El Dorado, Benson, LLC, 2015.

Data Review

The location of ADWR springs are shown on Figure 3, relative to the location of Saint David Cienega and the proposed Vigneto pumping wells.

Figure 4 shows a cross-section prepared in google earth pro along a white line from west to east through the primary spring within the Saint David Cienega (see arrows) and extending well east of the San Pedro river. It is clear that the spring occurs above the invert (thalweg) of the San Pedro river about 36 feet, suggesting that the source of spring flow may be different than from the San Pedro river. Though the actual source of water is unknown, one possibility is that groundwater upwells from deeper basin groundwater as the groundwater flow beneath the San Pedro encounters shallow bedrock and the relatively thick sequence of lower permeability fine- and medium-grained material (i.e., Figure 12 in Dickinson, et al, 2010).

Figure 5 shows ADWR and USGS NWIS groundwater wells in the vicinity of the Vigneto Boundary and Saint David Cienega. Clearly, the many wells will be impacted in the immediate vicinity of the proposed Vigneto pumping wells. Many of the wells shown were installed after the pre-1997 pumping well evaluation by Goode and Maddock, 2000.

Figure 6 summarizes surficial geology in the area, which offers no clear evidence that it influences the occurrence of springs within the Saint David Cienega. The spring could very well occur in this spot due to preferential upwelling along an unmapped fault (mapped faults are shown on the figure and do support explanation of the larger graben-structure of the entire drainage system).

Figure 7 and Figure 8 show isopach (thickness) maps of fine-grained and medium-grained provided digitally by Jesse Dickinson (USGS, Tucson, AZ).

Figure 9 shows the bedrock surface as included in the Goode and Maddock, 2000 Modflow model, which was mapped into the Feflow finite element model (as shown). The bedrock configuration could offer some explanation for the occurrence of spring flow within the Saint David Cienega, where groundwater flowing from the southern deeper basins (i.e., Huachuca and Tombstone) is forced upwards to the ground surface, due to the lower underlying bedrock permeability.

Figure 10 shows wet-dry mapping for June 2013, indicating that much of the San Pedro River downstream of Babocomari River is dry. This provides the basis for later modeling of stream stage being near zero in the vicinity of the Vigneto property and the Saint David Cienega.

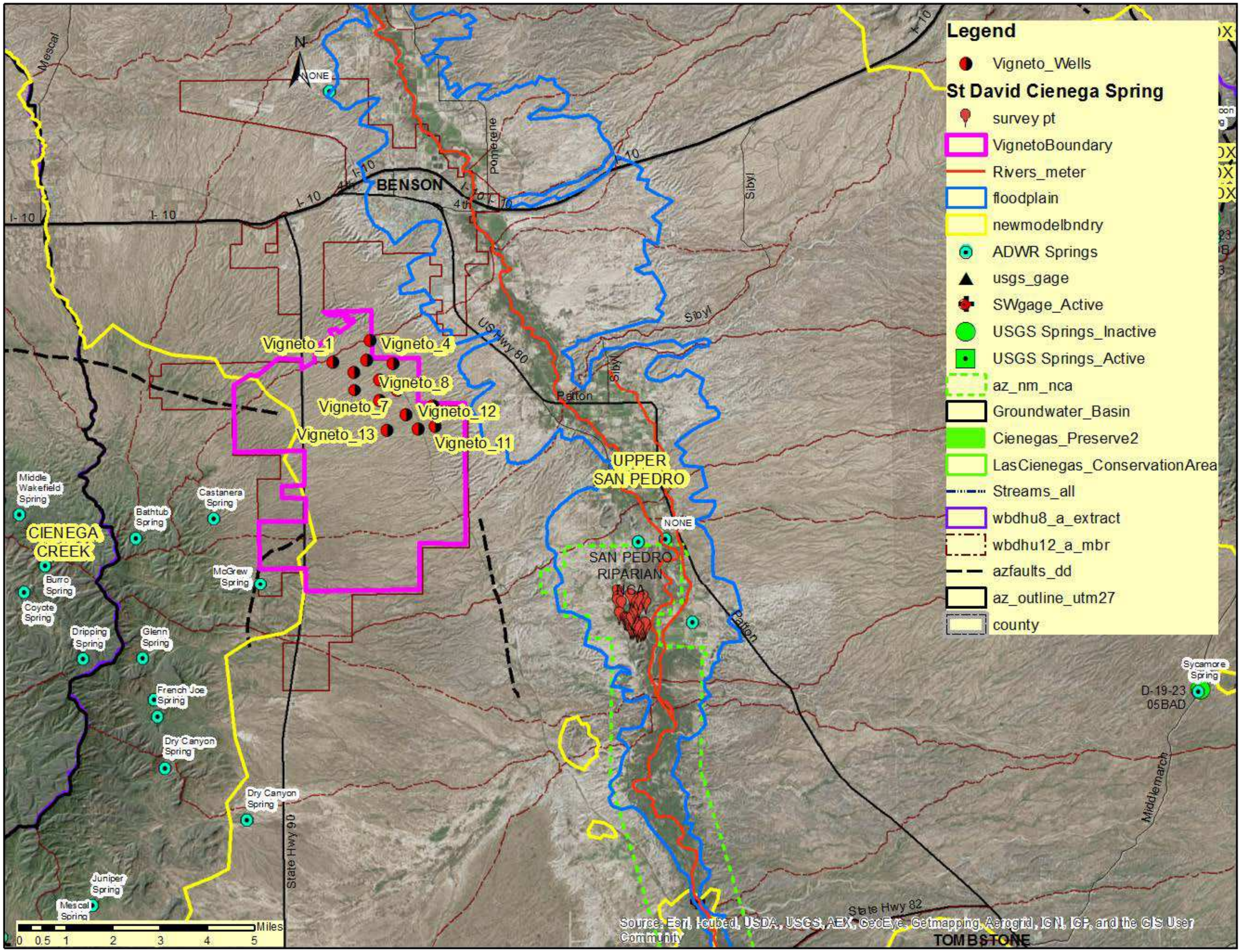

Figure 3. Location of ADWR Springs. Three additional springs are located immediately outside of the San Pedro NCA (green dashed line). The floodplain shown is from the Goode & Maddock, 2000 model dataset provided for this study.

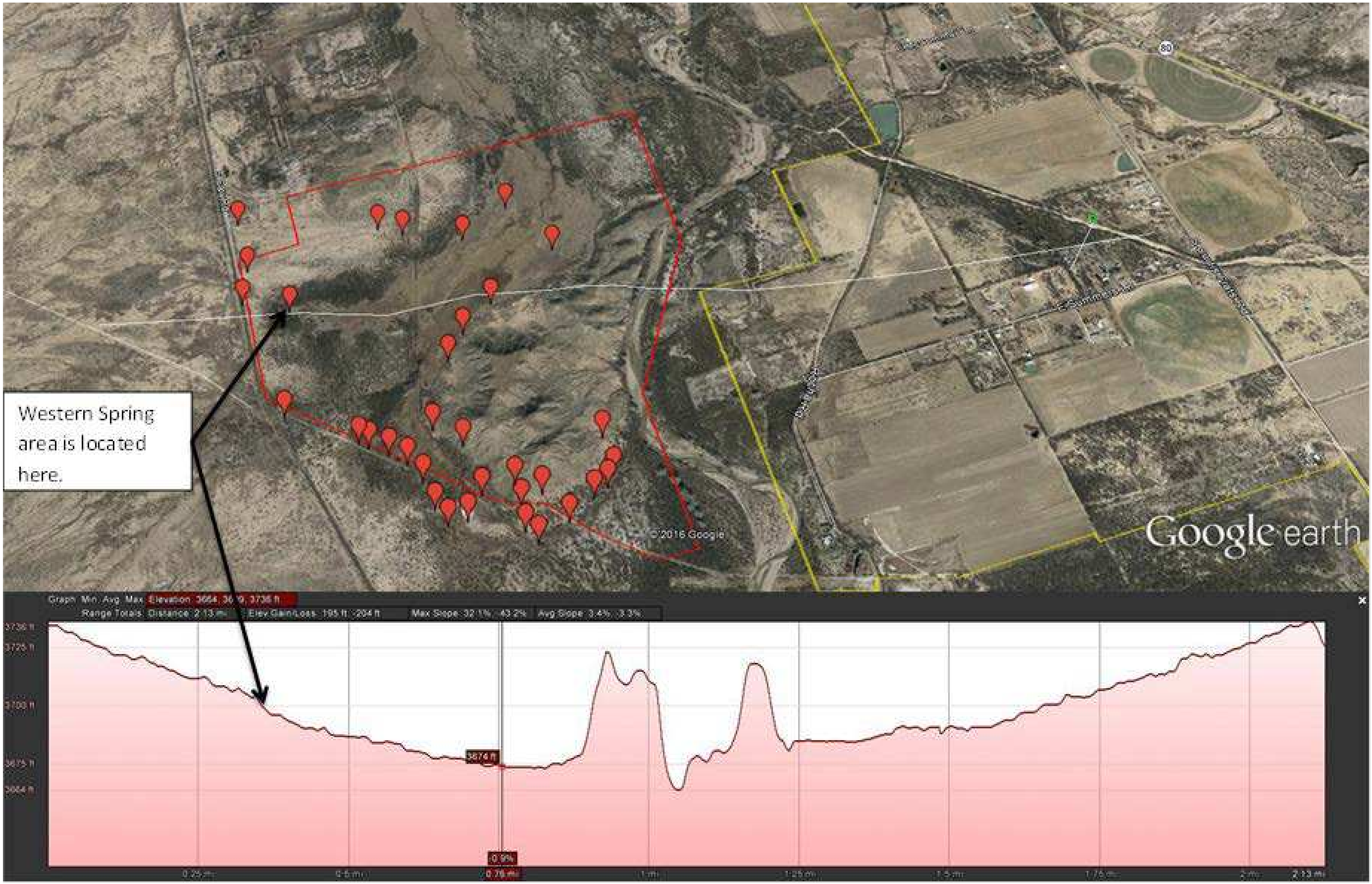

Figure 4. Apparent springflow within the western Saint David Cienega is ~36 feet higher than bottom of San Pedro Wash Invert and average stage.

