Appendix G

UPDATED GROUNDWATER MODEL

29 September 2015

Technical Memorandum

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Subject: Task 3 - Updated Groundwater Model
K/J 1344505*01

Introduction

This Technical Memorandum (TM) documents work, undertaken as part of Task 3, to setup and run the recently released version of the United States Geological Survey (USGS) model (Siade *et al,* 2014) of the Antelope Valley Groundwater Basin (AVGB or Basin) to evaluate groundwater banking alternatives for the Palmdale Regional Groundwater Recharge and Recovery Project (PRGRRP) for Palmdale Water District (PWD or the District).

Groundwater Banking Project Overview

The PRGRRP is an effort by PWD to develop a groundwater banking program utilizing new spreading grounds to recharge imported water, and potentially recycled water, to meet future water demands and improve reliability. The PRGRRP is located within the AVGB, which although arid, has been extensively used for agriculture over the past century. Due to the associated pumping, the AVGB has been in an overdraft condition (i.e., pumping greater than natural recharge) since about 1930, leading to rapidly declining groundwater levels and associated land subsidence in areas with susceptible sediment types.

In 1999, the process to adjudicate groundwater production rights in the Basin began; in 2011 the adjudication court ruled that the safe yield (equivalent to natural recharge plus return flows) of the Basin is 110,000 AFY (Siade *et al*, 2014). Although groundwater production has declined significantly from its peak in the 1950s and 1960s, it remains above safe yield. The adjudication process seeks to allocate the declared safe yield to the various groundwater producers in the Basin; this will result in groundwater producers having reduced access to groundwater resources in the future.

As a result of the adjudication process, the District is evaluating groundwater banking imported water from the State Water Project (SWP) and other sources when it is in surplus that can be recovered water when imported water is more limited. The PRGRRP water bank may also be used to store tertiary treated recycled water in combination with SPW for later recovery and use.

Antelope Valley

The AVGB covers about 920 square miles and is located at the western end of the Mojave Desert in southern California, covering parts of Kern, Los Angeles, and San Bernardino Counties (Figure 1). The Basin is topographically closed with respect to surface outlets, and was formed by alluvial deposits filling a structural depression resulting from tectonic activity in the area (Leighton and Phillips, 2003). Two dry lakes, Rosamond and Rogers Lakes, are found in the northern portion of the AVGB (Figure 1).

Faults are common and frequently act as barriers to groundwater flow. The AVGB is divided into seven groundwater subbasins largely on the basis of these faults (Durbin, 1978, Carlson *et al*, 1998). These groundwater subbasins include the Buttes, Finger Buttes, Lancaster, Neenach, North Muroc, Pearland, and West Antelope (Figure 2). The PRGRRP is located in the Lancaster subbasin near the boundary with the Buttes sub-basin (Figure 2). The Lancaster subbasin is the largest and most developed of these subbasins.

In the AVGB, the basin sediments consists of a series of unconsolidated to consolidated deposits that are in some places more than 5,000 feet thick. These deposits, based on their mode of deposition, are made up of alluvium and lacustrine sediments. The alluvium consists of unconsolidated to moderately indurated, poorly sorted gravels, sands, silts, and clays. The older deep units within the alluvium typically are more compacted and indurated than the younger shallow units (Dutcher and Worts, 1963; Durbin, 1978). The fine-grained lacustrine deposits consist of sands, silts, and clays that accumulated in a large lake or marsh that at times covered large parts of the study area. These lacustrine deposits consist primarily of thick layers of blue-green silty clay, known locally as the blue clay member, and a brown clay containing thin interbedded layers of sand and silt. Individual clay beds are as much as 100 feet thick, and the entire sequence of lacustrine deposits is as much as 300 feet thick in some areas (Dutcher and Worts, 1963).

Alluvial fans originating from the San Gabriel Mountains encroached upon the ancient lake where the lacustrine deposits were accumulating. The prograding alluvial fan deposits encroached upon the ancient lakes causing the lacustrine deposits to migrate northward over time (Durbin, 1978). The lacustrine deposits are overlain by as much as 800 feet of alluvium near Palmdale, but become progressively shallower towards the northeast (Figure 3) to where they are exposed at the land surface at Rogers Lake. The areal extent of the lacustrine deposits is not well defined, but its approximate extent is shown in Figure 2.

Durbin (1978) divided the Basin sediments into two aquifers separated by a confining unit formed of the lacustrine deposits. More recent work recognizes three aquifers: the upper, middle, and lower aquifers. The three aquifers, which were identified on the basis of hydrologic properties, age, and depth of the unconsolidated deposits, consist of gravel, sand, silt, and clay alluvial deposits and clay and silty clay lacustrine deposits (Siade *et al*, 2014).

Prior to groundwater development, groundwater recharge was primarily the infiltration of surface water runoff from the surrounding mountains. Groundwater flowed from the recharge areas to discharge areas around the dry lakes or playas where it discharged from the aquifer system as either evapotranspiration or from springs. Groundwater-level declines of more than 270 feet have occurred in portions of the AVGB due to groundwater pumping. These declines have eliminated the natural discharge. Groundwater pumping for agricultural and urban uses is now the primary source of discharge and infiltration of return flow from agricultural irrigation has become an important source of recharge to the aquifer system. Groundwater-level declines have resulted in an increase in pumping lifts, reduced well efficiency, and land subsidence of more than 6 feet in some areas (Siade *et al*, 2014).

USGS Groundwater Models

The USGS has developed three regional-scale groundwater-flow and land-subsidence models of the AVGB to better understand the aquifer system and to provide a tool to help manage the water resources of the valley. The sequence of models developed by the USGS for the AVGB includes:

- The first model was developed by Durbin (1978), referred to as AV-1978;
- the second model was developed by Leighton and Phillips (2003), referred to as AV-2003; and
- the most recent model was developed by Siade *et al* (2014), referred to as AV-2014.

Previous USGS Modeling Efforts

The original AVGB model, AV-1978 (Durbin, 1978) was developed on the basis of a simplified conceptualization of the ground-water system using a specially-developed computer code applying the Galerkin-finite-element method to simulate groundwater processes observable on a scale of several miles or greater. After calibration, AV-1978 was used to evaluate various groundwater management alternatives. Since the development of AV-1978, groundwater use in the AVGB has decreased substantially, and areas of groundwater withdrawals have changed from primarily agricultural areas to primarily urban areas (Leighton and Phillips, 2003).

Previous work for PRGRRP was based on AV-2003 (Leighton and Phillips, 2003). This model included new hydrogeological data and interpretation from USGS reports published after the completion of AV-1978. AV-2003 was developed using MODFLOW and contains a total of

2,083 active model cells, with each model cell representing one square mile. AV-2003 simulated a three-layer aquifer system with the lacustrine deposits included as low-transmissivity areas of the three layers, and faults were simulated to represent sub-basin boundaries where appropriate (Leighton and Phillips, 2003). AV-2003 included the simulation of land subsidence resulting from the large declines in groundwater head over time using the Interbed Storage (IBS) package (Leake and Prudic, 1991) that allowed for the prediction of the effect of groundwater management strategies on the future occurrence of land subsidence.

Overview of AV-2014 Model

The most recent USGS model of the AVGB, AV-2014 (Siade *et al,* 2014) updates and refines the AV-2003 model by incorporating updated hydrogeological data available since the completion of AV-2003. The goal of AV-2014 was to systematically address the uncertainty in estimates of natural recharge and related aquifer parameters by using the groundwater-flow and land-subsidence model with observational data and expert knowledge.

AV-2014 simulates groundwater conditions from 1915 to 2005. AV-2014 was calibrated to simulate steady-state conditions, represented by 1915 water levels and transient-conditions during 1915 to 2005, by using water-level and subsidence data. The start of the model period was chosen to be 1915 because groundwater pumping before this time was quite small, and so the basin was assumed to have been in steady state (Siade *et al,* 2014).

The calibrated AV-2014 model was used as the basis for developing future case scenarios to simulate the response of the aquifer to potential future pumping and aquifer recharge conditions over a 50-year period representing conditions from 2006 to 2055. These scenarios include:

- Scenario 1 - no change in the distribution of pumpage, or status quo;
- Scenario 2 - redistribution of pumpage; and
- Scenario 3 - artificial recharge.

All three of these scenarios specify a total pumpage throughout the Antelope Valley of 110,000 acre-feet per year (AFY) according to the safe yield value ruled by the Los Angeles County Superior Court of California (Siade *et al*, 2014), and agricultural and urban return flows were setup accordingly. Aquifer properties remained the same as the calibrated historical AV-2014 model. Natural recharge is uniform over the 50-year period using long-term average conditions, and specified head boundaries are held constant.

AV-2014 Model Setup

AV-2014 covers the majority of the AVGB (Figure 4) and was extended northward to include areas north of Rogers Lake. The lateral boundaries of the model domain are all no-flow (zero flux) boundaries except limited areas where specified-head boundaries were applied. One of these is located north of Rogers Lake where groundwater is allowed to flow into Fremont Valley, and the second is along the southeastern-most boundary to simulate potential groundwater exchange between AVGB and El Mirage Valley (Siade *et al,* 2014).

The areal discretization of AV-2014 was refined from the 1-mile square grid cells in the AV-2003 model to 1-kilometer (3,281 feet) square grid cells. The AV-2014 consists of 130-row by 118-column grid (Siade *et al,* 2014). The model units for length were changed from the English system (feet) in AV-2003 to the metric system (meters) in AV-2014. However, model results shown in Siade et al (2014) are reported using the English system of measurement.

Vertically, the AV-2014 aquifer system was initially divided into four layers to more accurately simulate the system dynamics throughout the Lancaster subbasin by subdividing the original model layer 1 from AV-2003 model into two layers (Figure 3). Model layer 1 in AV-2014 represents a shallow portion of the upper aquifer in the Lancaster subbasin coincident with the area of former Lake Thompson (Siade *et al,* 2014). This layer represents a confining unit, which is partially disconnected from the remainder of the upper aquifer system due to the presence of laterally extensive, shallow clay interbeds throughout the region just beneath model layer 1 (Siade *et al,* 2014).

Model layers 2 through 4 in AV-2014 are defined similarly to those in AV-2003, which are based on the conceptual model developed by Leighton and Phillips (2003). Model layer 2 of AV-2014 represents the remainder of the upper aquifer (Siade *et al,* 2014). The bottom elevation of model layer 2 is constant at 1,950 feet above sea level (ft asl), except where bedrock is higher. Model layer 3 represents the middle aquifer, and extends from the base of the upper aquifer (1,950 ft asl) to the top of the lower aquifer (1,550 ft asl) at all locations where bedrock is below 1,550 ft asl. Model layer 4 represents the lower aquifer, and extends from the base of the middle aquifer (1,550 ft asl) to the top of the basement complex, or 1,000 ft asl if the top of the basement complex is lower than this altitude. The sediments encountered beneath 1,000 ft asl usually are older continental deposits, which are assumed to yield little to no water to the groundwater-flow system (Siade *et al,* 2014).

Public water supply and agricultural well locations and pumpage rates were specified annually from 1915 through 2005. Locations of wells used previously remained the same as used in AV-2003. Locations for new public water supply and agricultural wells for 1996 through 2005, unless the specific well sites were verified in the field, were generally approximated based on land use or aerial photographs (Siade *et al,* 2014).

Recharge from to natural processes (mountain-front recharge and streambed infiltration) is simulated using the MODFLOW Recharge package (Siade *et al,* 2014). Natural recharge, applied along intermittent streams including Littlerock Creek and along the AVGB margin, averages about 30,000 AFY. Natural recharge is applied uniformly to all stress periods, meaning that there was no temporal variation in natural recharge (due to a lack of data). Similar to AV-2003, no infiltration of precipitation falling on the valley floor is assumed to occur because the reference evapotranspiration rate is much greater than the estimated average annual precipitation rate.

As described in Leighton and Phillips (2003), treated wastewater from reclamation plants is discharged to spreading ponds and is a source of artificial recharge. In AV-2014, this recharge is modeled with the MODFLOW Recharge package, with the dataset extended through 2005 (Siade *et al,* 2014).

Irrigation and urban return flows were applied using the UZF1 package (Niswonger and others, 2006) to simulate delays associated with travel time through the unsaturated zone. Irrigation return flows from 1915 to 2005 were estimated based on an assumption of 30 percent of the agricultural pumpage, which is the same assumption as used in AV-2003, in the model cell that include agricultural pumpage (Siade *et al,* 2014). Urban return flows resulting from landscape irrigation and septic effluent were not simulated in the AV-2003 model, but are included in AV-2014. An urban return flow rate of 7.2 inches per year was applied to urban areas (Siade *et al,* 2014). The use of UZF1 package replaces the 10-year delay assumption used in AV-2003 with a modeled process that accounts for hydraulic properties, time-varying annual recharge rate, and time-varying depth to groundwater.

AV-2014 utilizes updated versions and capabilities developed by the USGS for MODFLOW since the completion of AV-2003. These updated capabilities include:

- AV-2014 was developed using MODFLOW-NWT, which employs a Newton solver (Niswonger and others, 2011) with enhanced stability when simulating complex systems containing model cells that become dry or wet. AV-2003 was developed using MODFLOW-88 (McDonald and Harbaugh, 1988).

- Land subsidence was simulated using the MODFLOW Subsidence (SUB) package (Hoffman *et al*, 2003), which improves upon the IBS package (Leake and Prudic, 1991) through the addition to simulating the delayed dewatering of the thicker fine-grained interbeds in addition to instantaneous dewatering of the relatively thin fine-grained interbeds.

- Groundwater pumping from wells was simulated using the MODFLOW Multi-Node Well (MNW) Package (Halford and Hanson, 2002) to provide the capability to simulate wells with long screen intervals across multiple aquifers. The MNW package dynamically distributes flow between nodes under pumping, recharging, or unpumped conditions.

- Flow of agricultural and urban return flows through the unsaturated zone was simulated using the MODFLOW Unsaturated Zone Flow (UZF1) package (Niswonger *et al*, 2006) as one-dimensional vertical flow through the unsaturated simulated with a kinematic wave approximation of Richard's equation.