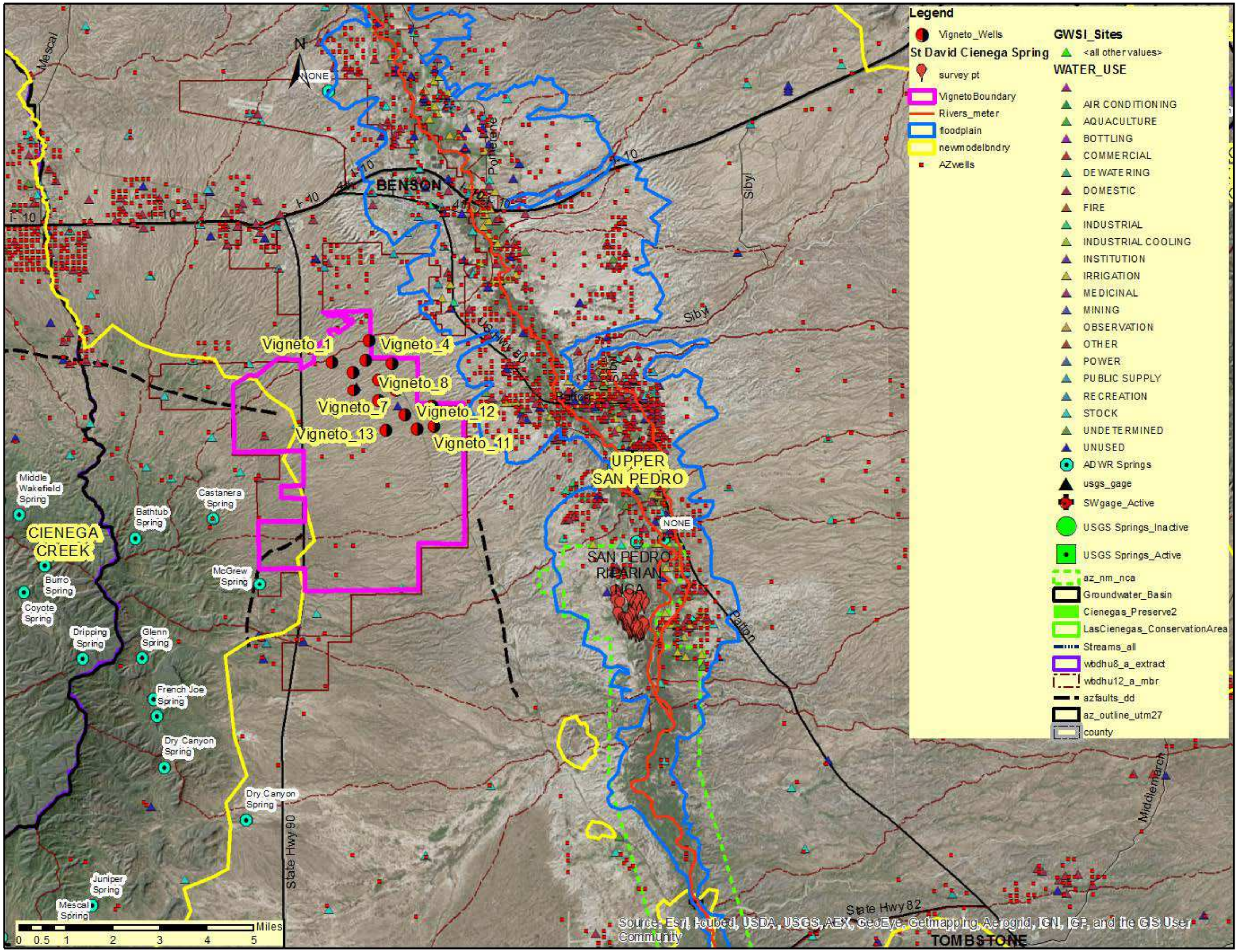

Figure 5. Groundwater Wells in the Area (ADWR and USGS NWIS data). San Pedro River National Conservation Area shown in dashed green line.

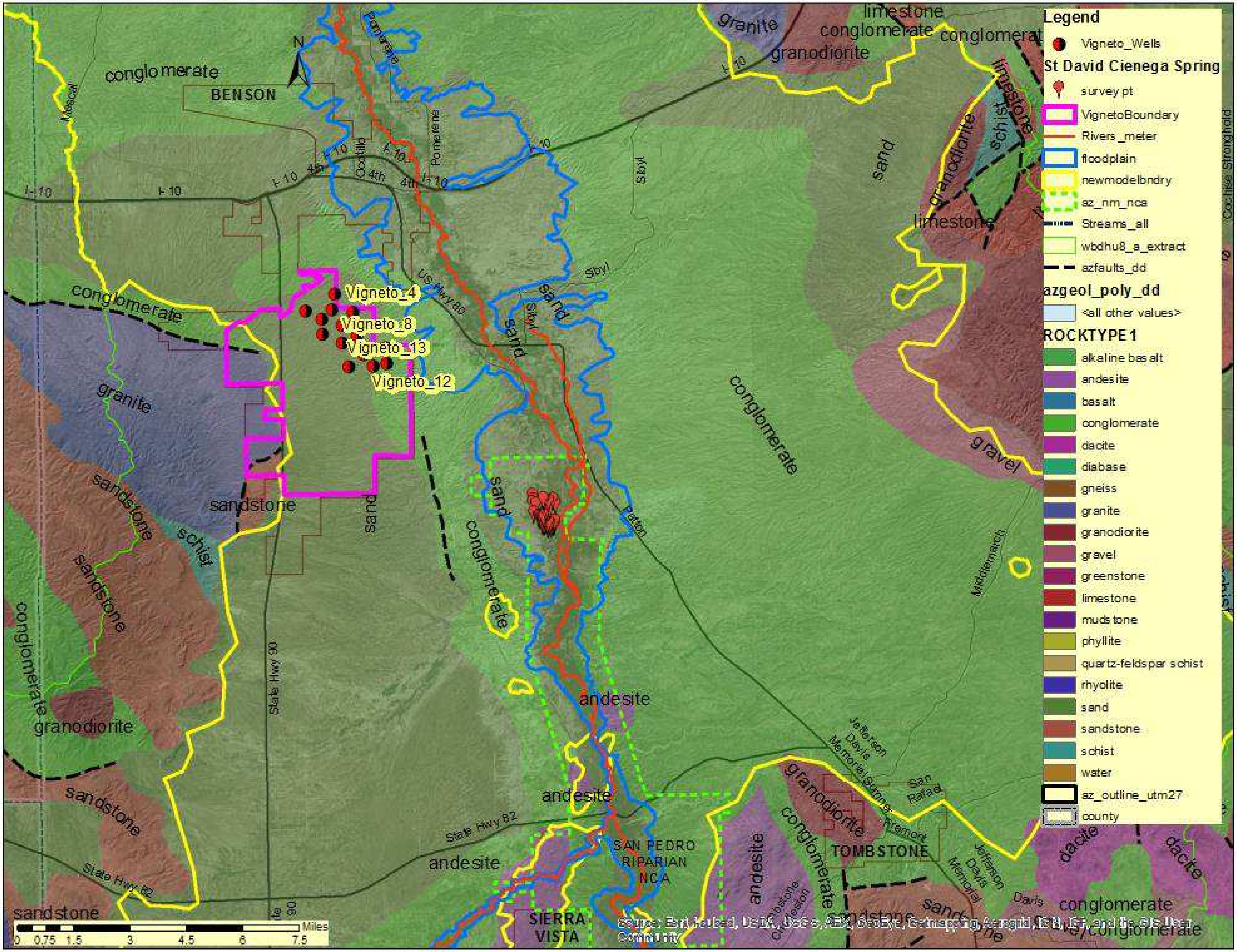

Figure 6. Surficial Geology (Arizona USGS). San Pedro River National Conservation Area is shown in dashed green line (same as az_nm_nca in legend.

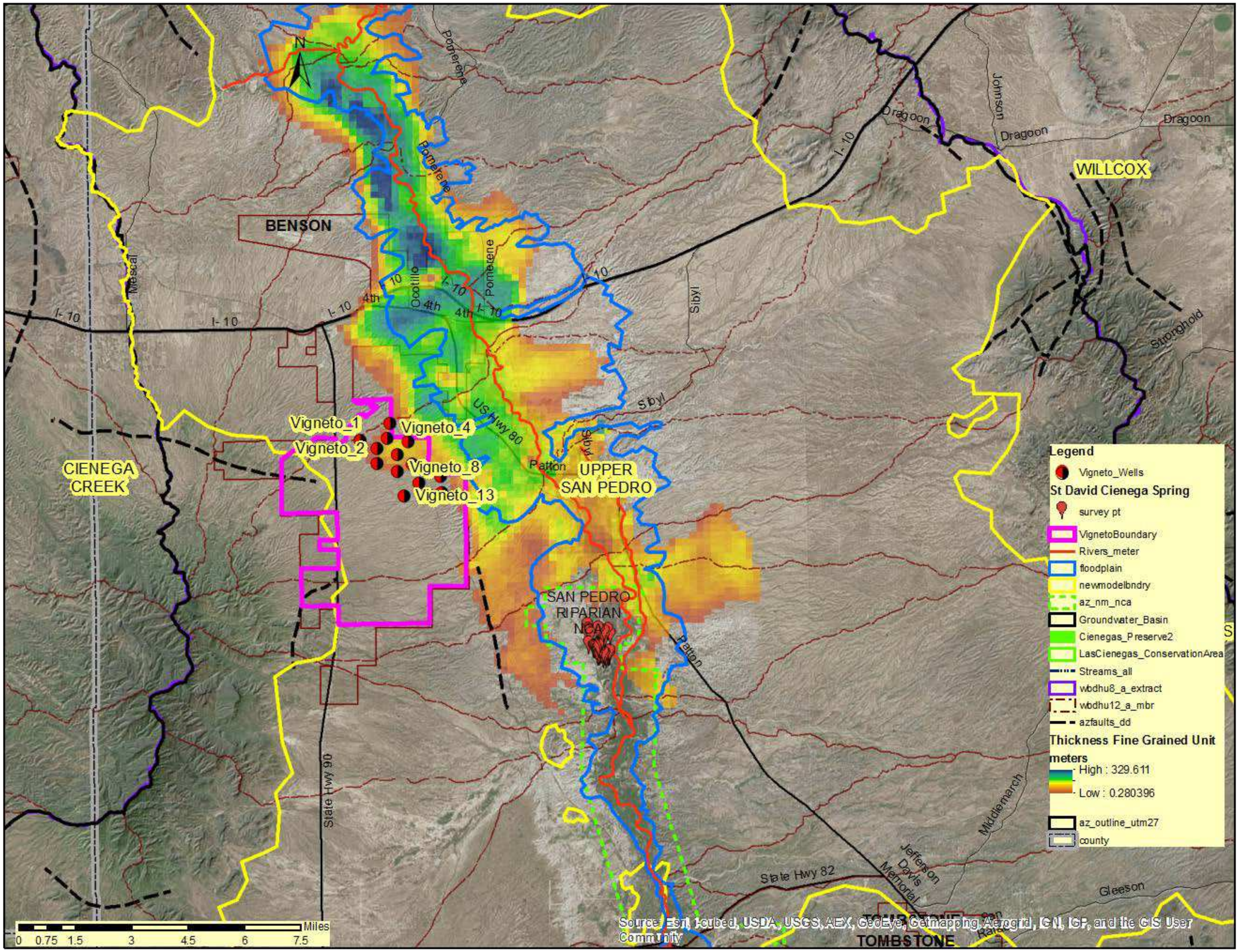

Figure 7. Fine-Grained Unit Thickness (meters) - from USGS. San Pedro River National Conservation Area is shown in dashed green line (same as az_nm_nca in legend.

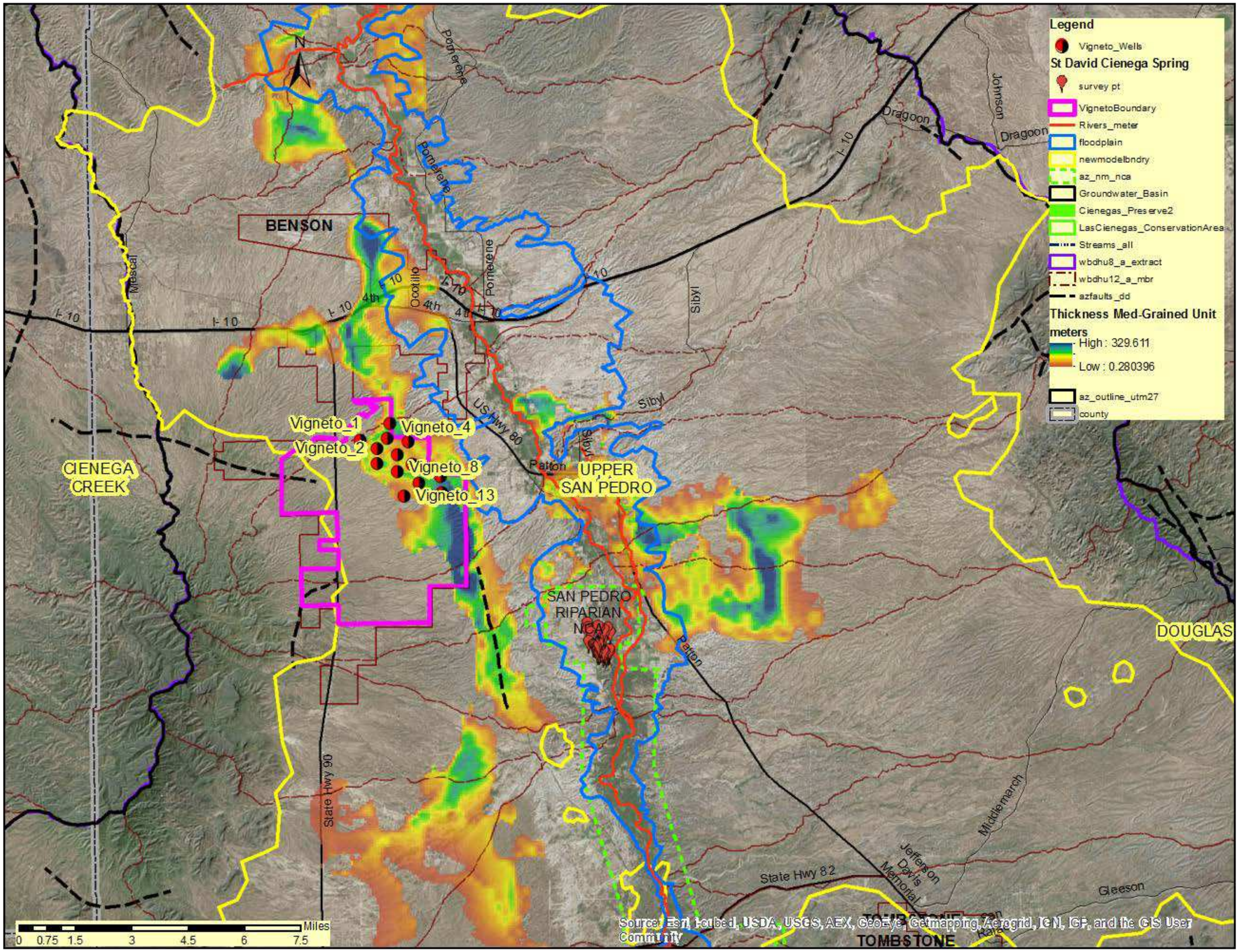

Figure 8. Medium-Grained Unit Thickness (meters) - from USGS. San Pedro River National Conservation Area is shown in dashed green line (same as az_nm_nca in legend.

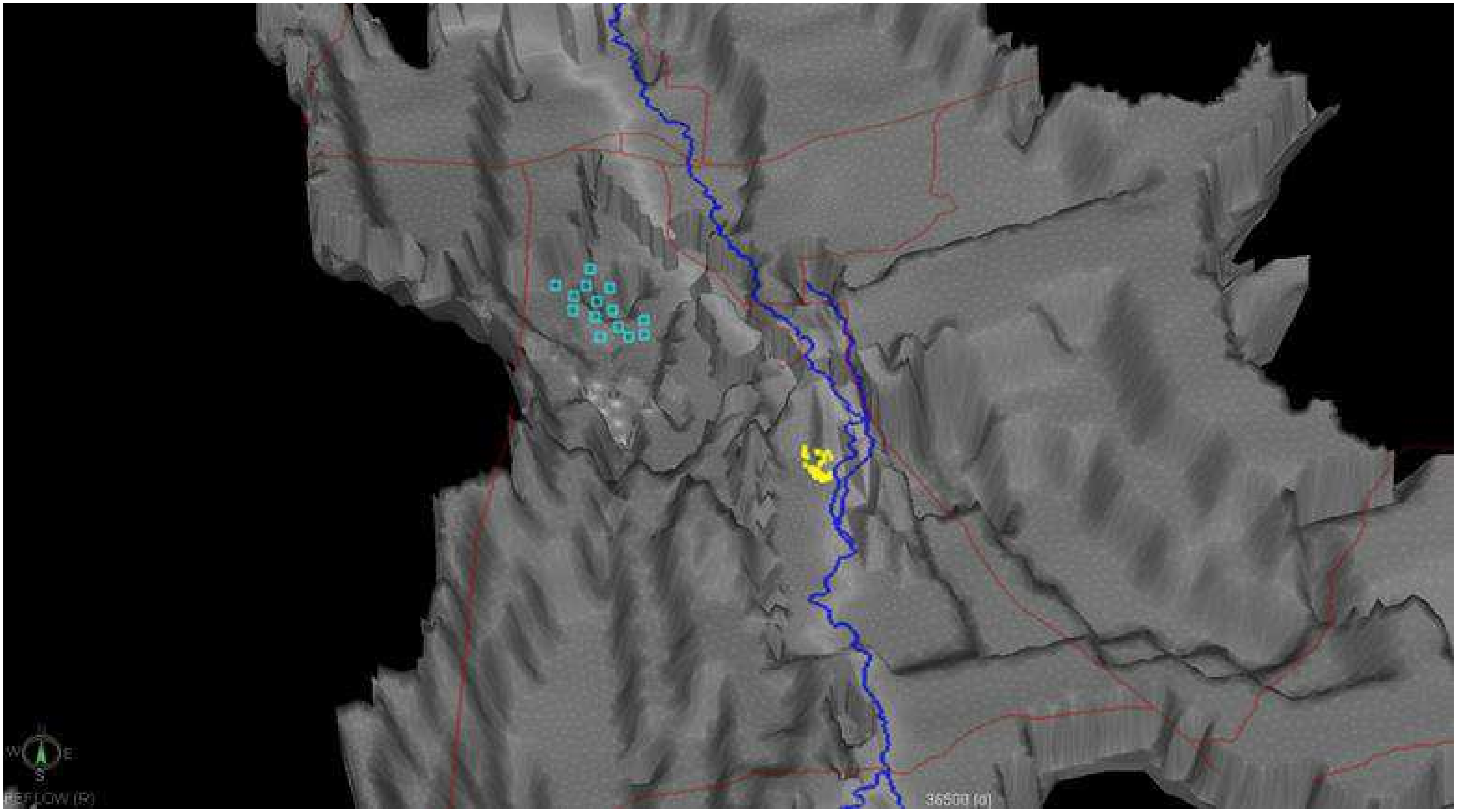

Figure 9. Modeled bedrock surface (from original Modflow model). The cyan symbols are Vigneto pumping wells, while yellow symbols are St. David Cienega spring. Roads are shown for reference (red). A notable trough exists, connecting the Benson and Huachuca basins (west of San Pedro). The Tombstone basin is shown east of the San Pedro river.

San Pedro River Surface Water Extent June 2013

- Wet River
- Dry River
- Unsurveyed River or Stream
- Major road
- San Pedro Riparian National Conservation Area
- The Nature Conservancy Preserves

Reach	Length (miles)	Surveyed (miles)	Wet (miles)	% wet
Mexico	18.0	14.2	11.5	81%
Upper basin	76.9	72.1	25.8	36%
Lower basin	78.7	57.3	9.1	16%
Total	**173.6**	**143.7**	**46.5**	**32%**

Also surveyed were:
Aravaipa Creek, with 26.9 miles surveyed, 20.6 miles (77%) wet,
Babocomari River, with 14.8 miles surveyed, 5.9 miles (40%) wet,
and 37 smaller tributaries.
Total tributary survey length was 165.4 miles.

Most surveys were conducted June 15, 2013,
but survey dates ranged from June 10 - 26.

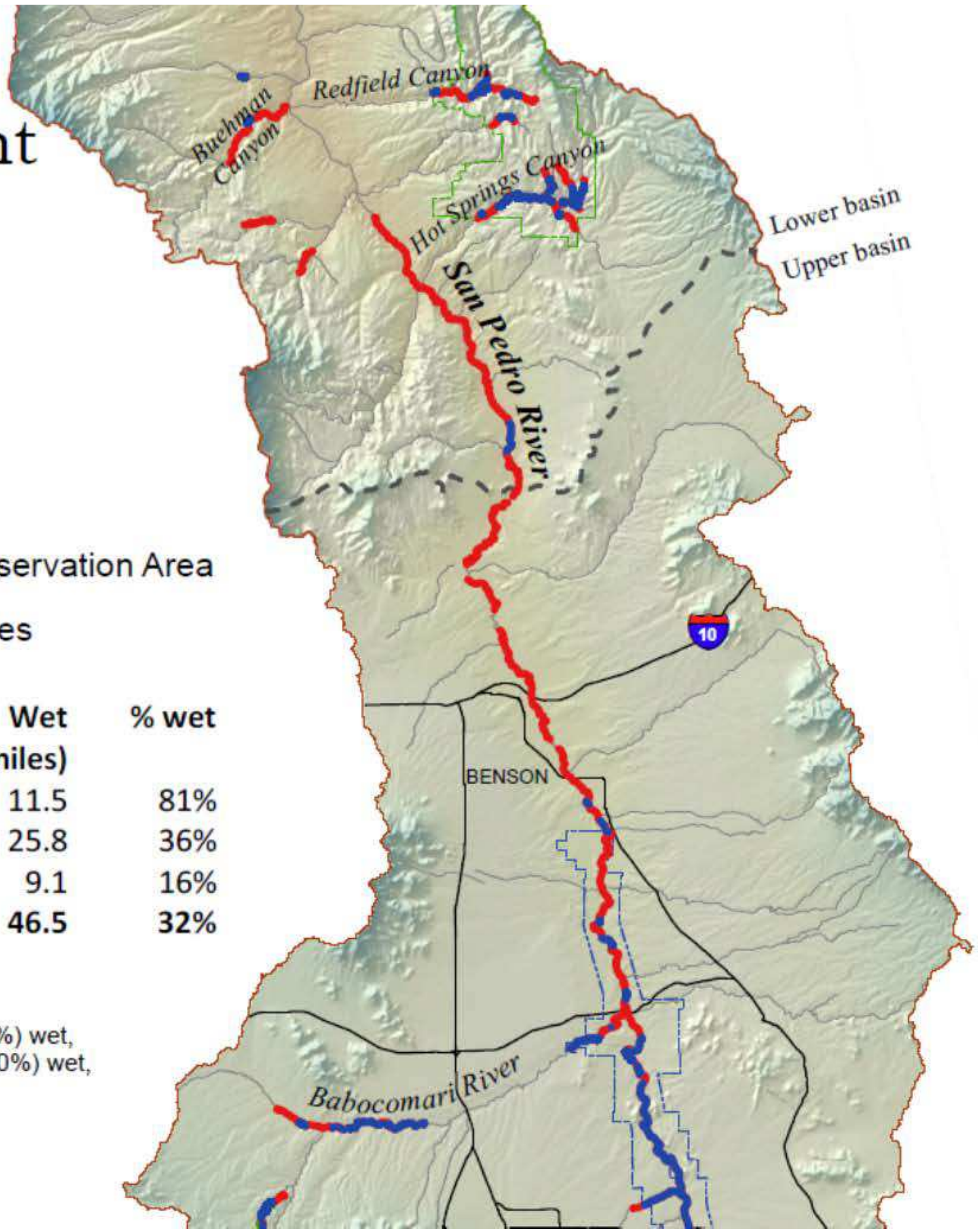

Figure 10. Wet-Dry Mapping of San Pedro River (June 2013) - The Nature Conservancy, 2013. Results are similar for 2014 and 2015 surveys, showing mostly dry river north of the confluence of San Pedro River with Babocomari River.

Proposed Groundwater Well Pumping for Villages at Vigneto Development

Projected Demand at Vigneto

1) Errol L Montgomery & Associates 2005 estimated the following demand over a 100-year period. This has clearly been revised in the recent Vigneto development plans.