USGS Model Setup

Previous modeling work for the PRGRRP was based on local-scale models derived from AV-2003. With the release of AV-2014 (Siade *et al*, 2014), subsequent modeling for the PRGRRP will be based on local-scale models derived from AV-2014 to take advantage of additional data, expanded hydrogeological understanding of the AVGB, improved calibration procedures, and updated MODFLOW capabilities.

Approach

To evaluate operational scenarios for the PRGRRP, a local scale model was developed based on AV-2014. The local-scale model was developed based on the AV-2014 Scenario 1. For convenience, the model was setup to run using Groundwater Vistas 6 (GWV 6), a graphical user interface for the MODFLOW family of groundwater modeling computer programs (ESI, 2011). The primary steps in the development of the new local-scale model include:

- Convert the historical AV-2014 model parameters from meters to feet and verify that input model parameters are input consistently with those reported by Siade et al (2014)

- Run the historical AV-2014 model to verify that the results match the published results in Siade et al (2014) for groundwater levels and land subsidence over time.

- Run the AV-2014 Scenario 1 to verify that the results match the published results in Siade et al (2014) for groundwater levels and land subsidence over time.

- Develop the local-scale model for the PRGRRP site using the telescopic mesh refinement (TMR) feature of GWV 6 (ESI, 2011).

- Apply appropriate initial conditions to represent 2015 groundwater conditions based on the results of Scenario 1.

The overall objective for the reproducing the historical AV-2014 model and Scenario 1 was verify that our version of the model was reproducing the results published in Siade *et al* (2014) for groundwater levels and land subsidence over time. The local scale-model was derived from Scenario 1. Scenario 1 is a base case scenario that assumes total pumpage within the AVGB of 110,000 AFY conforms to the safe yield value ruled by the Los Angeles County Superior Court of California (Siade *et al*, 2014). Scenario 1 provides a peer-reviewed future case scenario for AVGB groundwater conditions from 2005 to 2055. Scenario 1 is considered the most appropriate model for basing an assessment groundwater conditions associated with the PRGRRP.

AV-2014 Regional Model Conversion

The original USGS MODFLOW files for the AV-2014 historical model and Scenario 1 were downloaded from the USGS web site (http://pubs.usgs.gov/sir/2014/5166/). The files were reviewed for completeness.

The initial step was to convert model units for length back from metric (meters) to the English system (feet). This was done because model input for the PRGRRP project from surveyed locations, recharge and pumping volumes are determined using the English system, and results were expected to be presented using the English system. Therefore, it was considered more straightforward to perform the unit conversion during the model setup rather than continually performing conversion on input and results for each subsequent model use.

The MODFLOW file structure provides an input location for conversion factors for unit conversion. In this case, the units were converted from meters to feet using a conversion factor of 3.28084 feet equals one meter. All input parameters were systematically reviewed to identify input parameters that included a unit of length requiring the application of a conversion factor to be converted to feet. Conversion factors were applied to:

- Model structure parameters including grid spacing and model layer elevations
- Aquifer properties including hydraulic conductivity and specific storage
- Specified head boundaries
- Recharge and evapotranspiration rates
- Fault and drain conductance values
- Specified well pumping volumes and physical well parameters
- Subsidence parameters for preconsolidation head, starting head, vertical hydraulic conductivity, elastic and inelastic specific storage and interbed thickness

- Solver convergence criteria
- Initial groundwater elevations

The converted MODFLOW input files were read using the GWV 6 processor for file management. There are some limitations in using GWV 6 that required some additional work. GWV 6 does not read the fault data, so the faults were hand digitized and input parameters were added. GWV 6 produced an error in writing the MODFLOW Subsidence (SUB) package file. This was resolved by developing a separate MODFLOW Subsidence package input file from the USGS input file and copying that into the appropriate subdirectory for the model run. GWV 6 has a limitation in utilizing the MODFLOW Unsaturated Zone (UZF1) file. The USGS applied UZF1 only for return flows but not natural recharge and evapotranspiration; however, GWV 6 does not allow for that portioning. This was not resolved using GWV 6, so the return flows were added to the MODFLOW recharge package similar to how they were applied in AV-2003.

All input data and model results were compared the published results to verify that the converted model was working properly. Through this comparison process, however, an error was found in the MODFLOW Multi-Node Well (MNW) input file through comparison of the published water budget data. After review, it was found that this was the result of a formatting error in the posted USGS version of the MNW package that caused a portion of the well input data not to be read correctly. The error was identified and corrected so that the MNW package performed properly and the appropriate well pumpage data in the water balance matched the published data.

After completion of this process, the final results of the converted historical AV-2014 model were compared to the published results presented in Siade *et al* (2014) and were found to be in good agreement. Following conversion of the historical AV-2014 Model, AV-2014 Scenario 1 was converted using the same methods and procedures. After completion of the conversion process, the final results of the converted AV-2014 Scenario 1 were in good agreement with the published results presented in Siade *et al* (2014).

Local-scale PRGRRP Model Development

The local-scale PRGRRP Model is derived from the USGS AV-2014 Scenario 1 that simulates future AVGB groundwater conditions from 2005 to 2055. Scenario 1 assumes uniform groundwater pumping of 110,000 AFY, and agricultural and urban return flows are set up accordingly. Natural recharge is uniform over the 50-year period using long-term average conditions, and specified head boundaries are held constant.

Local Scale Model Setup

The regional-scale AV-2014 model (Siade *et al*, 2014) is not designed to investigate local-scale changes in groundwater elevations due to the coarse grid size of the finite-difference model grid consisting of one-kilometer square cells. The local-scale model was developed for the PRGRRP site using the telescopic mesh refinement (TMR) feature of GWV 6 (ESI, 2011). The local-scale model was developed for a 110 square mile area centered on the PRGRRP site (Figure 4) using a uniform grid spacing of 164 feet by 164 feet. The local-scale model grid is composed on 300 rows and 380 columns. This grid spacing increases the resolution of the single one-kilometer grid cell in AV-2014 Scenario 1 into 400 grid cells. This increase in grid resolution provides the capability to evaluate local groundwater mounding and drawdown effects resulting for PRGRRP operations.

The PRGRRP site is located in the bottom central portion of the local scale model domain (Figure 4). The model domain was setup to evaluate recharge and recovery operations at the PRGRRP site based on current design layout planned for the site (Figure 5). It covers a portion of the Buttes and Lancaster Subbasins (Figure 6). To the south and east, the local model grid reaches noflow or restricted flow conditions to form a natural boundary. To the north and west, the model domain was extended sufficiently to minimize boundary constraints.

Boundary Conditions

To represent the regional groundwater flow conditions from AV-2014 Scenario 1 onto the local-scale model, the TMR process assigns constant head boundaries along the lateral boundaries of the local-scale model domain that are derived directly from the regional model (Figure 6). The specified groundwater elevations were assigned to these boundaries for each model stress period so that they capture the regional changes over time.

Groundwater pumping from wells was converted directly from AV-2014 Scenario 1. However, the increased resolution from the TMR refinement converts that single cell into 400 cells. It is assumed that the AV-2014 Scenario 1 grid cells with larger assigned pumping volumes represent multiple wells. Therefore, grid cells with total assigned pumping greater than 575 AFY were split into 4 wells in the local scale model, and all four wells are located within the area of the original one-kilometer square cell. Grid cells with less than 575 AFY were assigned to a single cell in the local scale model. Within the local scale model, a total pumpage of 35,785 AFY is assigned. Wells are assigned using the GWV 6 analytical element (AEM) feature (ESI, 2011), which is comparable to the MODFLOW MNW package, for convenience. The distribution of wells is shown on Figure 6.

Natural recharge, agricultural and urban return flows and other applied water are derived directly from AV-2014 Scenario 1. Since these are applied as a rate that the model distributes over the designated area rather than a volume, no conversion was necessary. The total recharge from these sources within the local-scale model domain is approximately 14,600 AFY.

Aquifer Properties

Hydraulic conductivity (K) is a physical parameter that defines how water will move through the aquifer. K can vary within the aquifer due to condition of the original deposition of the sediments. Consequently, in the typical alluvial setting, the horizontal hydraulic conductivity (K_h) is substantially higher than the vertical hydraulic conductivity (K_v).

Storage parameters define how much groundwater is released from an aquifer in response to a change in groundwater elevation. There are two main storage parameters, specific yield (S_y) and specific storage (S_s). S_y represents the volume of water released by a unit volume of aquifer material through the pore drainage, and is typically represents the effective porosity of the sediments. S_s represents the volume of water released as a result of expansion of the pressurized groundwater and/or change in the aquifer compaction. S_s is vertically integrated over the aquifer thickness and expressed as storativity, S. Typically, S_y is much larger than S_s. S_y is the dominant storage parameter in an unconfined aquifer whereas S_s is dominant in a confined aquifer.

Within Model Layer 2, where the PRGRRP recharge and recovery operations take place, four different aquifer property zones from the original AV-2014 model are located (Figure 7). A summary of the aquifer properties for these Model Layer 2 zones are summarized below:

- Zone 1 - K_h = 6.3 feet per day (ft/d) , K_v = 0.029 ft/d , S_s = 0.000001 1/feet , S_y = 0.164
- Zone 2 - K_h = 9.9 ft/d , K_v = 0.0012 ft/d , S_s = 0.000001 1/feet , S_y = 0.178
- Zone 3 - K_h = 10.6 ft/d , K_v = 0.069 ft/d , S_s = 0.000001 1/feet , S_y = 0.153
- Zone 4 - K_h = 77.1 ft/d , K_v = 0.0058 ft/d , S_s = 0.000001 1/feet , S_y = 0.175

Subsidence Properties

Land subsidence is the gradual compaction of susceptible aquifer systems that can accompany groundwater-level declines caused by groundwater overdraft (Galloway and others, 1999). This occurs when groundwater pressures are removed from susceptible sediments, typically poorly-consolidated fine-grained silts and clay layers. Subsidence represents a one-time release of water from these fine-grained layers. Once the groundwater pressure is removed, the sediments realign into a denser packing arrangement, causing these sediments to permanently compact resulting in a loss of aquifer volume that is manifested as a lowering of the ground surface elevation. Subsidence is a progressive mechanism in that as groundwater levels decline additional subsidence is possible; however, if groundwater levels rise, then the mechanism for subsidence is removed.

In the AVGB, poorly-compacted lacustrine deposits have the potential for compaction leading to permanent subsidence. These deposits consist primarily of fine-grained interbeds within the aquifer that can be tens of feet thick. Multiple interbeds can lead to a total interbed thickness greater than 100 feet.

The MODFLOW Subsidence (SUB) Package (Hoffman *et al*, 2003) simulates elastic (recoverable) compaction and expansion, and inelastic (permanent) compaction of compressible fine-grained beds (interbeds) within the aquifers. The SUB Package supersedes the Interbed Storage Package (IBS1) which was used in AV-2003. The primary change is the SUB package accounts for delayed release of water from storage or uptake of water into storage in the interbeds.

For the nodelay interbeds, parameters assigned to define subsidence include: S_{fe} is the elastic (recoverable) skeletal storage coefficient, and S_{fv} is the inelastic (permanent) skeletal storage coefficient. In the local-scale model, these parameters are derived directly from AV-2014. In AV-2014, no-delay parameters were assigned to Model Layers 1 and 2; however, the area of susceptible sediments in Model Layer 1 is outside the local scale model domain, so are all zero. The distribution of the no-delay beds is shown on Figure 8. The distribution was interpolated from the larger one-kilometer grid spacing to the denser local grid spacing. The no-delay subsidence parameters applied in the local scale model include:

- In Model Layer 2, S_{fe} varies from 4.0×10^{-5} to 1.4×10^{-4} (dimensionless) and S_{fv} varies from 1.0×10^{-2} to 3.6×10^{-2} (dimensionless).

For the delay interbeds, slightly different parameters are assigned. S_{se} is the elastic (recoverable) specific storage (1/feet), S_{si} is the inelastic (permanent) specific storage (1/feet), and K_{vi}.is the vertical hydraulic conductivity of the interbeds. In AV-2014, delay parameters were assigned to Model Layers 2 and 3.

- In Model Layer 2, S_{se} is 1.7×10^{-6} (1/feet), S_{si} is 3.3×10^{-4} (1/feet), and K_{vi} is 1.3×10^{-5} (ft/d).

- In Model Layer 3, S_{se} is 1.3×10^{-6} (1/feet), S_{si} is 7.6×10^{-4} (1/feet), and K_{vi} is 1.9×10^{-5} (ft/d).

In addition to the physical parameters, an additional parameter required for land subsidence modeling is the preconsolidation head. This is the lowest groundwater head elevation that has been reached historically in an aquifer. If the groundwater head falls below this level, irreversible aquifer compaction can occur. The delay interbeds also requires a starting head input reflecting groundwater levels in the interbeds at the start of the simulation. Both the preconsolidation and starting head are tracked within MODFLOW. Therefore, the preconsolidation and starting head is derived directly from AV-2014 Scenario 1 input files that reflects the cumulative effect from the historical AV-2014 model.

PRGRRP Operational Model Setup

The layout of the PRGRRP facility used for these simulations from Figure 5 is shown in context with the model domain in Figure 9. The recharge facilities consist of four recharge basins laid out in a rectangle covering about 80 acres. Sixteen recovery wells are laid out along a rectangle of about 1.5 miles on a side using a well spacing of approximately 2,000 feet. The wells are laid out along existing roads with 95th Street East on the west, East Avenue K-8 on the north, 110th Street east on the east and East Avenue M on the south (Figure 5).

The PRGRRP Operational Model was setup to represent the 10-year hypothetical recharge and recovery (extraction) cycle as ten one-year time steps. AV-2014 Scenario 1 simulates a 50-year period starting from the end of the historical model cycle in 2005 through 2055. To represent groundwater conditions in 2015, initial conditions were derived to represent Simulation Year 10 in AV-2014 Scenario 1. The initial groundwater elevations (Figure 10) and MODFLOW SUB package preconsolidation and starting heads are generated from the MODFLOW results from AV-2014 Scenario 1. Constant head elevations applied to the local-scale model boundaries are derived from Simulation Years 11 to 20 in AV-2014 Scenario 1 to represent conditions from 2015 to 2024. Groundwater pumping and recharge are kept constant throughout AV-2014 Scenario, and these rates are retained in the PRGRRP Operational Model. Using these initial conditions provides an appropriate representation of current conditions in the PRGRRP area to assess groundwater conditions and potential for subsidence in the project area.