Projected average water demand over the 100-year period for San Pedro Partners is estimated to be **329.5 AFY**, and summarized as follows:

SAN PEDRO PARTNERS PROPOSED WATER USE	SAN PEDRO PARTNERS PROPOSED ANNUAL GROUNDWATER DEMAND (AFY)
Single-Family Residential	265
Other Non-Residential Landscaping	30
Lost and Unaccounted	29.5
Construction *(including mass grading and infrastructure)*	5
Total Demand	**329.5[a]**

[a]Equivalent to about 204 gpm

2) Recent Vigneto Development plans (El Dorado Benson, LLC, 2015) indicate the following demands:

Page 49 states:

Water Wells - New groundwater wells will be drilled and developed to serve drinking water needs. The preferred location for the new wells is in the northeast portion of Vigneto. However, the final location and spacing of the wells will be determined with the first Planning Unit Plan. In order to meet the build-out capacity, approximately twelve new wells, plus two backup wells, of an average of 800 gallons per minute ("gpm") each are proposed and anticipated. The final number of wells will be subject to change based on actual buildout demand and capacity of wells. Well No. 1 is an existing 1200 gpm well that will continue to pump into the system as it is currently configured. The remaining wells will be piped to two new water plants. Water Plant No. 2 and No. 3 will serve as central locations for possible future water treatment needs.

Page 54 states:

Potable Water Demand Projections - A preliminary build-out of the potable water demand has been calculated based on the CMP land use plan (See Section 7.A – Land Use Final Development Plan and Land Use Budget) and potable water demand criteria in this section. Residential potable water demand is calculated based on 75 percent of the maximum 28,000 residential units will be age-targeted and 25 percent will be traditional family homes. The net estimated ground-water demand for the Villages at Vigneto is 5,739 acre feet per year. The preliminary estimate of the ADD is approximately 8,519 acre feet per year ("af/yr").

Potable Water Demand Projections Table

Use Type	Acreage per Use Type	# Units/ Students	ADD (gpd)	ADD (gpm)	PDD (gpm)	PHD (gpm)
Residential	7,305.2	28,000	5,575,500	3872	6970	11616
Mixed Use	678.3		949,620	659	1186	1977
Infrastructure, Civic, and Recreation	133		185,500	129	232	387
Elementary Schools	100	4000	100,000	69	124	207
High School	50	2400	103,200	72	130	216
Vigneto Subtotal			**6,838,820**	**4,749**	**8,548**	**14,247**
Lost & Unaccounted for Water (10%)			683,882	475	855	1425
Vigneto Total			**7,522,702**	**5,224**	**9,403**	**15,672**

From the September 8, 2015 Final Community Master Plan and Development Plan for The Villages at Vigneto, proposed total pumping capacity will be 9,500 gpm from 12 wells averaging 800 gpm each as shown on Figure 11. The master plan states:

Well Capacity - The total preliminary well capacity for the system is estimated at approximately 9,500 gpm. This is equivalent to twelve (12) wells at an average 800 gpm each. This is a good approximate average for the area based on existing aquifer data, as some wells will produce more and others will produce less. The system requires enough capacity with the greater of either the largest well out of service or 10% reserve capacity. 10% reserve capacity is 950 gpm, which is greater than the largest well of 800 gpm. Therefore, two additional wells are shown for a total of 14 wells for the Conceptual Potable Water Master Plan. Actual number of wells and capacity will vary due to fluctuations in actual available capacity of designed wells are constructed and placed into service.

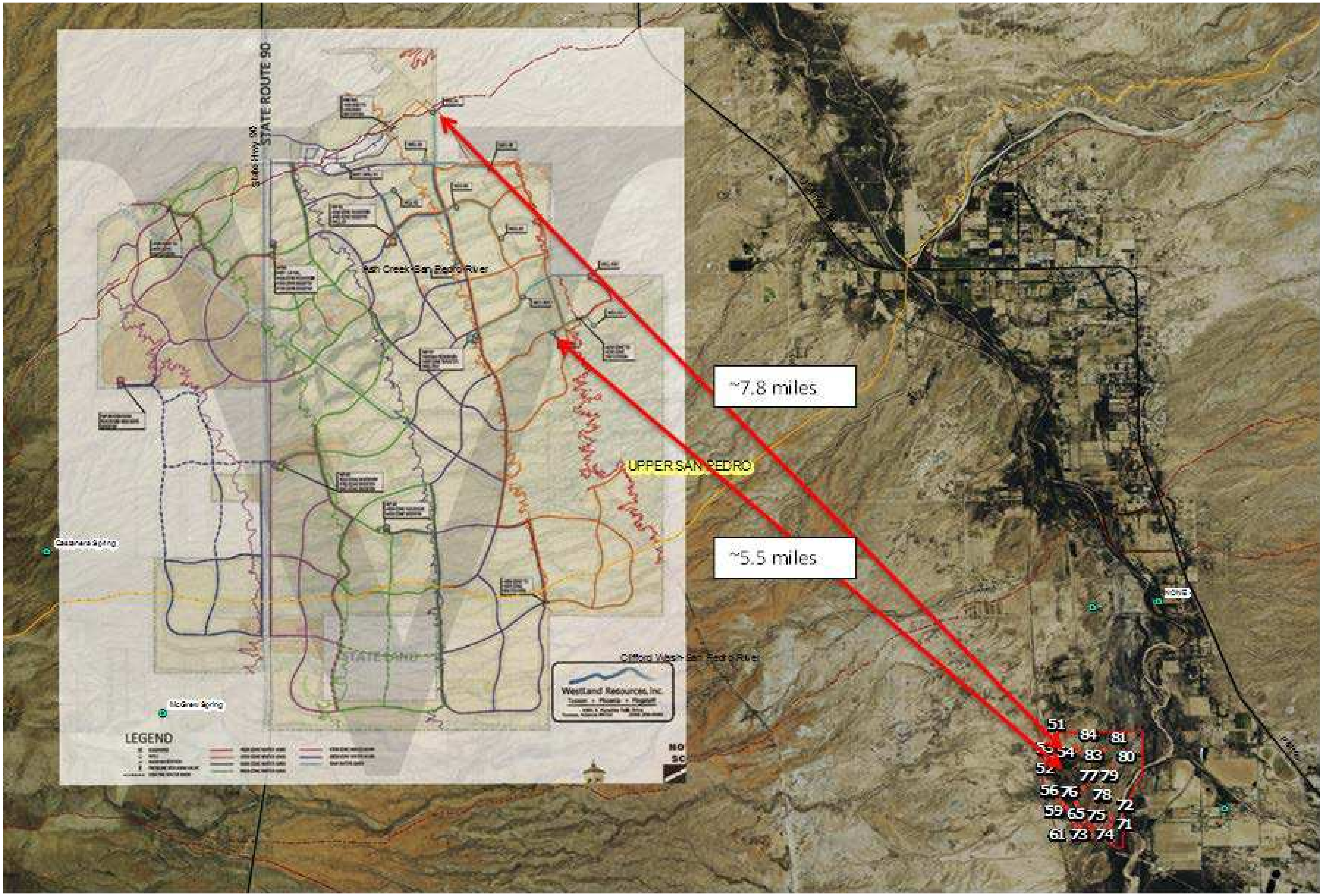

Figure 11. Shows approximate well pumping locations proposed in Vigneto Master Plan and approximate distances to BLM springs to the southeast of the development, adjacent to the San Pedro River.

Conceptual Flow Model

I prepared a conceptual flow model illustrated on Figure 12 and based on data/interpretations reviewed in this evaluation.

The illustration provides one explanation of how proposed Vigneto groundwater pumping may impact groundwater levels beneath the Saint David Cienega, and reduce its discharge at ground surface. Drawdown induced by pumping at the Vigneto wells propagates mostly via more permeable units above and below the confining fine- and medium-grained units. The impacts are transmitted to beneath the spring more effectively via the lower confined permeable lower basin fill material. It is more effective because translation is higher in confined units that don't require actual pore-dewatering, as occurs in unconfined aquifers (which dampens translation).

Remarkably, the lower permeability, confining fine- and medium-grained units, though continuous throughout much of the Vigneto/Benson City area, are absent in the vicinity of the Saint David Cienega (see Figure 7 and Figure 8), which supports the concept that the spring flow could be due to both shallowing bedrock and occurrence of lower permeability material immediately downgradient of the spring location, which could act to force groundwater upwards to the ground surface as spring discharge. Clearly, more data is required to fully justify this conceptualization (i.e., geochemical water sampling of spring water – age dating, isotopic signatures etc.).

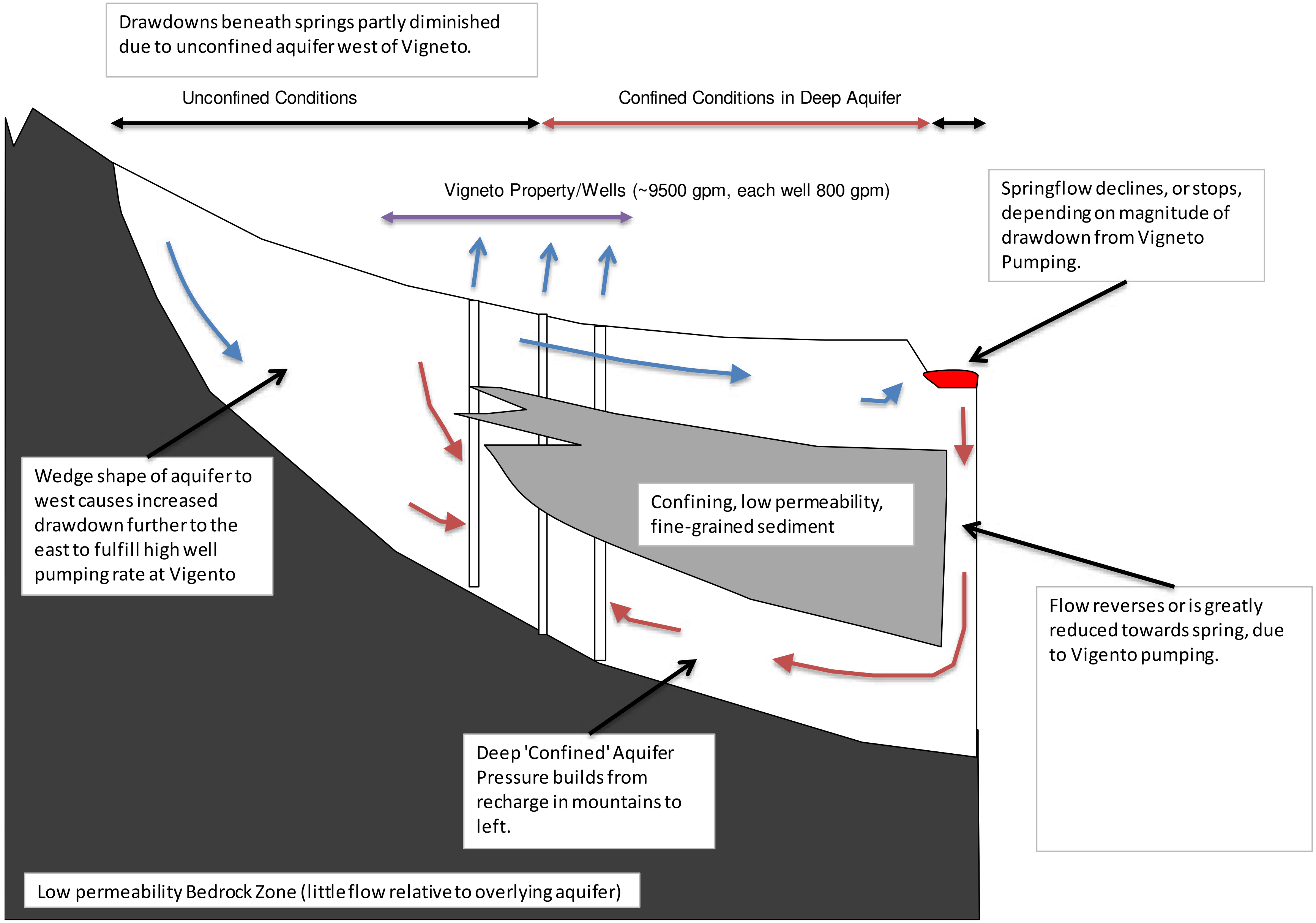

Figure 12. Conceptual section shows influence of proposed Vigneto pumping on spring flow located south of Vigneto and groundwater deep aquifer flows.