The general groundwater flow direction across most of the PRGRRP site is towards the northwest (Figure 10). Local depressions are the result of groundwater pumping from wells. Steeper hydraulic gradients in the Butte Subbasin reflect lower transmissivities than in the Lancaster Subbasin. The PRGRRP site is located in the Lancaster Subbasin where transmissivities are relatively higher.

Travel time from the PRGRRP recharge ponds to the recovery was estimated using the MODFLOW model and the particle tracking code by MODPATH (Pollack 1994). Particles were placed around the perimeter of the recharge basins. MODPATH uses the groundwater velocities calculated by MODFLOW to estimate the potential travel time through the aquifer by tracking the paths of these particles.

PRGRRP Operational Scenarios

The goal of the PRGRRP is to store water in the aquifer of the project area and to later extract it when the need arises. One of the expected results of this activity is that groundwater elevations will rise and fall in the course of regular project operations. Therefore, it is important to understand the effect of project operations on groundwater conditions and potential for subsidence in the project area. This section presents the setup and results of the operational scenario simulations for the PRGRRP utilizing the updated local-scale model derived from AV-2014, the most recent version of the USGS model (Siade *et al,* 2014).

Operational Scenario Setup

The operation of the PRGRRP is subject to a series of criteria:

- Shallow groundwater not to form a mound as a result of artificial recharge that rises to within 50 feet of the ground surface.
- Extraction well field(s) not to generate groundwater drawdowns which will locally dewater the shallow aquifer and/or lead to appreciable land subsidence.
- Recharged water travel times in groundwater not to be less than one year between the recharge basin and associated extraction well network.

To evaluate these criteria a series of operational scenarios were developed. A Base Case and four PRGRRP operational scenarios were developed using the local-scale PRGRRP model to assess the effects of PRGRRP operations on local groundwater conditions and the potential for subsidence. Scenario 1 includes the proposed operational method by PWD, and Scenarios 2 through 4 assess PWD operations along with additional of recharge and recovery by a partner agency.

The operational scenarios were setup using a 10-year hypothetical recharge and recovery (extraction) cycle during which recharge and recovery rates were varied. The annual simulated volumes of water recharged to and extracted from the PRGRRP for each operational scenario are shown in Table 1 through 4. Groundwater recharge was simulated to occur at the water table at a constant rate for years 1 - 5 and 10. Years 6 - 9 represent drought years with limited recharge water available and higher groundwater.

The scenarios assess PWD operations at PRGRRP along with additional scenarios to assess the effects of adding a Partner Agency into the project. A Partner Agency may provide potential financial and engineering benefits. These scenarios provide an initial assessment of the viability of adding a Partner Agency with respect to the effects on groundwater conditions and potential for subsidence in the project area. The scenarios developed for this assessment include:

- Base Case Scenario – No PRGRRP operations are included in the Base Case. This scenario provides a comparison to assess potential background influences occurring in the vicinity that may be reflected in the model results.

- Scenario 1 – Includes only PWD activities at PRGRRP. Recharge water includes recycled water at an annual 6,536 AFY, and a variable schedule of PWD recharge water from SWP that totals 77,692 acre-feet over the 10-years. PWD extraction is a uniform rate of 13,090 AFY for all 10 years (Table 1).

- Scenario 2 – adds 67,640 acre-feet of Partner Agency recharge and recovery to the existing PWD operations. All the conditions of Scenario 1 are included, plus a variable schedule of Partner Agency recharge water from SWP that totals 67,642 acre-feet during Years 1 - 5 and 10, and extraction of 67,640 acre-feet during Years 6 - 9 (Table 2).

- Scenario 3 – adds 80,000 acre-feet of Partner Agency recharge and recovery to the existing PWD operations. All the conditions of Scenario 1 are included, plus a variable schedule of Partner Agency recharge water from SWP that totals 80,000 acre-feet during Years 1 - 5 and 10, and extraction of 80,000 acre-feet during Years 6 - 9 (Table 3).

- Scenario 4 – adds 100,000 acre-feet of Partner Agency recharge and recovery to the existing PWD operations. All the conditions of Scenario 1 are included, plus a variable schedule of Partner Agency recharge water from SWP that totals 100,000 acre-feet during Years 1 - 5 and 10, and extraction of 100,000 acre-feet during Years 6 - 9 (Table 4).

Operational Scenario Groundwater Results

Figure 11 provides hydrographs of groundwater elevations over time for four key locations to evaluate the results of the 10-year PRGRRP operational scenarios. The locations were selected to represent conditions both near the recharge basins and at the recovery wells. These locations are shown on Figure 5 and include:

- Recovery Well 2 (RC-2) located in the southern line of wells located along East Avenue M.

- Recovery Well 7 (RC-7) located in the western line of wells along 95th Street East.

- Recovery Well 11 (RC-11) located in the northern line of wells along East Avenue K-8.
- Location adjacent to the west margin of recharge basins.

The results of the Base Case Scenario on Figure 11 show level that there are no significant background conditions influencing the results. The relative change in groundwater elevations for the Base Case Scenario relative to the operational scenarios is insignificant; therefore, no filtering of background conditions is necessary for evaluating the operational scenario results. Depths to groundwater, based on the simulated Base Scenario groundwater elevations, range from 290 to 320 feet below ground surface.

For the operational scenario, recharge volumes during Scenario Years 1 through 5 greatly exceed extraction volumes, so there is a net increase in groundwater levels over this period, reaching a maximum mounding effect during Scenario Year 5. During Scenario Years 6 through 9, groundwater levels decline because extraction volumes exceed recharge volumes, reaching a maximum drawdown in Scenario Year 9. Scenario Year 10 is a switch back to higher recharge and less extraction, that lead to an increase or recovery of groundwater levels. Since Scenarios 1 and 4 represent the end members, the following discussion will focus on these two scenarios, and the results for Scenarios 2 and 3 would be intermediate to these two scenarios.

Scenario 1 represents PRGRRP operations with only recharge and recovery by PWD. Therefore, this Scenario has the smallest recharge and recovery rates and represents the potential minimum effects of PRGRRP operations. For Scenario 1, Figures 12, 13 and 14 provide maps to summarize groundwater conditions.

Figure 12 shows the change in groundwater levels for Scenario 1 during the period of maximum mounding during Scenario Year 5. Mounding ranges from a maximum of about 40 feet underneath the recharge basin to between 10 and 20 at the recovery wells. The recovery wells are operating during this time, but at a rate less than the recharge operations. The effects of the mounding extend about one mile from the PRGRRP.

Figure 13 shows the change in groundwater levels for Scenario 1 during the period of maximum drawdown during Scenario Year 9. Drawdown ranges from a maximum of about 30 feet near the recovery wells along the southern perimeter, to 20 feet beneath the recharge basins, to between 10 and 20 feet in the recovery wells along the northern and western perimeter. The recharge basins are operating during this time, but at a rate less than the extraction.

Figure 14 shows the flowpath analysis from MODPATH for Scenario 1. The flowpaths are for each representative particle is shown as a green line. The distance between arrowheads along this line represents one year of travel within the aquifer. Travel times are posted next to the arrows in days. The minimum travel time for recharge water to reach a recovery well is about two years to RC-8 and RC-9 along the northern perimeter (see also Figure 5). Some flowpaths extend beyond the perimeter of recovery wells along the northern boundary for Scenario Years 1 – 5, but these flowpaths turn back towards the recovery wells in Scenario Years 6 – 9 when recharge is less. Maximum travel times are to wells along the southern perimeter on the order of about 5 to 6 years.

Scenario 4 represents PRGRRP operations that include recharge and recovery by PWD and 100,000 AFY by a Partner Agency. Therefore, this Scenario has the largest recharge and recovery rates and represents the potential maximum effects of PRGRRP operations. For Scenario 4, Figures 15, 16 and 17 provide maps to summarize groundwater conditions.

Figure 15 shows the change in groundwater levels for Scenario 4 during the period of maximum mounding during Scenario Year 5. Mounding ranges from a maximum of about 100 feet underneath the recharge basin to between 47 to 58 feet at the recovery wells. Since the depth to groundwater at the start of the scenario ranged from 290 to 320 feet in the PRGRRP area, the depth to groundwater at maximum mounding is still on the order of 200 to 250 feet below ground surface. The effects of the mounding extend two miles or more from the PRGRRP.

Figure 16 shows the change in groundwater levels for Scenario 4 during the period of maximum drawdown during Scenario Year 9. Drawdown ranges from a maximum of about 60 to 70 feet near the recovery wells along the southern perimeter, to 30 feet beneath the recharge basins, to between 30 and 40 feet in the recovery wells along the northern and western perimeter. The recharge basins are operating during this time, but at a rate less than the extraction. More significant drawdown occurs along the southern perimeter due to the influence for lower hydraulic conductivity sediments in the adjacent Butte Subbasin.

Figure 17 shows the flowpath analysis from MODPATH for Scenario 4. The minimum travel time for recharge water to reach a recovery well is about 1.5 years to RC-8 and RC-9 along the northern perimeter (see also Figure 5). The northern flowpaths extend beyond the perimeter of recovery wells for Scenario Years 1 – 5, but these flowpaths turn back towards the recovery wells in Scenario Years 6 – 9 when pumping is increased due to meet the projected Partner Agency demands. Maximum travel times are to wells along the southern perimeter on the order of about 3 to 4 years.

Operational Scenario Subsidence Results

As shown, the operations of the PRGRRP cause the groundwater elevations to rise and fall in response to recharge and recovery activities. Because of the presence of potentially susceptible sediments to subsidence in the PRGRRP area, it is important to understand the effect of project operations on the occurrence of subsidence in the project area.

The results for the PRGRRP operational scenarios using the updated model based on AV-2014 do not show that any additional subsidence would occur. The changes in groundwater levels in response to the range of operations evaluated by the scenarios do not fall below the critical head; therefore, no additional subsidence is indicated by MODFLOW.

Previous modeling efforts for the PRGRRP project based on the AV-2003 model had indicated the potential for subsidence. The no-delay subsidence properties are essentially the same in AV-2014 as in AV-2003. However, delay subsidence properties were added. The primary changes as a result of updating the model to AV-2014 are the aquifer properties and the preconsolidation head.

The preconsolidation heads used in AV-2014 also better capture the lowest historical groundwater elevations than for AV-2003. These values are generated by MODFLOW and carried forward into the scenarios.

In AV-2014, the aquifer properties for hydraulic conductivity and storage developed during the conceptualization and recalibration of AV-2014 are significantly higher than those in AV-2003 based on a review of local data and calibration to groundwater levels. The increased aquifer properties dampen the groundwater mounding and drawdown from PRGRRP operations so that they do not exceed the preconsolidation head. A review of tests shown on well logs for private wells in the vicinity of the PRGRRP show a range of specific capacities between 15 to 50 gallons per minute per foot of drawdown (gpm/ft). This is consistent with an estimated 20 gpm/ft of drawdown based on the aquifer properties in the model. Therefore, the increased aquifer properties in AV-2014 appear more consistent with field data.

The initial groundwater elevations for the model are more representative of the current groundwater levels which are higher than the lowest historical groundwater elevations. Therefore, there is more operational capacity for change in groundwater levels prior to initiation of conditions that may potentially lead to subsidence.

Because of these factors, the updated AV-2014 based PRGRRP operational scenarios do not indicate that initiation of subsidence due to PRGRRP operations.

Summary and Conclusions

This technical memorandum describes the development of an updated model of the PRGRRP based on the most recent version of the MODFLOW model for the AVGB (AV-2014) developed by Siade *et al* (2014). With respect to the operational criteria to be evaluated with the operational scenarios, the following conclusions were observed:

(1) Groundwater mounding resulting from recharge operations at the PRGRRP stay well below the criteria of 50 feet of the ground surface. At maximum mounding, groundwater levels are still on the order of 200 to 250 feet below ground surface

(2) Drawdowns resulting from recovery operations at the PRGRRP do not locally dewater the shallow aquifer and/or lead to appreciable land subsidence. At maximum drawdown, groundwater levels are about 30 to 70 feet lower relative to starting groundwater levels. The MODFLOW analysis did not indicate than these drawdowns would initiate additional subsidence in the project area.

(3) The MODPATH analysis found that the minimum groundwater travel times between the recharge basin and associated extraction well network was about 1.5 years to wells along the northern perimeter, and were about 3 to 4 years to wells along the southern perimeter.