Evaluation of Impacts – 3-dimensional Groundwater Flow Model

Approach for Model Development

1) Obtained Goode and Maddock, 2000 Modflow flow model input datasets. Figure 12 shows the extent and model grid used in the 2000 Modflow model.
2) Reviewed setup for steady and transient state models.
3) Used modeling shapefiles and converted Modflow flow model inputs into a 3-dimensional Feflow model.
4) Further modified the converted 4-layer Goode and Maddock model into a 6-layer Feflow model (Figure 13 and Figure 14 show updated vertical model layering and horizontal finite element mesh):
    a. Combined former Modflow Layer 1 and 2 into a single layer in the Feflow model (Layer 1).
    b. Embedded fine and medium-grained material distributions from the USGS (Jesse Dickinson) within former Modflow layers 3 and 4. See Figure 13.
    c. Utilized top surface elevations and thicknesses provided by Jesse Dickinson w/USGS to determine vertical placement of these two units within the former Goode and Maddock model. I utilized an excel spreadsheet algorithm to embed these two units into the input for the Feflow model.
    d. I assumed hydraulic properties for these units based on texture. Conductivity values of 0.01 m/d (similar to a clay) and 0.2 m/d were specified for the fine- and medium-grained units.
    e. No regional wells added to the model (thousands of wells). Re-calibration of the model needs to incorporate updated wells throughout the model
    f. Careful evaluation of the Goode & Maddock model showed that flow in the bedrock was assumed insignificant and not explicitly modeled.
    g. Instead of modeling the stream-aquifer interaction using the STR stream package used in the Goode & Maddock model, which included routing, I utilized something simpler, similar to the RIV package, which allows bi-directional flow between the river and aquifer, but does not route water away, or allow the stage to change. This was justified mainly because the San Pedro downstream of Babocomari River is largely dry based on The Nature Conservancy Wet-Dry studies (see 2013, 2014 and 2015). I further evaluated the sensitivity of the model predictions to different river stage.
    h. I also included a somewhat permeable bedrock unit beneath the entire Goode & Maddock model to allow flows between the overlying basin

deposits and underlying bedrock, which can represent permeable weathered limestone, sedimentary or crystalline rock. This allowed me to further evaluate sensitivity of drawdowns beneath the St. David Cienega due to pumping at the Vigneto property.

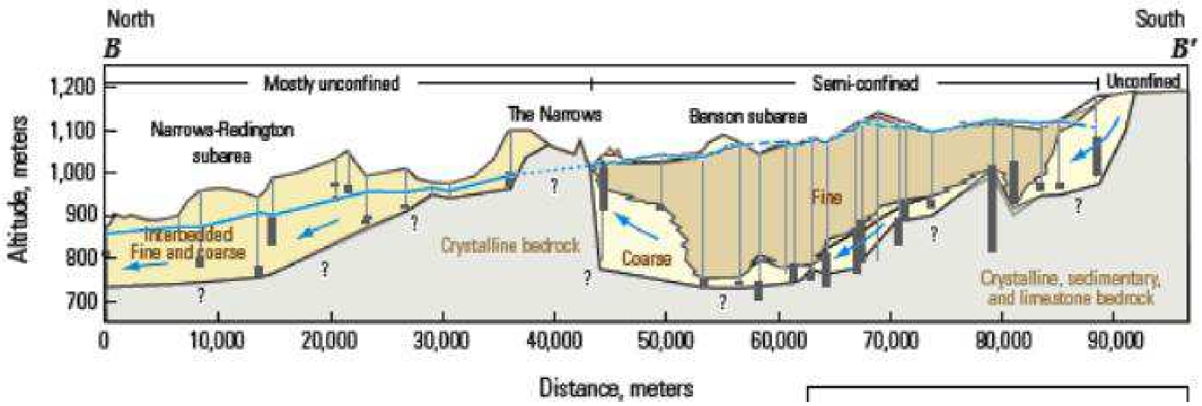

Figure 13. From Figure 12, in Cordova et al, 2013, shows a vertical profile from north to south, mostly along the San Pedro River. Wells toward the south (~80000 m), beneath Saint David Cienega, appear screened within the bedrock, implying the bedrock is somewhat permeable (i.e., weathered crystalline, sedimentary or limestone).

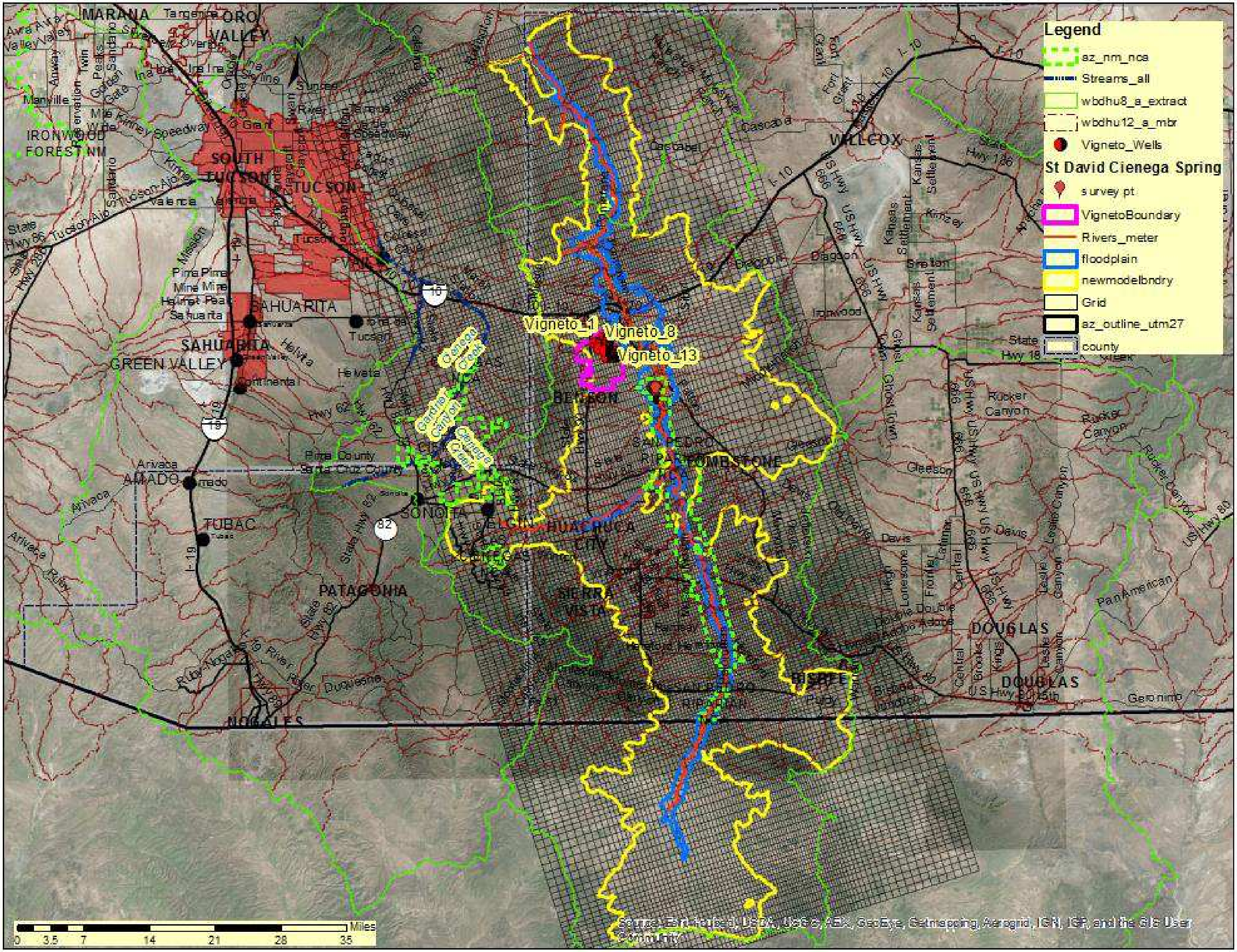

Figure 14. Modflow Grid, Goode and Maddock, 2000. The yellow boundary represents the extent of the active model domain (which did not include bedrock). San Pedro River National Conservation Area is shown in dashed green line (same as az_nm_nca in legend.

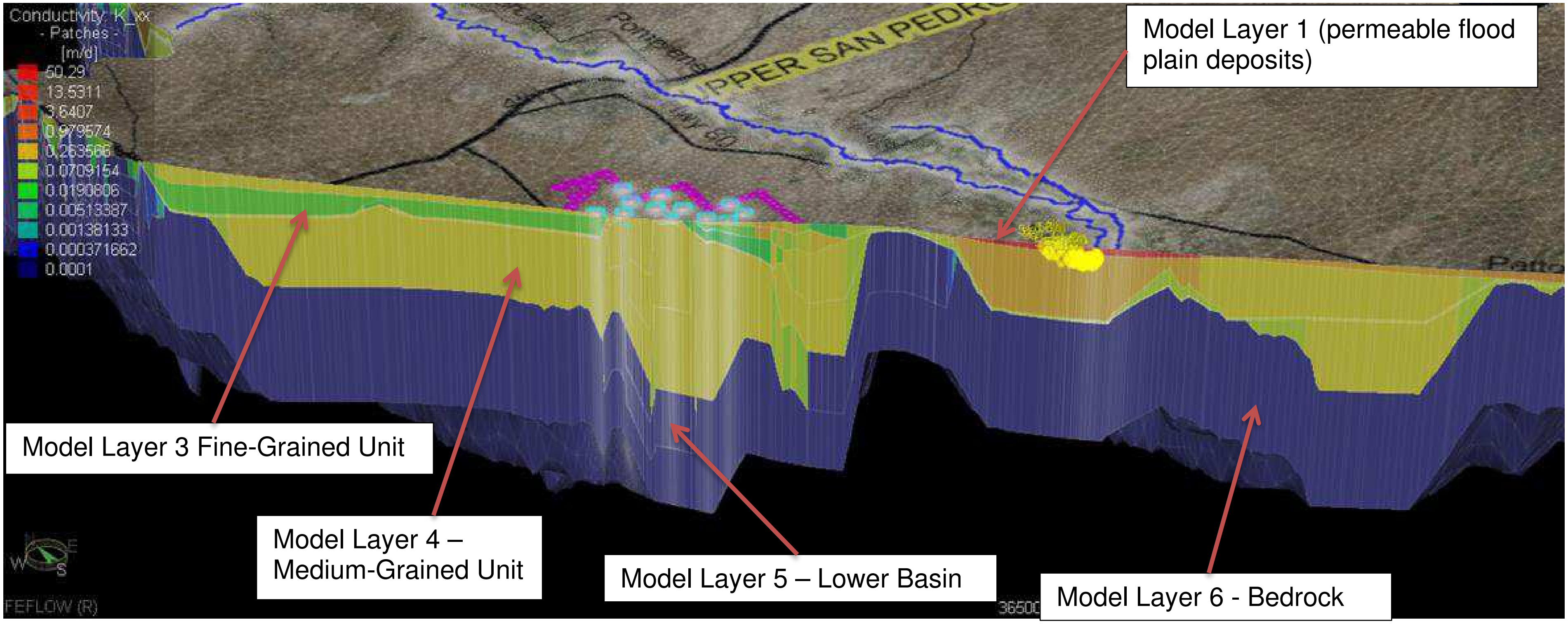

Figure 15. Cross-section shows 6 updated model layers, incorporating the fine- and medium-grained confining units and an underlying bedrock layer (dark color - layer 6).