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Table List

Figure List

15. Scenario 4 – Change in Groundwater Levels after 5 Years (maximum mounding)

16. Scenario 4 – Change in Groundwater Levels after 9 Years (maximum drawdown)

17. Scenario 4 – Flowpaths with Travel Times over 10 years of Operations

Table 1 - Scenario 1 recharge and recovery rates for PWD Activities Only

Year	Recharge, AF				Recovery, AF			Allocation	SWP Allot (%)
	RW	SWP - PWD	SWP - Partners	Total	PWD	Partners	Total		
1	6,536	12,111	0	18,647	13,090	0	13,090	Normal	74%
2	6,536	12,111	0	18,647	13,090	0	13,090	Normal	74%
3	6,536	15,005	0	21,541	13,090	0	13,090	Normal	85%
4	6,536	12,111	0	18,647	13,090	0	13,090	Wet	74%
5	6,536	12,111	0	18,647	13,090	0	13,090	Normal	74%
6	6,536	533	0	7,069	13,090	0	13,090	Dry	31%
7	6,536	533	0	7,069	13,090	0	13,090	Dry	31%
8	6,536	533	0	7,069	13,090	0	13,090	Dry	31%
9	6,536	533	0	7,069	13,090	0	13,090	Dry	31%
10	6,536	12,111	0	18,647	13,090	0	13,090	Normal	74%
TOTAL	**65,360**	**77,692**	**0**	**143,052**	**130,900**	**0**	**130,900**		

Table 2 - Scenario 2 recharge and recovery rates for PWD plus Partners at 67,640 AF

Year	Recharge, AF				Recovery, AF			Allocation	SWP Allot (%)
	RW	SWP - PWD	SWP - Partners	Total	PWD	Partners	Total		
1	6,536	12,111	10,737	29,384	13,090	0	13,090	Normal	74%
2	6,536	12,111	10,737	29,384	13,090	0	13,090	Normal	74%
3	6,536	15,005	10,737	32,278	13,090	0	13,090	Normal	85%
4	6,536	12,111	13,957	32,604	13,090	0	13,090	Wet	74%
5	6,536	12,111	10,737	29,384	13,090	0	13,090	Normal	74%
6	6,536	533	0	7,069	13,090	16,910	30,000	Dry	31%
7	6,536	533	0	7,069	13,090	16,910	30,000	Dry	31%
8	6,536	533	0	7,069	13,090	16,910	30,000	Dry	31%
9	6,536	533	0	7,069	13,090	16,910	30,000	Dry	31%
10	6,536	12,111	10,737	29,384	13,090	0	13,090	Normal	74%
TOTAL	**65,360**	**77,692**	**67,642**	**210,694**	**130,900**	**67,640**	**198,540**		

Table 3 - Scenario 3 recharge and recovery rates for PWD plus Partners at 80,000 AF

Year	Recharge, AF				Recovery, AF				
	RW	SWP - PWD	SWP - Partners	Total	PWD	Partners	Total	Allocation	SWP Allot (%)
1	6,536	12,111	12,797	31,444	13,090	0	13,090	Normal	74%
2	6,536	12,111	12,797	31,444	13,090	0	13,090	Normal	74%
3	6,536	15,005	12,797	34,338	13,090	0	13,090	Normal	85%
4	6,536	12,111	16,017	34,664	13,090	0	13,090	Wet	74%
5	6,536	12,111	12,797	31,444	13,090	0	13,090	Normal	74%
6	6,536	533	0	7,069	13,090	20,000	33,000	Dry	31%
7	6,536	533	0	7,069	13,090	20,000	33,000	Dry	31%
8	6,536	533	0	7,069	13,090	20,000	33,000	Dry	31%
9	6,536	533	0	7,069	13,090	20,000	33,000	Dry	31%
10	6,536	12,111	12,797	31,444	13,090	0	13,090	Normal	74%
TOTAL	**65,360**	**77,692**	**80,002**	**223,054**	**130,900**	**80,000**	**210,540**		

Table 4 - Scenario 4 recharge and recovery rates for PWD plus Partners at 100,000 AF

Year	Recharge, AF				Recovery, AF				
	RW	SWP - PWD	SWP - Partners	Total	PWD	Partners	Total	Allocation	SWP Allot (%)
1	6,536	12,111	16,130	34,777	13,090	0	13,090	Normal	74%
2	6,536	12,111	16,130	34,777	13,090	0	13,090	Normal	74%
3	6,536	15,005	16,130	37,671	13,090	0	13,090	Normal	85%
4	6,536	12,111	19,350	37,997	13,090	0	13,090	Wet	74%
5	6,536	12,111	16,130	34,777	13,090	0	13,090	Normal	74%
6	6,536	533	0	7,069	13,090	25,000	38,090	Dry	31%
7	6,536	533	0	7,069	13,090	25,000	38,090	Dry	31%
8	6,536	533	0	7,069	13,090	25,000	38,090	Dry	31%
9	6,536	533	0	7,069	13,090	25,000	38,090	Dry	31%
10	6,536	12,111	16,130	34,777	13,090	0	13,090	Normal	74%
TOTAL	**65,360**	**77,692**	**100,000**	**243,052**	**130,900**	**100,000**	**230,900**		

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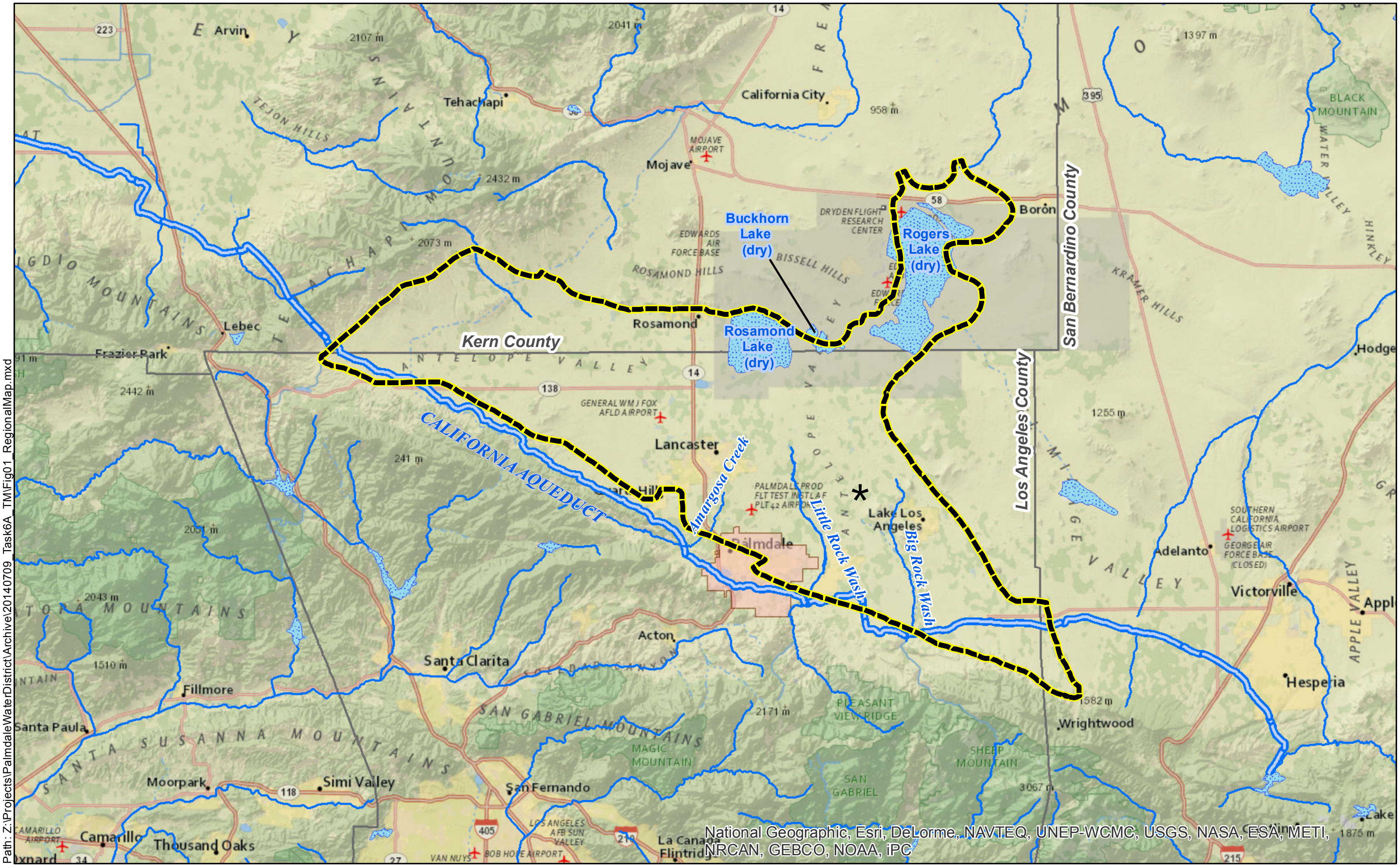

Legend

Antelope Valley Groundwater Basin (from Leighton and Phillips, 2003)

Palmdale Water District

* Recharge Project Site

N

0 5 10

Scale: Miles

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Palmdale, CA

Regional Map of Antelope Valley

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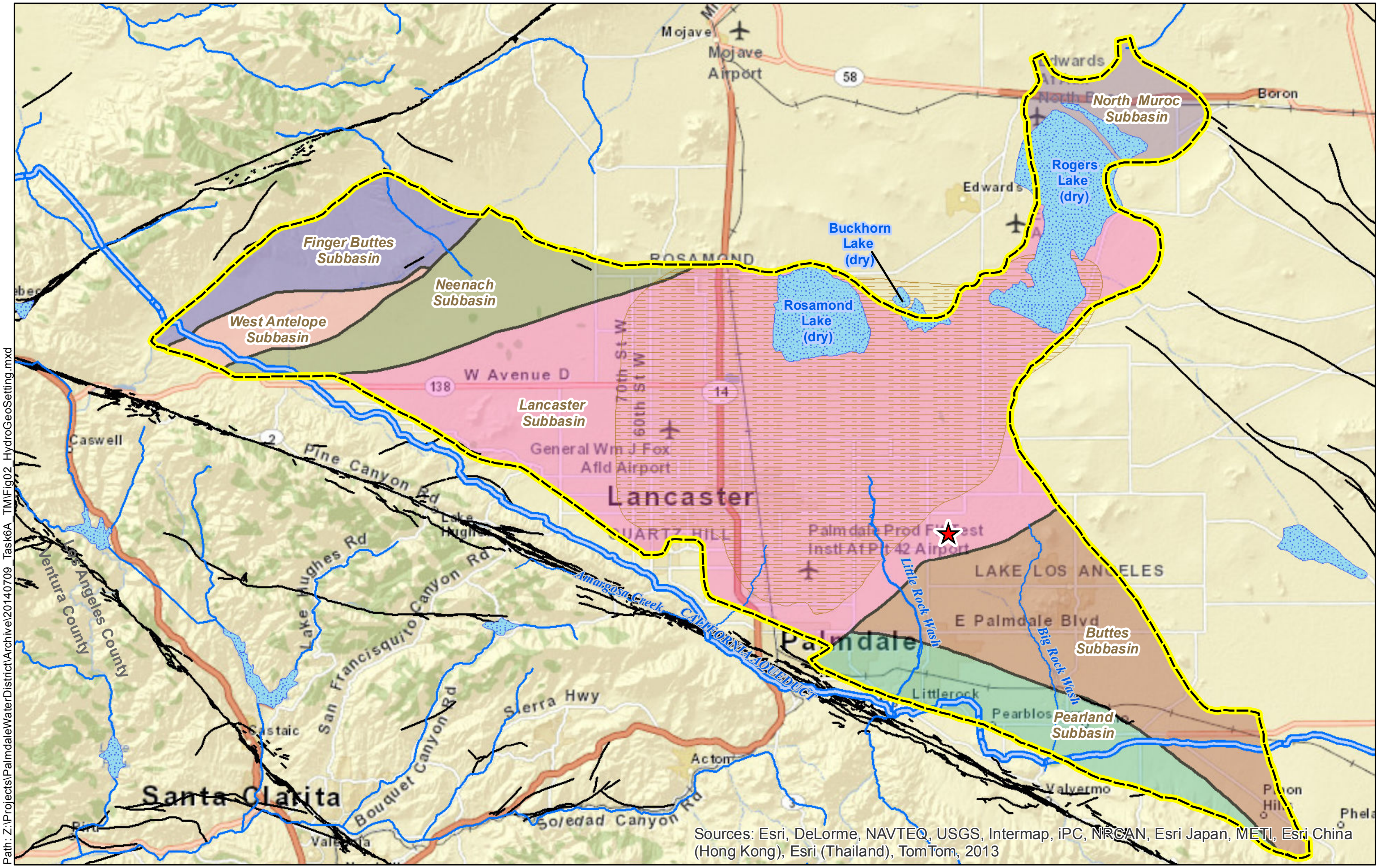
September 2015

Figure 1



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Note: Antelope Valley Groundwater Basin and sub-basin boundaries from Leighton and Phillips (2003). Extent of lacustrine deposits modified from Leighton and Phillips (2003).

Legend

- Antelope Valley Groundwater Basin Boundary
- Faults Mapped by USGS
- Lacustrine Deposits
- Groundwater Subbasin Boundary
- Recharge Project Site

N

0 4 8

Scale: Miles

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Hydrogeologic Setting of the Antelope Valley Groundwater Basin

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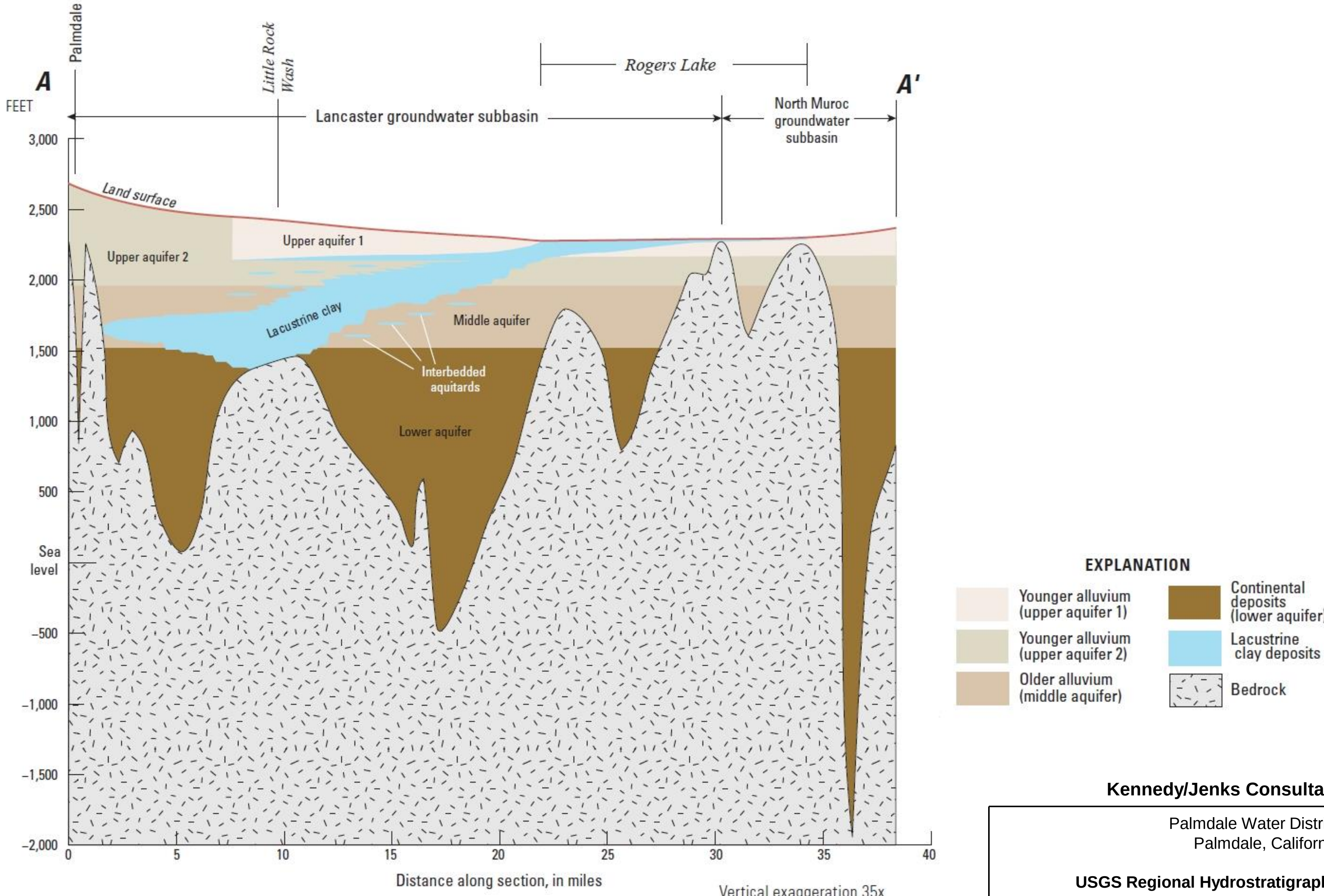
Figure 2



Note: Figure taken from Figure 3 of USGS Scientific Report 2014-5166 (Siade *et al*, 2014)

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USGS Regional Hydrostratigraphy

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Figure 3

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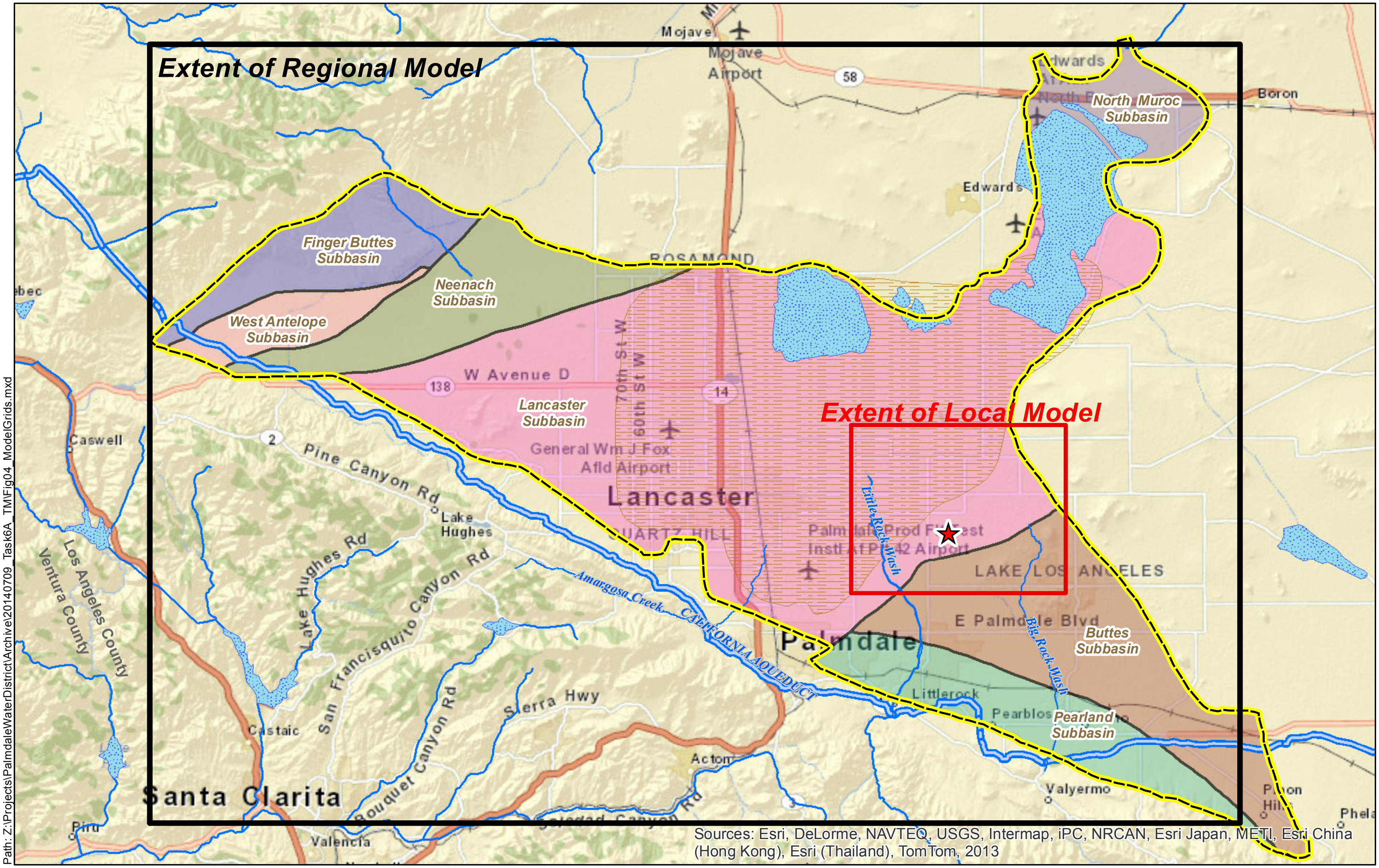

Note: Antelope Valley Groundwater Basin and sub-basin boundaries from Leighton and Phillips (2003). Extent of lacustrine deposits modified from Leighton and Phillips (2003).

Legend

- SubregionalModelExtent
- Antelope Valley Groundwater Basin Boundary
- Lacustrine Deposits
- Groundwater Subbasin Boundary
- Recharge Project Site

N

0 4 8

Scale: Miles

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Extent of Regional and Local Groundwater Flow Models

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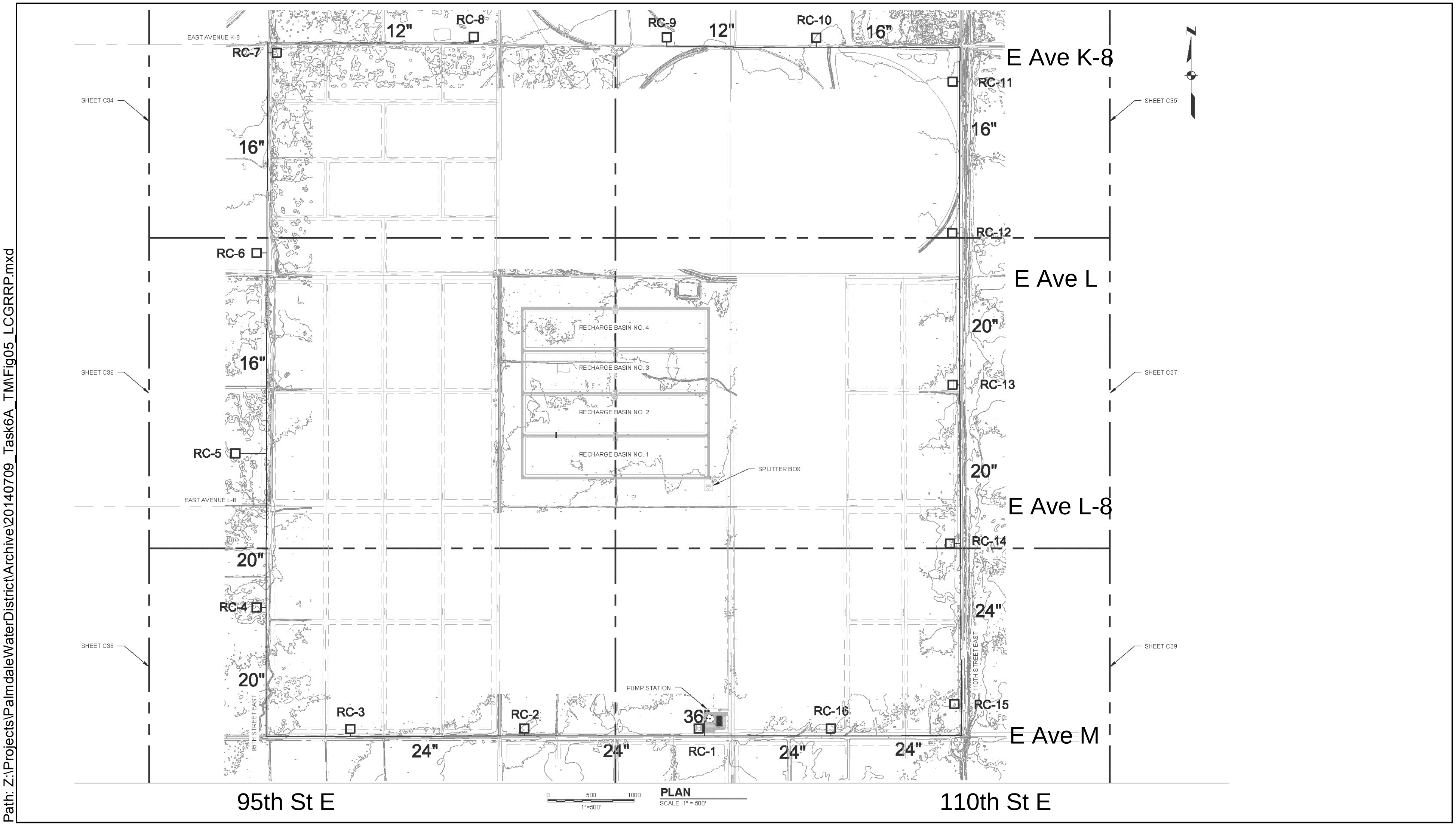
Figure 4



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RC = Recovery Well

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Palmdale LCGRRP Project
Layout for Wells and Recharge Basins

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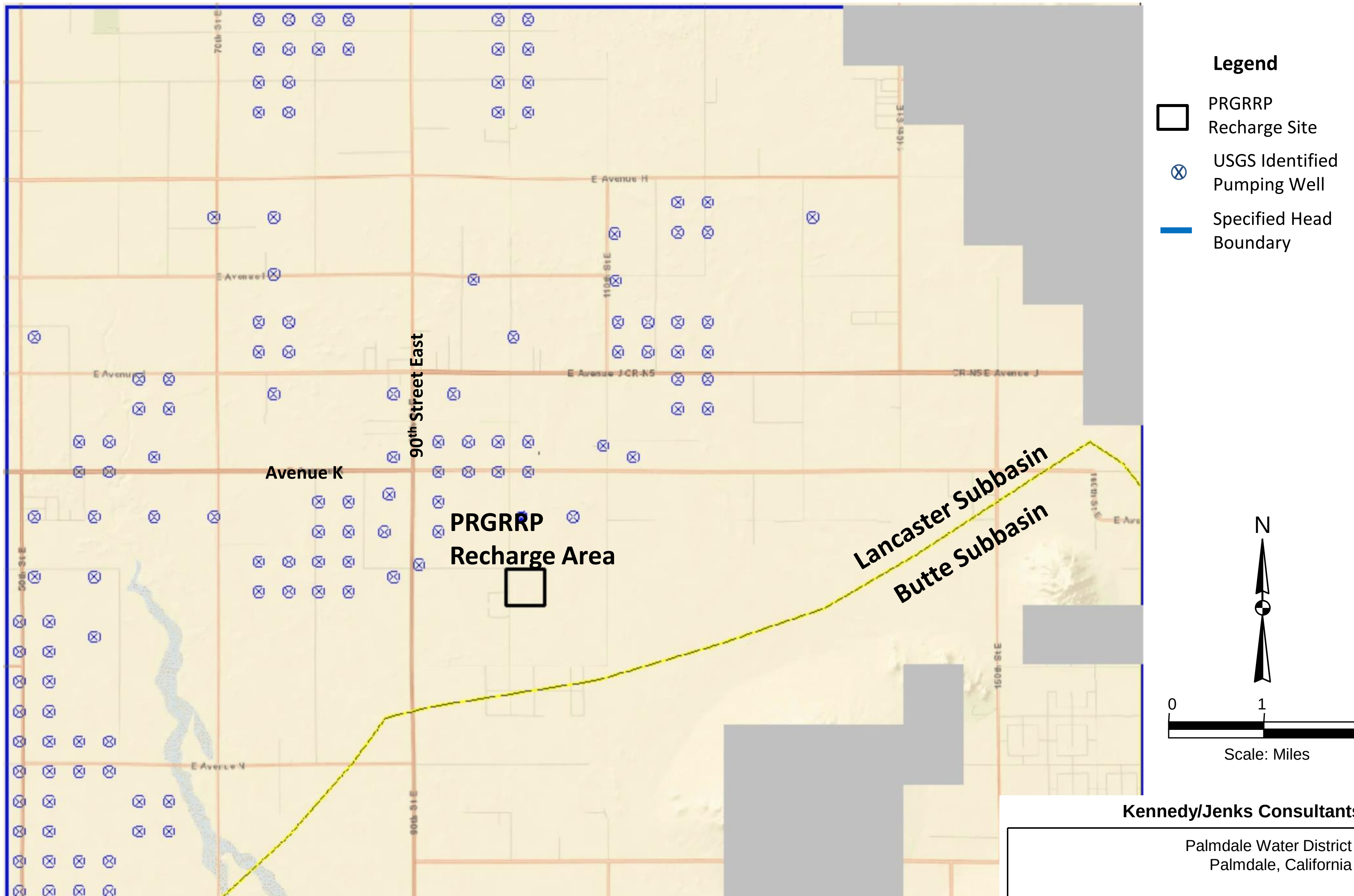
Figure 5



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Local Groundwater Model Domain and Boundary Conditions