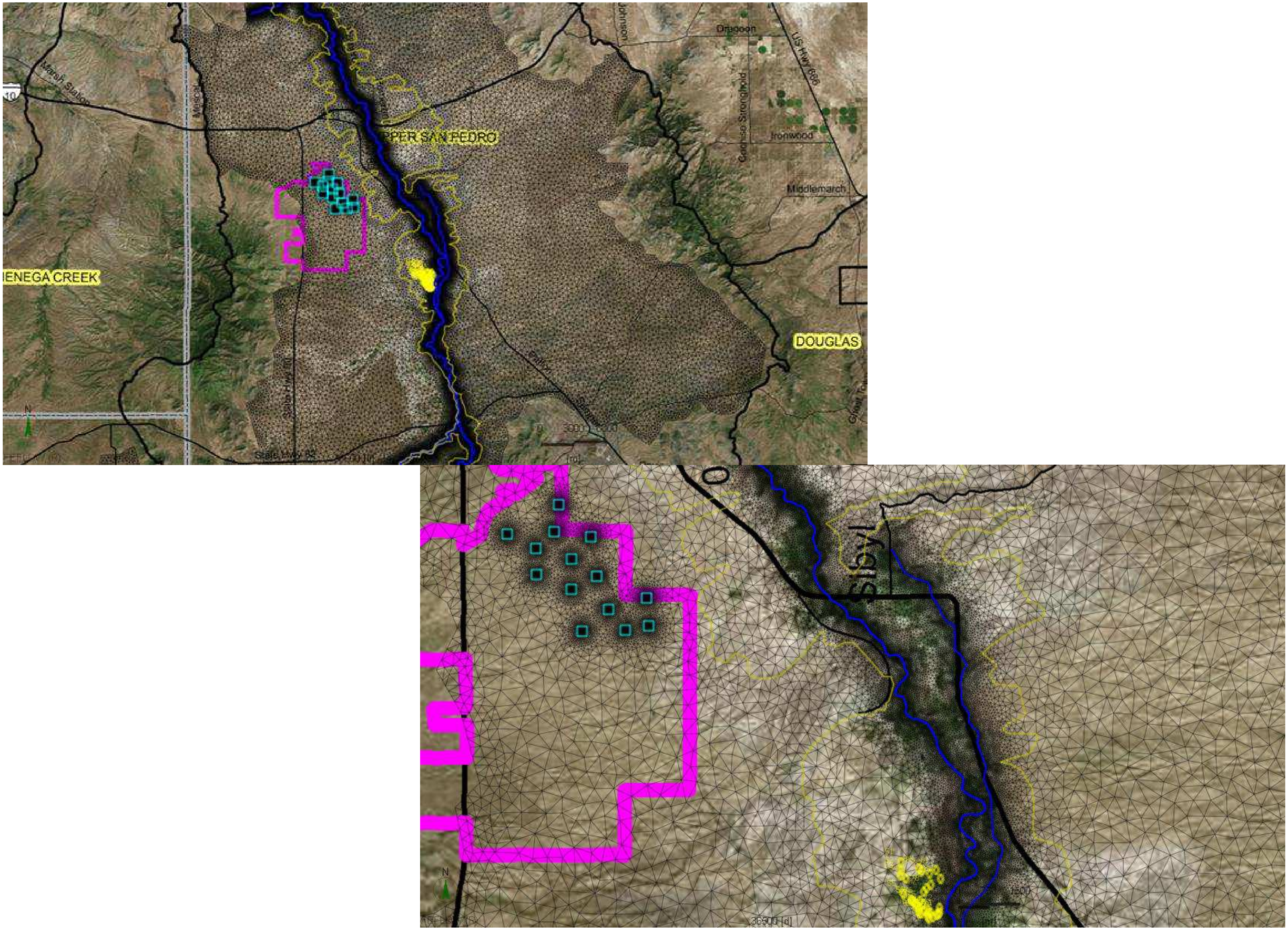

Figure 16. Feflow finite element model mesh, refined around wells and the river.

Modeling Scenarios/Results

Scenarios

I made no attempt to re-calibrate the updated flow model, though I did use previous calibrated model inputs from the Goode and Maddock, 2000 model. It is reasonable to use the updated model to evaluate potential impacts of the Vigneto pumping on groundwater beneath the Saint David Cienega area, though the model should be re-calibrated to newer observation data to provide better estimates of the impacts. The addition of the fine- and medium-grained units are expected to change the former calibration, but the simulated change in groundwater levels due to proposed pumping at the Vigneto development are still probably reasonably estimated as simulated here without re-calibration, and much better than previous estimates (see Errol L. Montgomery & Associates, 2005) which don't consider large scale factors that clearly influence estimation of impacts, such as the bedrock surface configuration, fine-/medium-grained unit configuration/hydraulic properties, floodplain deposits, regional pumping etc. As such, results here are believed reasonable for estimating the nature of impacts at the springs.

Table 1 summarizes six runs that I made, evaluating different combinations of river stage, bedrock permeability and regional wells. For each scenario, I ran the following:

1) Steady state w/new baseline configuration
2) Transient state baseline w/pumping to 100 years

Table 1. Summary of Scenarios Simulated, and Results

Scenario	River Stage (m)	Bedrock K (m/d)	Regional Pumping	Comments/Results
1	2	0.09	none	The high river stage strongly influences the extent/magnitude of drawdown. The drawdown beneath the spring is about 0.4 m in both layer 1 (shallow) and layer 5 (deep).
2	0.66	0.09	none	Drawdown beneath Saint David Cienega is about 0.45 m, or about 1.5 feet. See Figure 18
3	0.01	0.0001	none	Reduced river stage to negligible amount, reflecting The Nature Conservancy Wet-Dry annual mapping (see The Nature Conservancy, 2013, 2014 and 2015). Results showed negligible impact at the spring.
4	0.01	0.0001	yes	This simulation ran fine with regional well pumping, but failed during the Vigneto pumping transient simulation, which appeared to overlap with regional pumping at some locations and over-simulate drawdowns (i.e., unrealistic). This may have run OK in the Goode & Maddock 2000 model because they provided more surface water (losing) and didn't simulate the fine/medium grained units. No

				conclusions could be drawn otherwise – i.e. that with regional pumping, the added Vigneto pumping might affect groundwater levels beneath the spring even more than not simulating the regional pumping. Either way, updated regional pumping should be included in the model re-calibration to better simulate effects of the Vigneto pumping.
5	0.01	0.09	none	Drawdown at St. David Spring is about 0.25 m, or just about 1.0 foot. See Figure 17

Results

Figure 17 shows simulated drawdowns for Scenario 6 at 100 years, for the lower basin fill (Layer 5), extend well east, beneath the River, though clearly influenced by the river-aquifer interaction and associated San Pedro River higher permeability floodplain deposits, which dampen the magnitude of the drawdown.

Figure 18 shows 3-dimensional simulated groundwater level contours (every 10 m) for the shallow aquifer (i.e. water table). The effects of the Vigneto pumping are evident by the concentric groundwater contours in the area, indicating heads in the general vicinity drop several tens of meters. Contours in general show that the groundwater system discharges to the surface water drainages (i.e., San Pedro River, Babocomari etc.).

Figure 19 and Figure 20 show simulated head levels with time (days) for the 100 year simulation for Scenarios 6 and 3, respectively. Symbols with flags have labels (numbers) that correspond to the shallow and deep (layers 1 and 5, respectively) shown on Figure 19. Results clearly show that observations beneath the spring decline about 0.25 m (Scenario 6) and about 0.45 m (Scenario 3), or observation points 1 and 2 (shallow layer 1) and 5 and 6 (deeper layer 5). Levels would continue to decline beyond 100 years.

Figure 21 shows a 3-dimensional drawdown (meters) through a section between Vigneto pumping wells and the spring. Results are shown over a 3-dimensional distribution of hydraulic conductivity (m/d), where brighter colors (red) indicate higher permeabilities and darker colors are lower. Drawdowns are clearly damped around the shallow, high permeability floodplain deposits/stream, but actually reach the spring.

Figure 22 shows 100 year backward particle pathlines, that give a sense of the 3-dimensional extent of where groundwater is intercepted by Vigneto pumping by model layer. Layers 2, 3 and 4 appear to draw groundwater from the furthest distance.

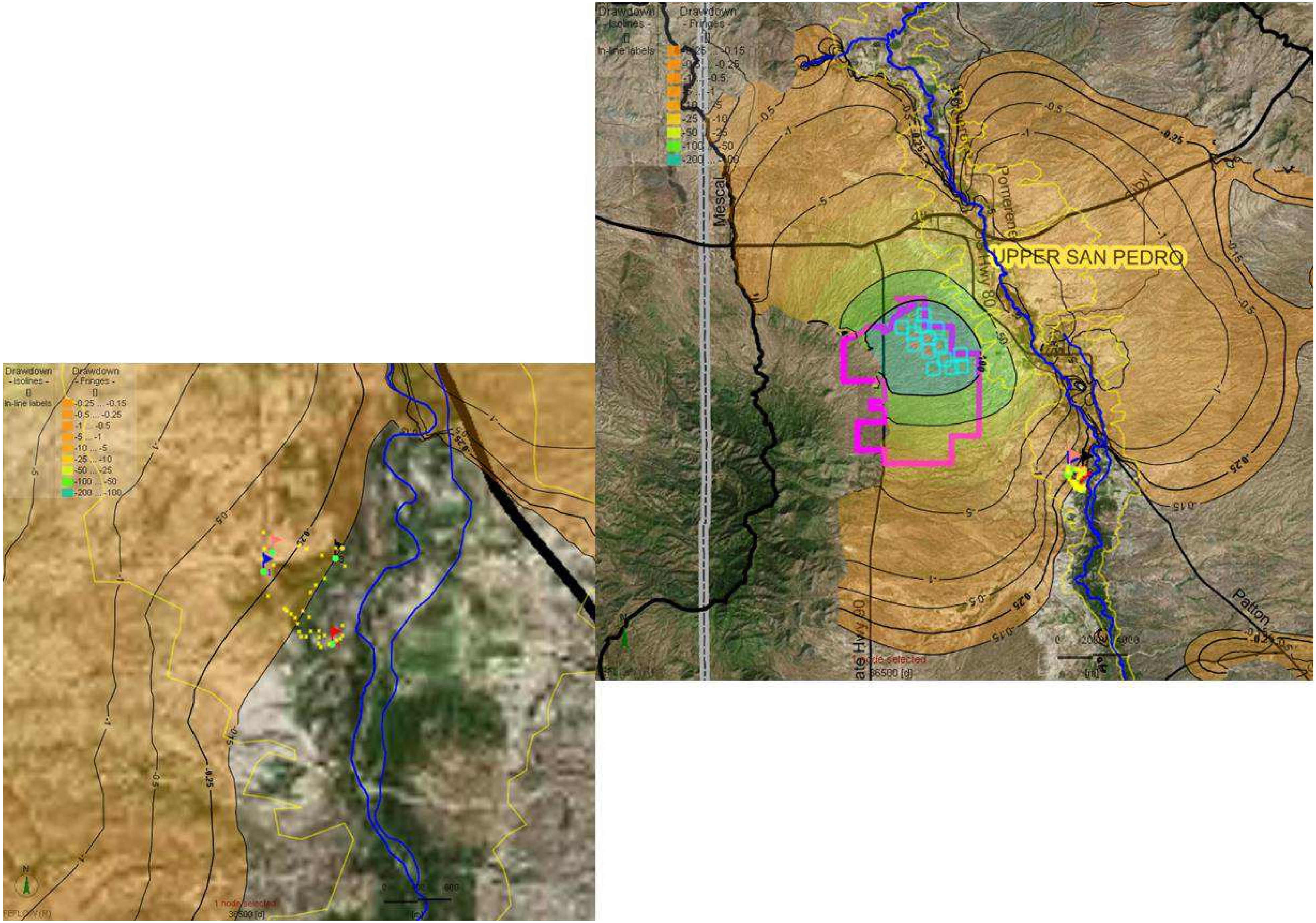

Figure 17. Simulated Drawdown (100 yrs., meters) for lower basin unit (Layer 5).

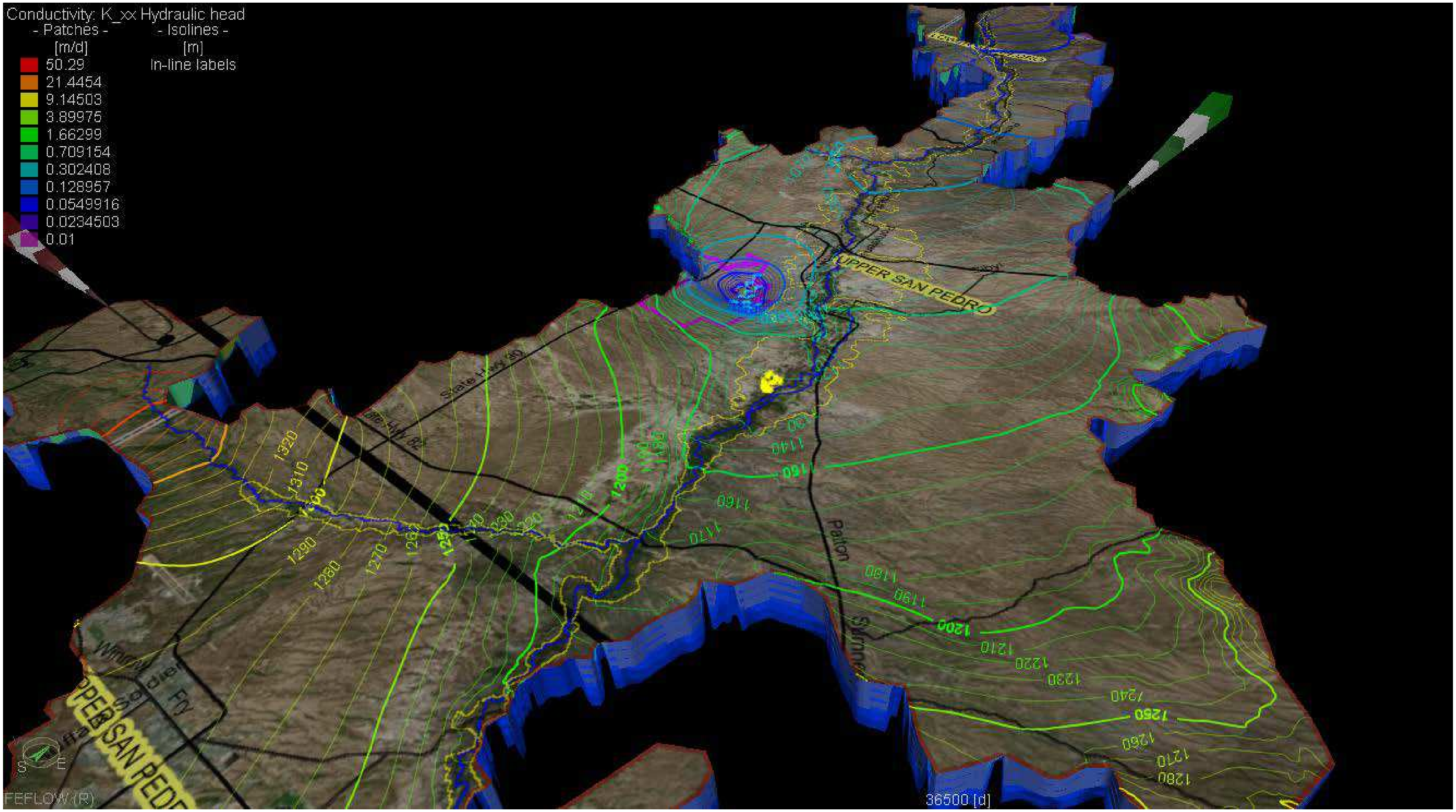

Figure 18. Simulated Groundwater Elevation Contours for Scenario 6, shown every 10 m (amsl) after 100 Years. Contours are for Layer 1 (shallow) and show the depression around the Vigneto Wells.

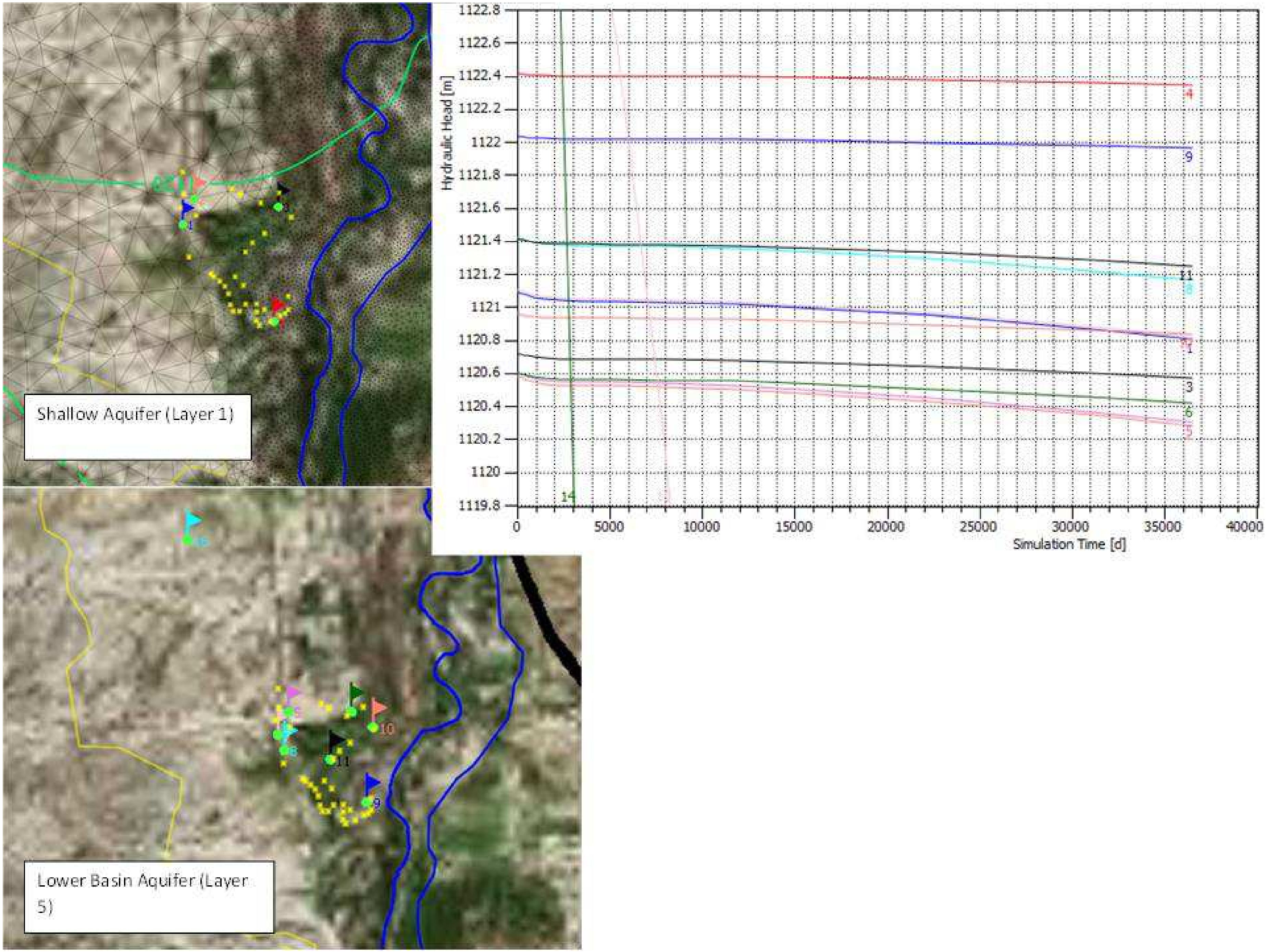

Figure 19. Simulated head (Scenario 6) for 100 years at specific model observation points (points with flags and labels in two maps on left). The numeric labels correspond to the simulated heads in the graph shown. Observation point 1 (shallow) and points 5 and 8 (deep) reflect water levels at the spring. The drawdown at these points is ~0.25 m after 100 years.

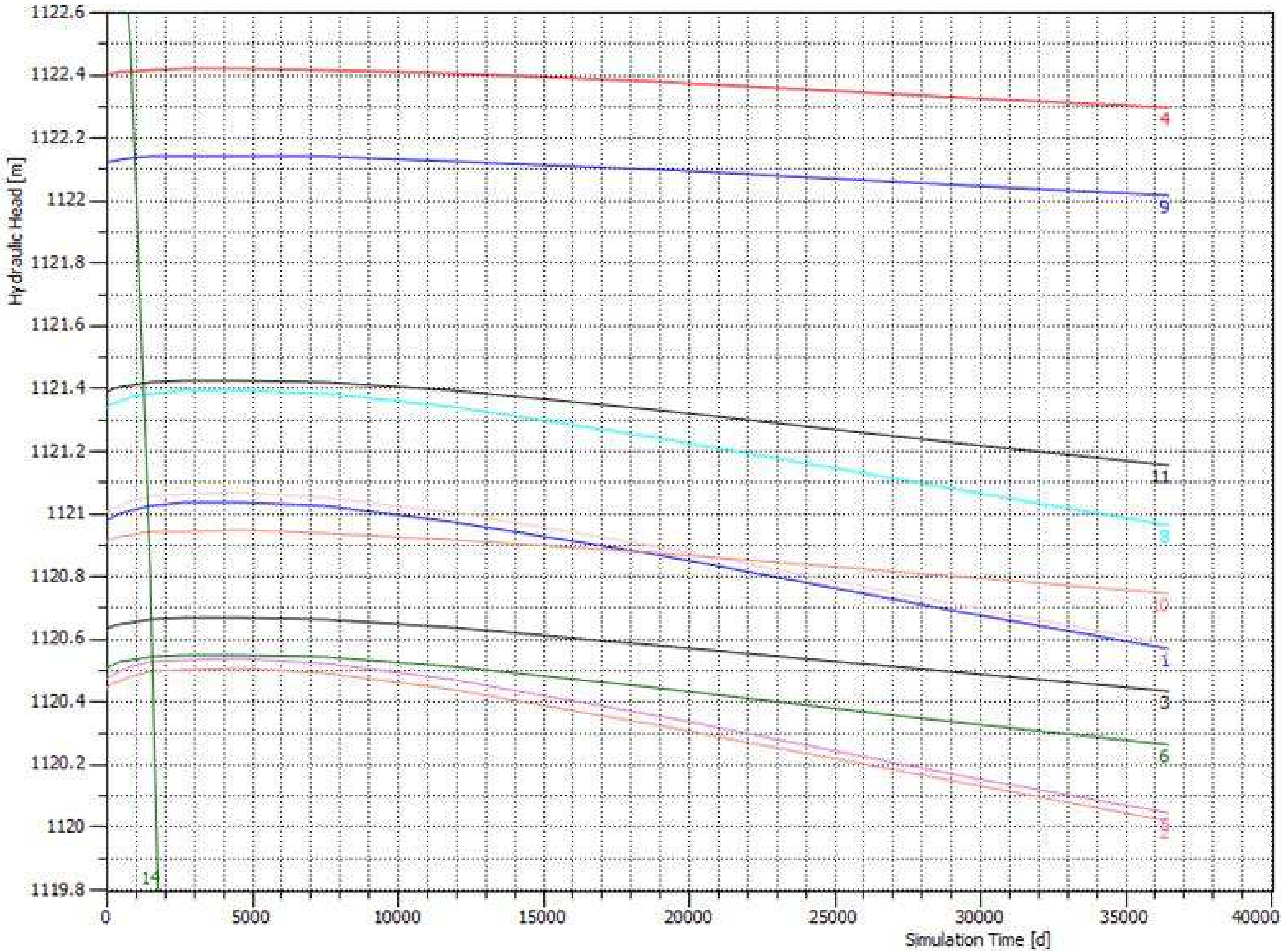

Figure 20. Simulated head beneath the Saint David Cienega (Scenario 3) over 100 years. Drawdown is highest (~0.45 m) for observation points 1 and 2 (Shallow) and points 5 and 8 (Deep), near the actual spring discharge point, or about 0.45 meters after 100 years.