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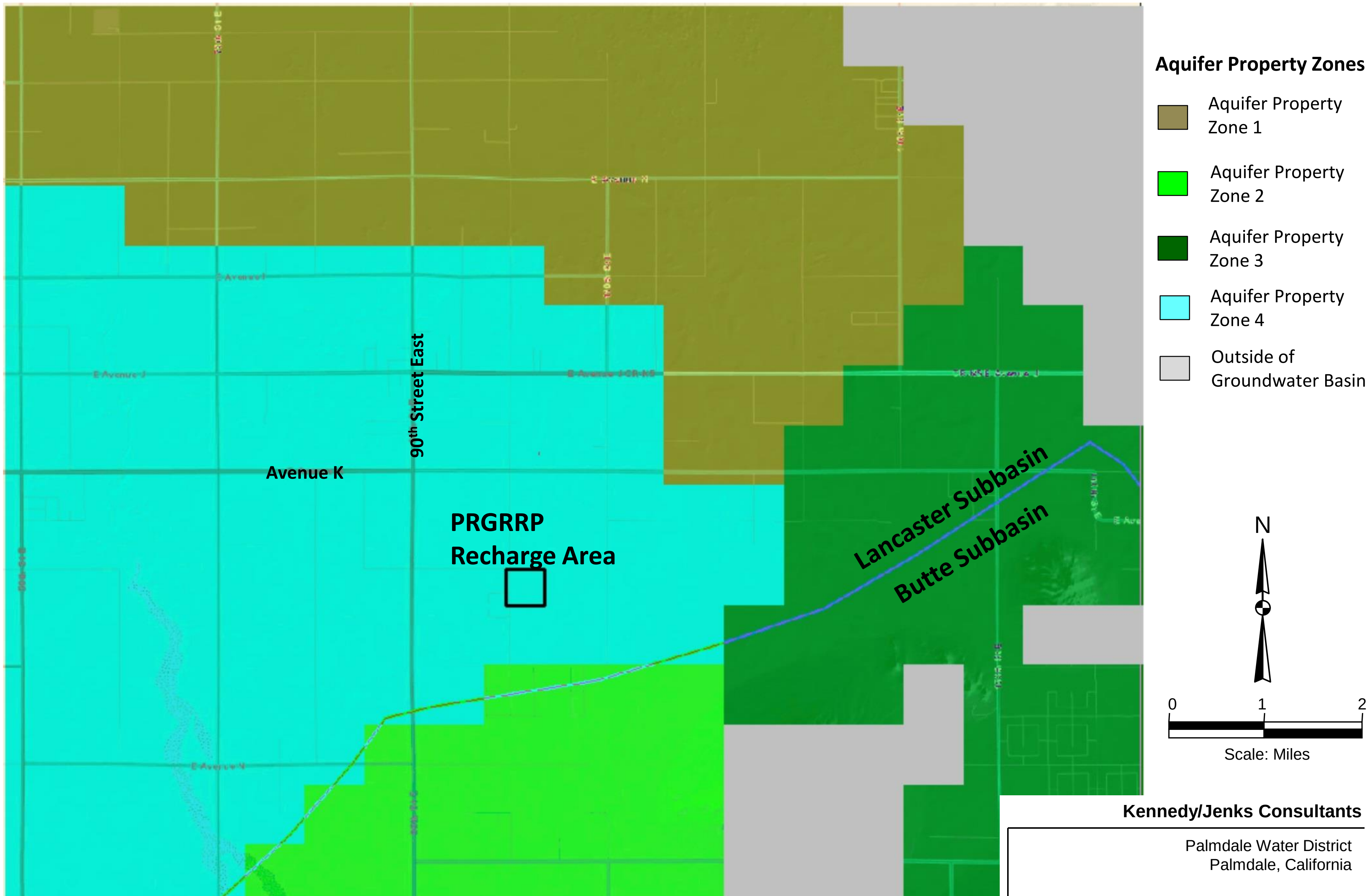
Figure 6



Note: Aquifer Property values listed in the text

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Local Groundwater Model Setup
Aquifer Properties

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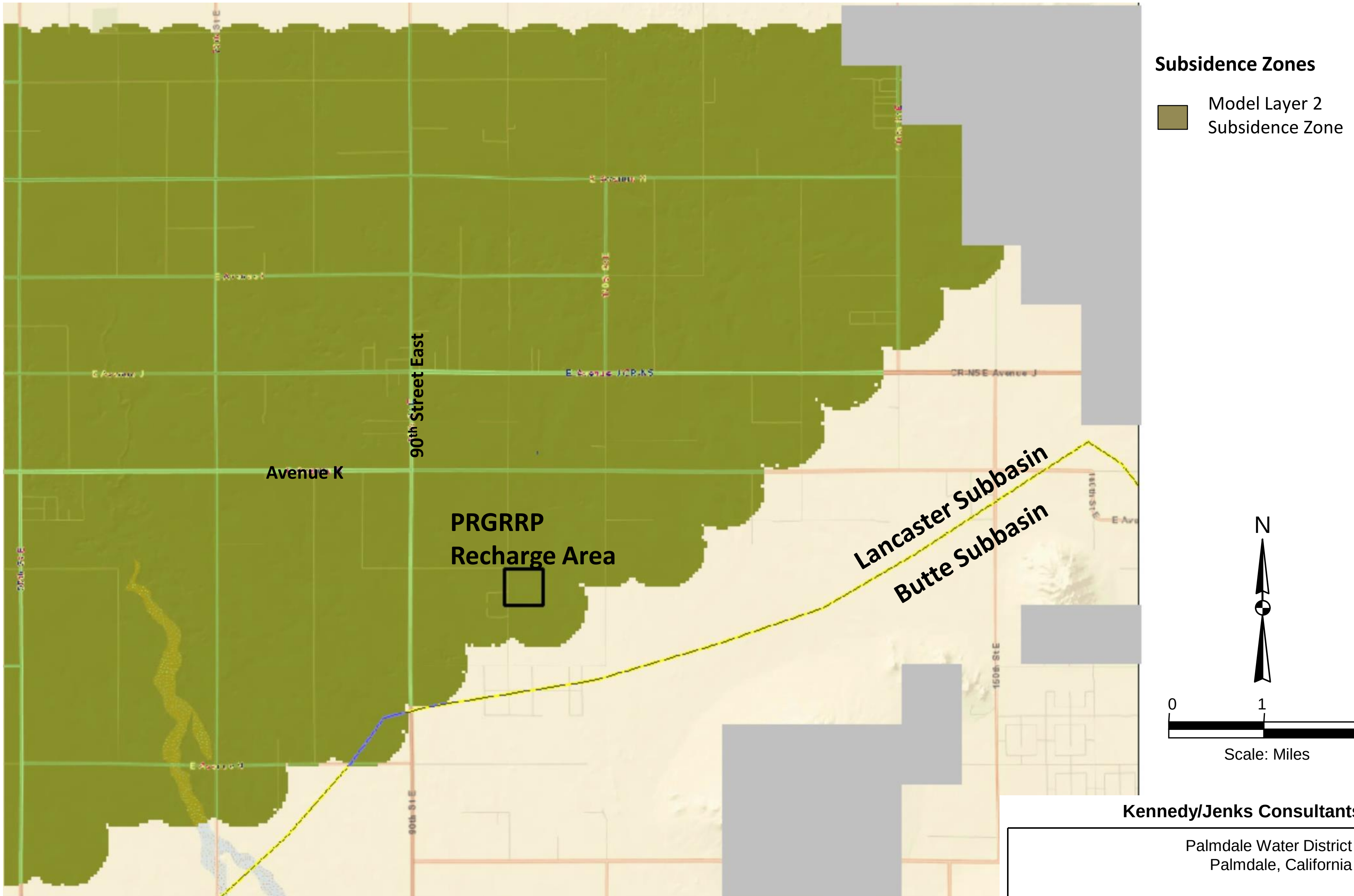
Figure 7



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Local Groundwater Model Setup
Layer 2 Assigned Subsidence Properties

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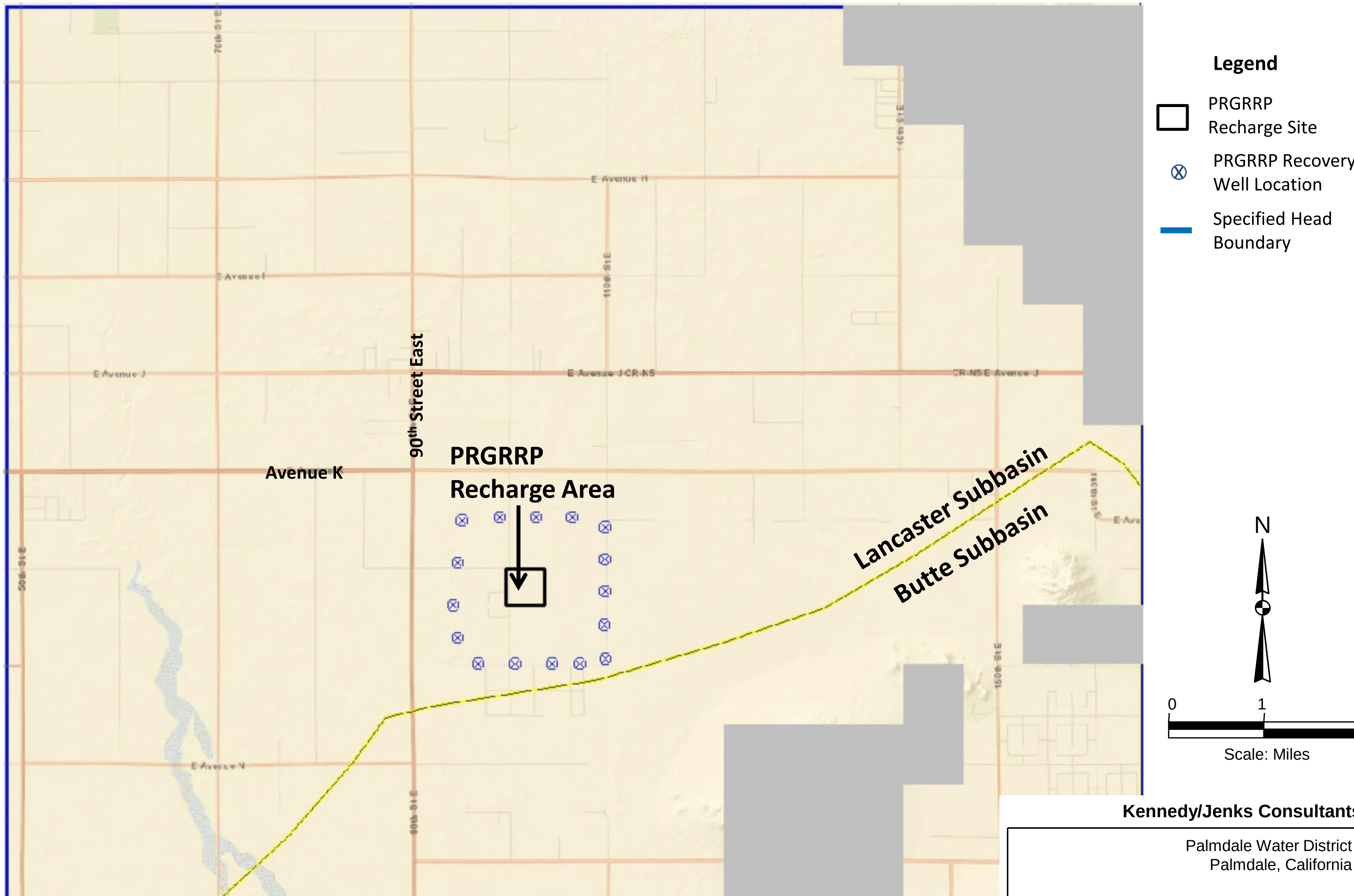
Figure 8



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Local Groundwater Model Setup
Recharge Basin and Recovery Wells

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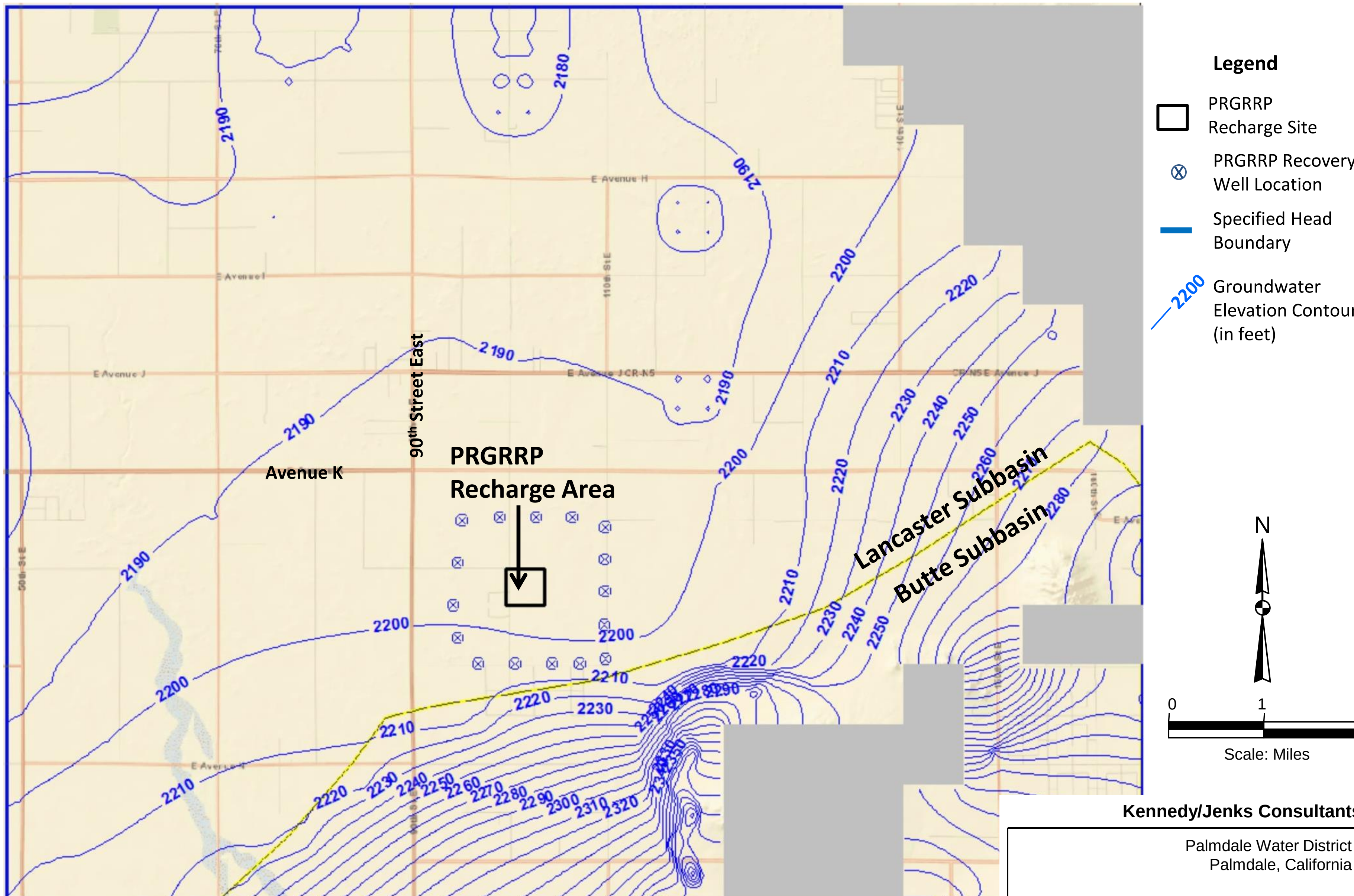
Figure 9



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Local Groundwater Model Setup
Initial Groundwater Elevations

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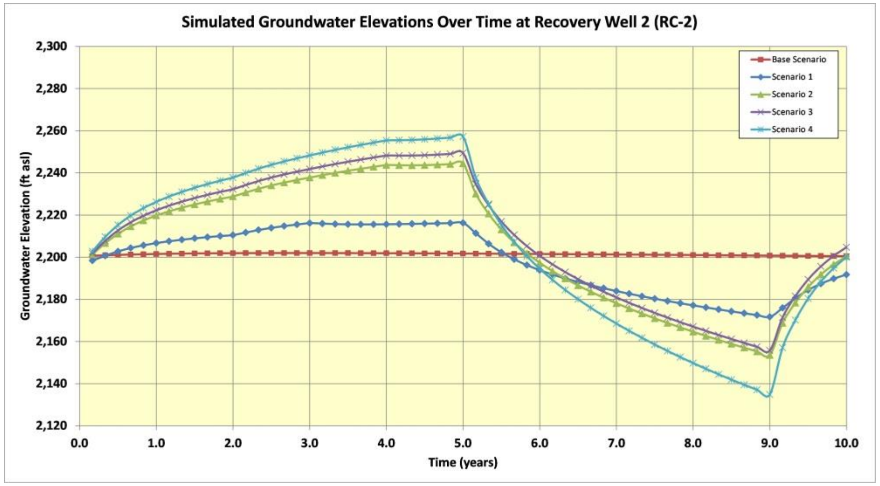
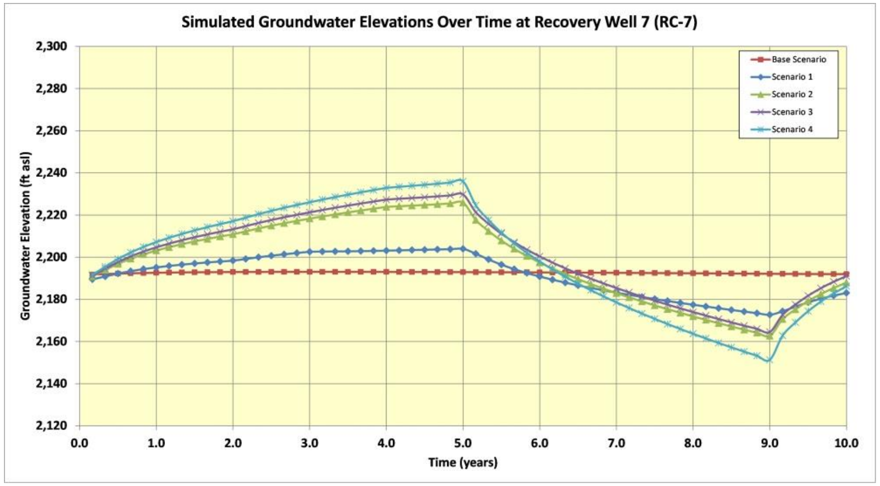
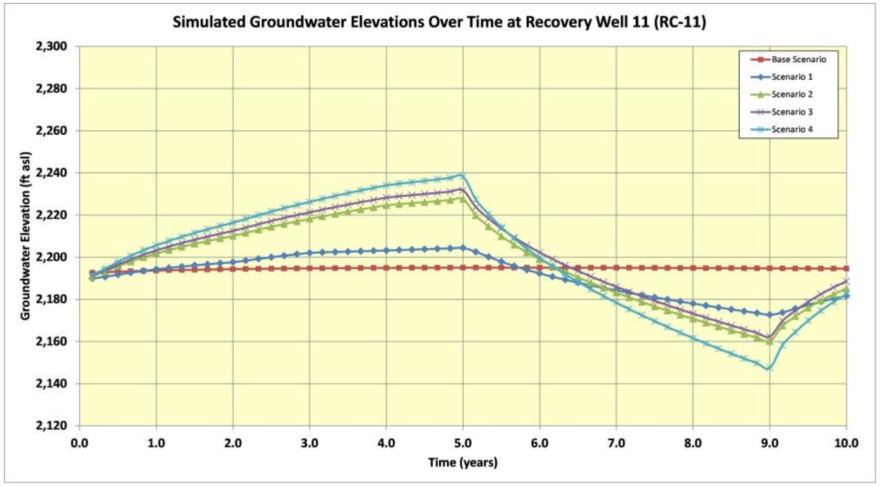
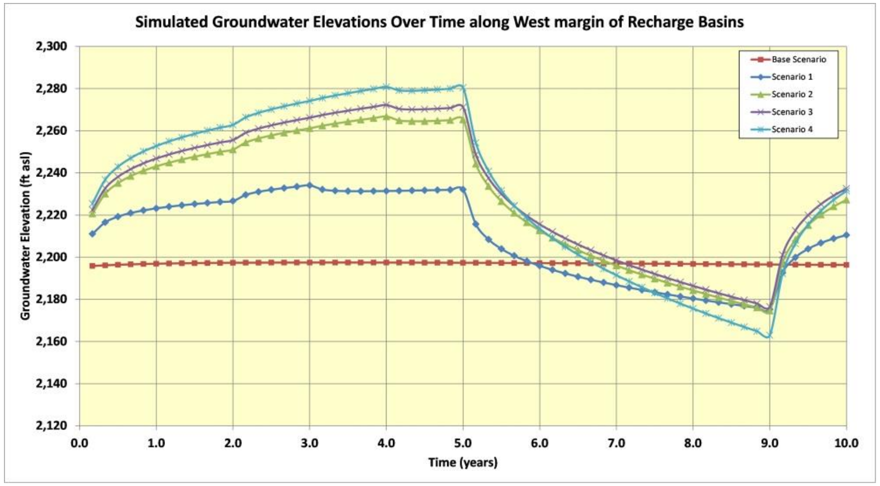
Figure 10









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Local Groundwater Model Results
Representative Hydrographs

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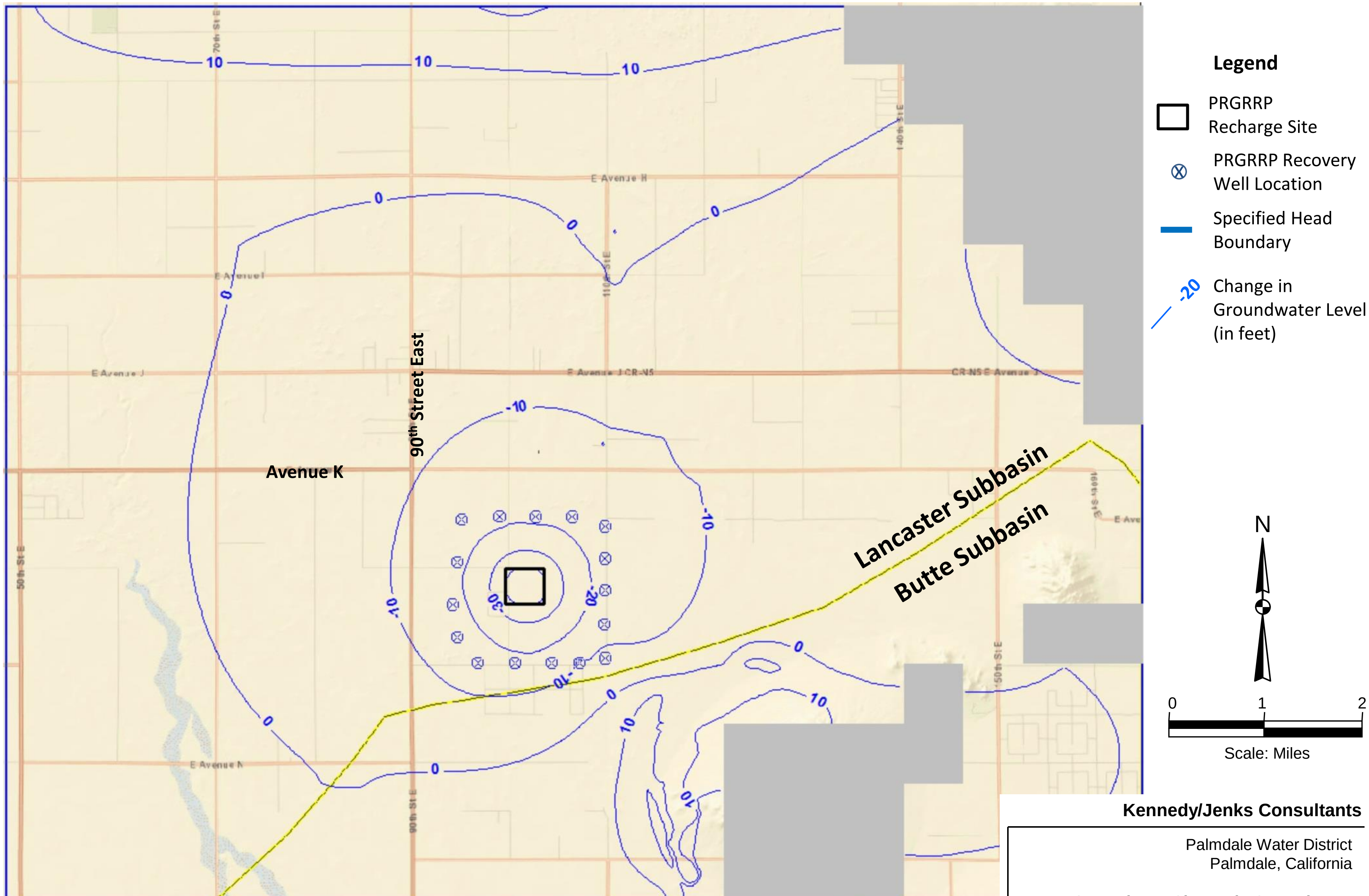
Figure 11



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Scenario 1 – Change in Groundwater Levels after 5 Years (maximum mounding)

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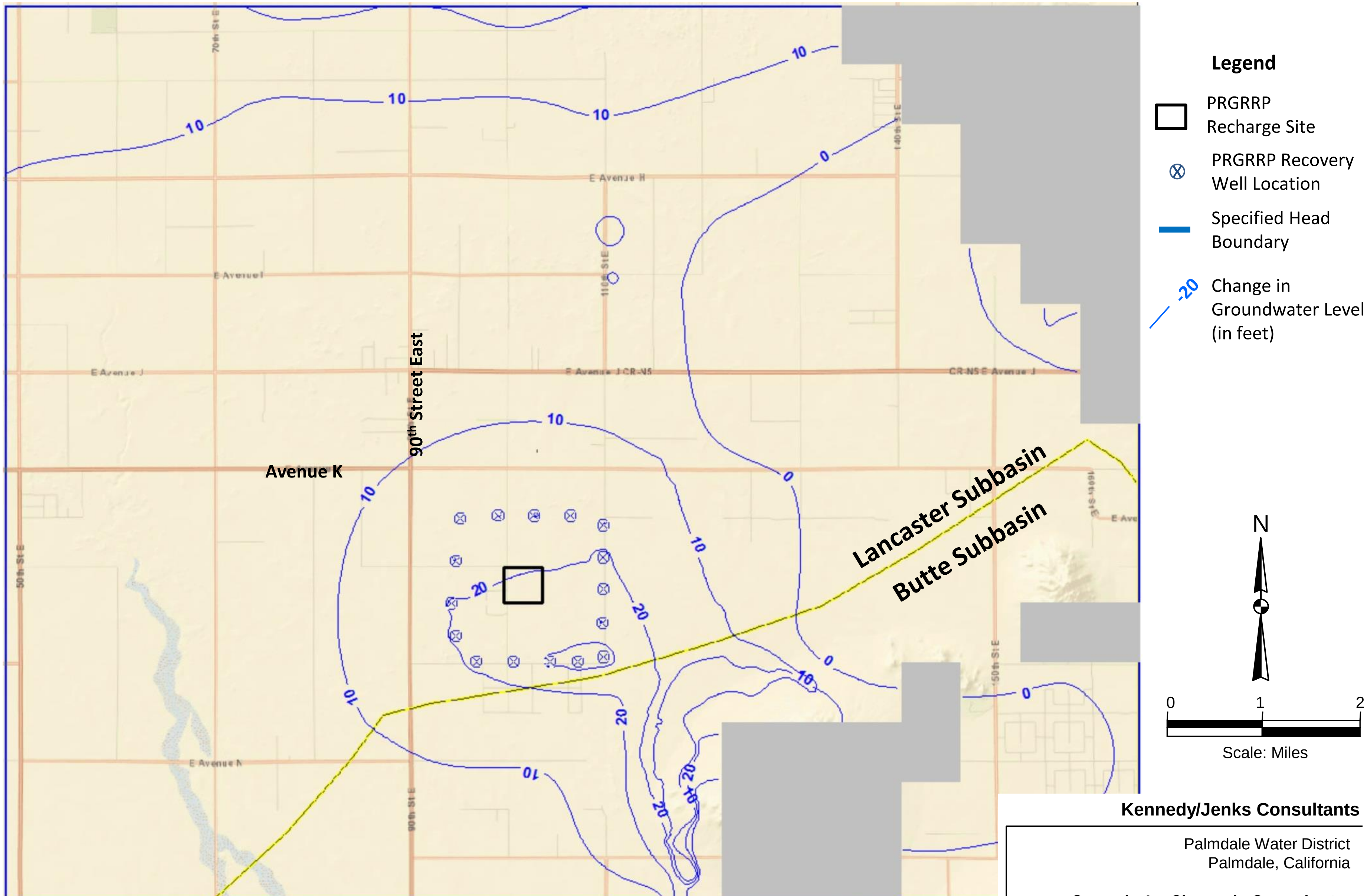
Figure 12