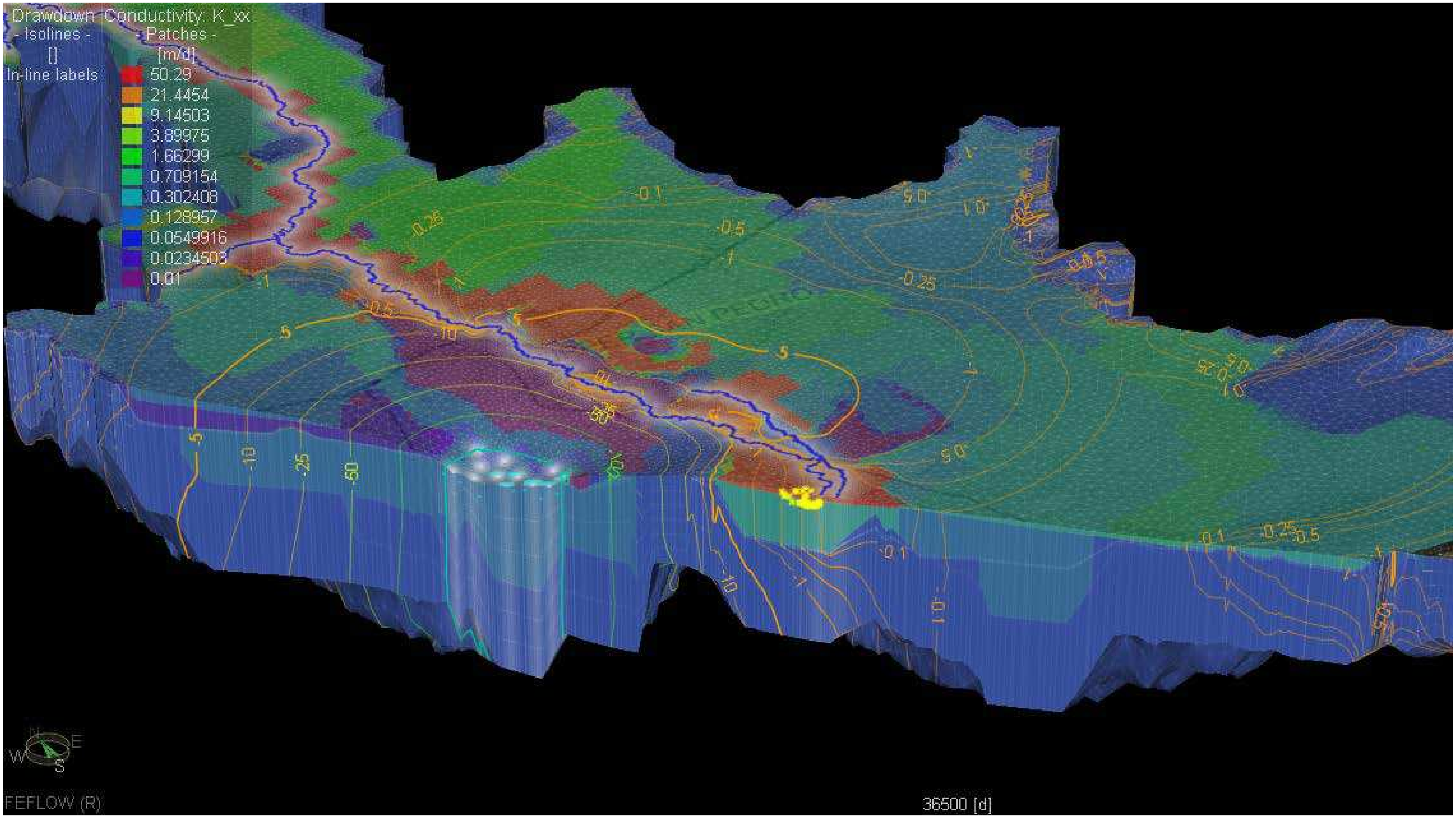

Figure 21. Simulated Drawdown (m) in cutaway through Vigneto Development (refined grid in the center) and Saint David Cienega (yellow symbols). Lowest model layer shown represents a 500 m thick weathered bedrock zone, using 0.01 m/d conductivity. Results clearly show that drawdown from Vigneto pumping is largely damped due to the higher permeability flood plain deposits, colored lighter red here, adjacent to the San Pedro River. Still, water levels beneath the Saint David Cienega area decline about 1 foot.

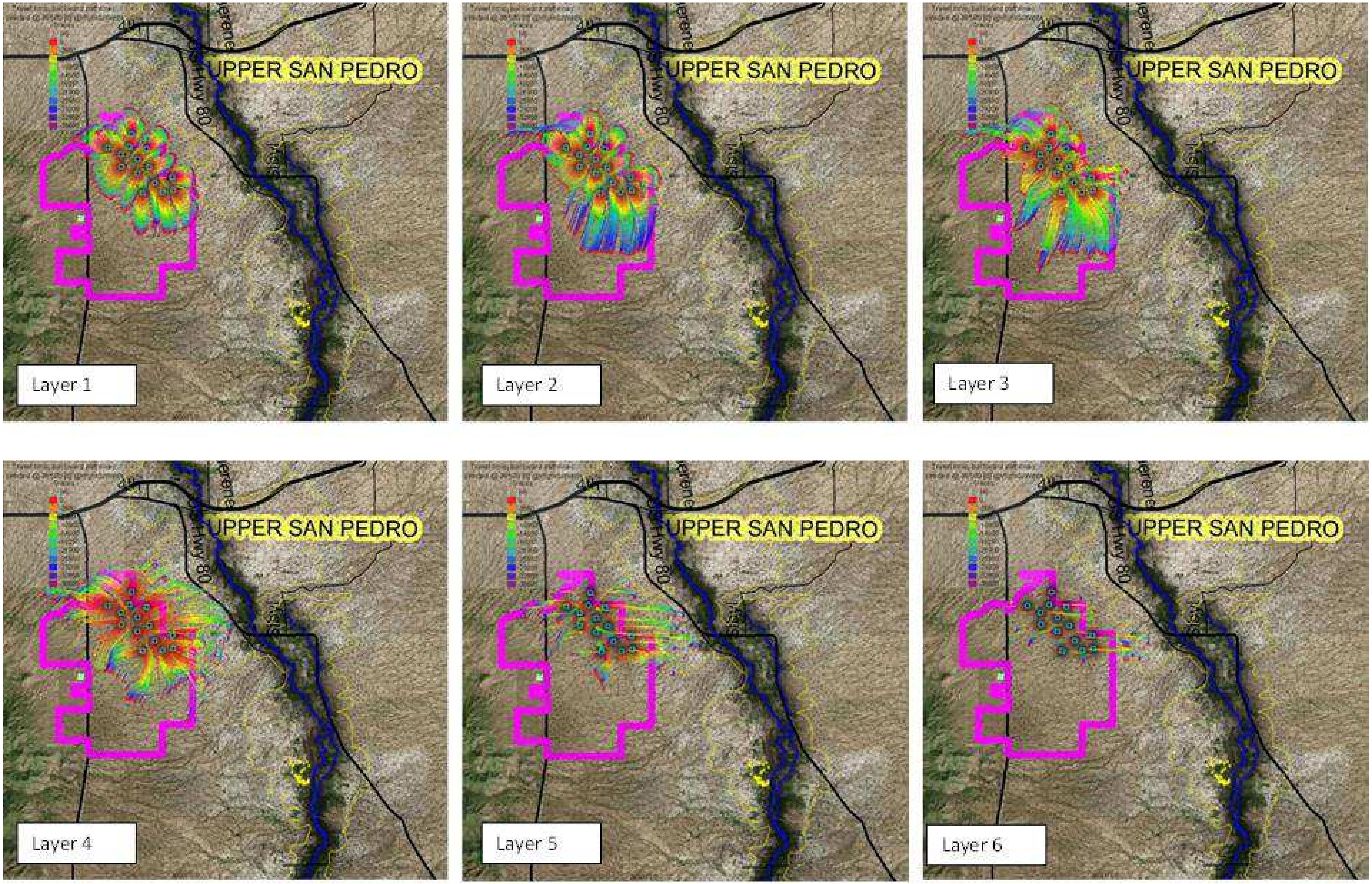

Figure 22. Reverse Pathlines (100 Yrs.), Scenario 6 by Model Layer. Layer 6 is weathered bedrock, while Layer 5 is lower basin fill material. The changes in color reflect the different age of groundwater along each individual path to Vigneto wells.

Conclusions

1) It seems clear, following this evaluation, that proposed pumping at the Vigneto Development has the potential to adversely impact spring flow within the Saint David Cienega area, by lowering the water table.
2) Noticeable impacts at the spring will likely take decades to develop, but the model shows a decline in the water table beneath the springs on the order of 0.25 to 0.45 meters after 100 years, using reasonable hydraulic properties (Scenarios 1, 2 and 5).
3) I evaluated several factors that influence the magnitude/extent of the drawdown due to the Vigneto groundwater pumping, including bedrock permeability, annual river stage and regional well pumping (as of 1997).
    a. Impacts beneath Saint David Cienega (and the northern San Pedro National Conservation Area) increases with river stage.
    b. Impacts decrease with decreasing bedrock permeability (negligible with impermeable bedrock). The likelihood of impermeable bedrock is unknown, but weathered limestone and sedimentary and even crystalline bedrock may very well contribute to the transmission of groundwater dewatering impacts beneath Saint David Cienega.
    c. Effects of regional pumping could not be assessed without further adjustments in the model (i.e., updating regional pumping, hydraulic properties within the various model layers). It is likely that the Vigneto drawdowns simply add to what is already induced by the regional pumping beneath Saint David Cienega.
4) Vigneto pumping was distributed vertically throughout the well. If it were actually to come from much lower depths, greater drawdowns may occur beneath the spring.
5) If the mountain front recharge is disrupted by Vigneto development, it could lead to greater drawdowns beneath Saint David Cienega.
6) The combined effects of climate change and probably continued increase in groundwater use in the Benson area will only add to the impact of Vigneto pumping beneath Saint David Cienega. It is also likely that drawdown from Vigneto pumping will increase loss of San Pedro River surface water into the underlying groundwater aquifer immediately east of the Vigneto development. I did not evaluate this impact, but the Feflow model could be further refined to evaluate the spatial/temporal nature of surface water loss.
7) I simulated flow conditions and effects of Vigneto pumping for 100 years, but drawdowns will continue to decline beyond this (i.e., 200 years etc), just based on continued pumping from Vigneto wells.
8) It is difficult to see how groundwater beneath Kartchner Caverns might be impacted by Vigneto pumping, as the hydrogeologic system and groundwater

flow system appears isolated and located well above the basin aquifer system. Vigneto drawdowns range from about 10 to 20 meters within the basin aquifer system, downgradient from the caverns.

Recommendations

1) Calibrate the model:
    a. Use current observation data (i.e., post 1997).
    b. Include more recent pumping (post 1997) (i.e., new wells, revised rates).
    c. Include changes in land use past decades
    d. Include changes in vegetation and ET estimates.
    e. Incorporate changes in surface water use.
    f. Incorporate all recent USGS interpreted subsurface hydrogeologic unit datasets in the area.
    g. Estimate better recharge estimates, for example using a fully integrated, fully-distributed hydrologic/hydraulic code (i.e., MIKESHE/MIKE11, GSFLOW, Hydrogeosphere etc.) to determine more appropriate long-term distributed recharge estimates for the model.
2) Once calibrated, evaluate a range of possible impacts to the Saint David Cienega, considering uncertainty in model inputs (i.e., parameter uncertainty, conceptual uncertainty – like including bedrock, data uncertainty etc.) and different possible flow configurations for the Vigneto pumping wells (i.e., different screened depths, flow rates at individual wells, lower rates etc.).