Note: Contours represent change in groundwater levels as drawdown, so negative are increase in groundwater levels whereas positive are decreased groundwater levels relative to initial groundwater elevations shown on Figure 10



Note: Contours represent change in groundwater levels as drawdown, so negative are increase in groundwater levels whereas positive are decreased groundwater levels relative to initial groundwater elevations shown on Figure 10

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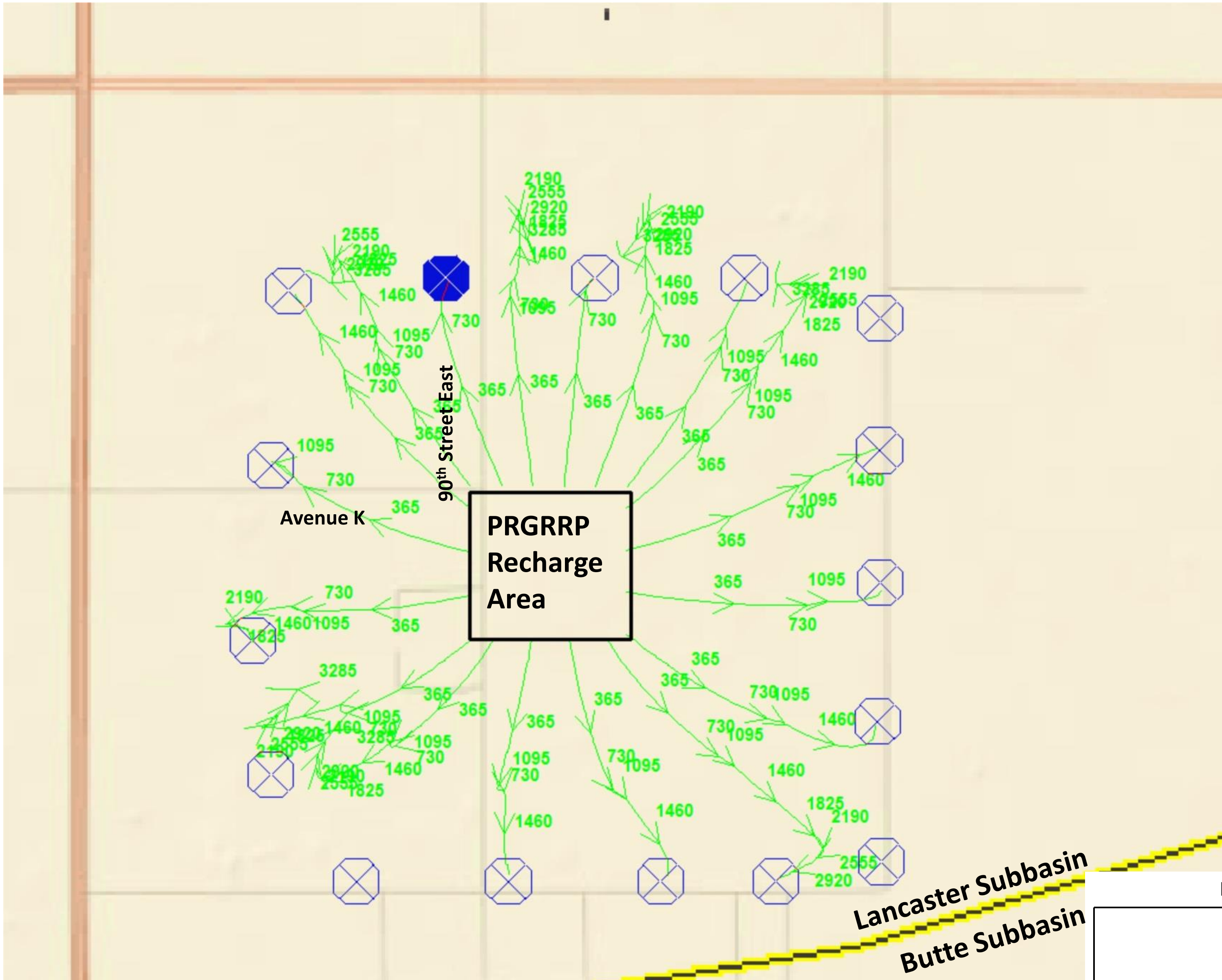
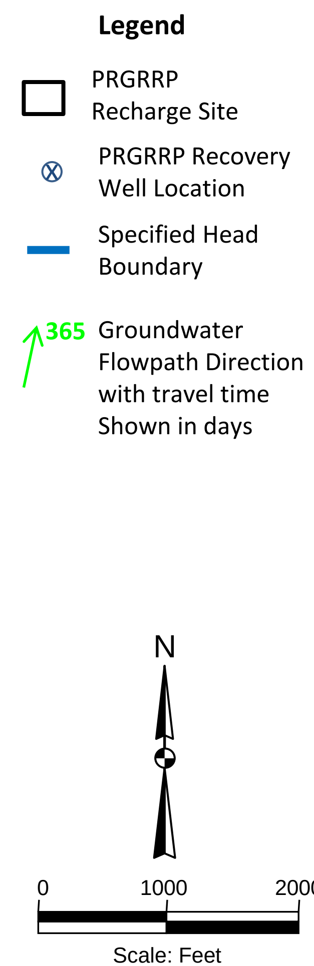
Scenario 1 – Change in Groundwater Levels after 9 Years (maximum drawdown)

K/J 1344505*01
September 2015

Figure 13





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Scenario 1 – Flowpaths with Travel Times over 10 years of Operations

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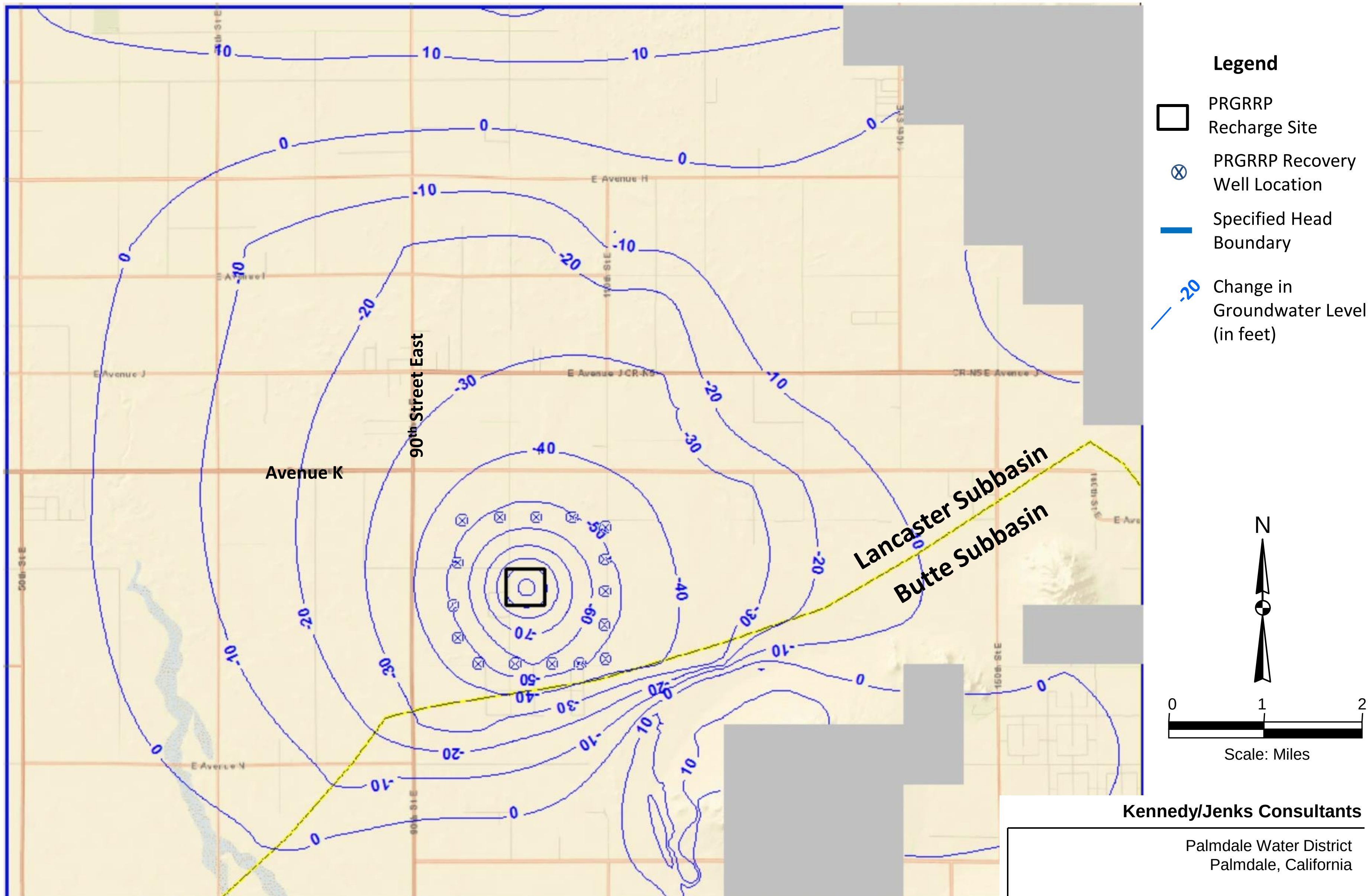
Figure 14

Note: Flowpaths represent flow direction of water from recharge area. Distance between arrowheads represents one year of travel time (shown as total days). Solid well is target location for Tracer Study.



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Scenario 4 – Change in Groundwater Levels after 5 Years (maximum mounding)

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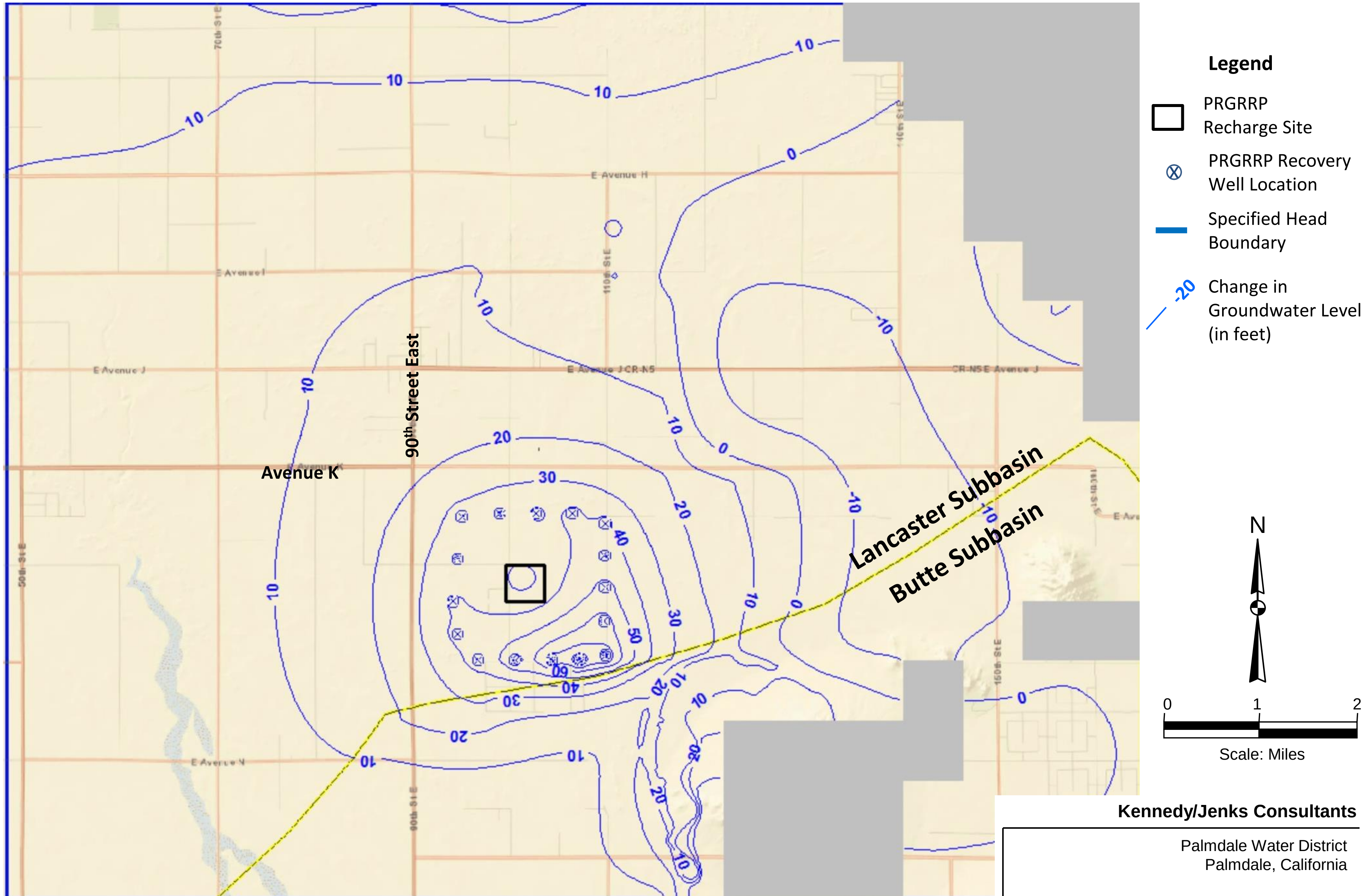
September 2015

Figure 15

Note: Contours represent change in groundwater levels as drawdown, so negative are increase in groundwater levels whereas positive are decreased groundwater levels relative to initial groundwater elevations shown on Figure 10



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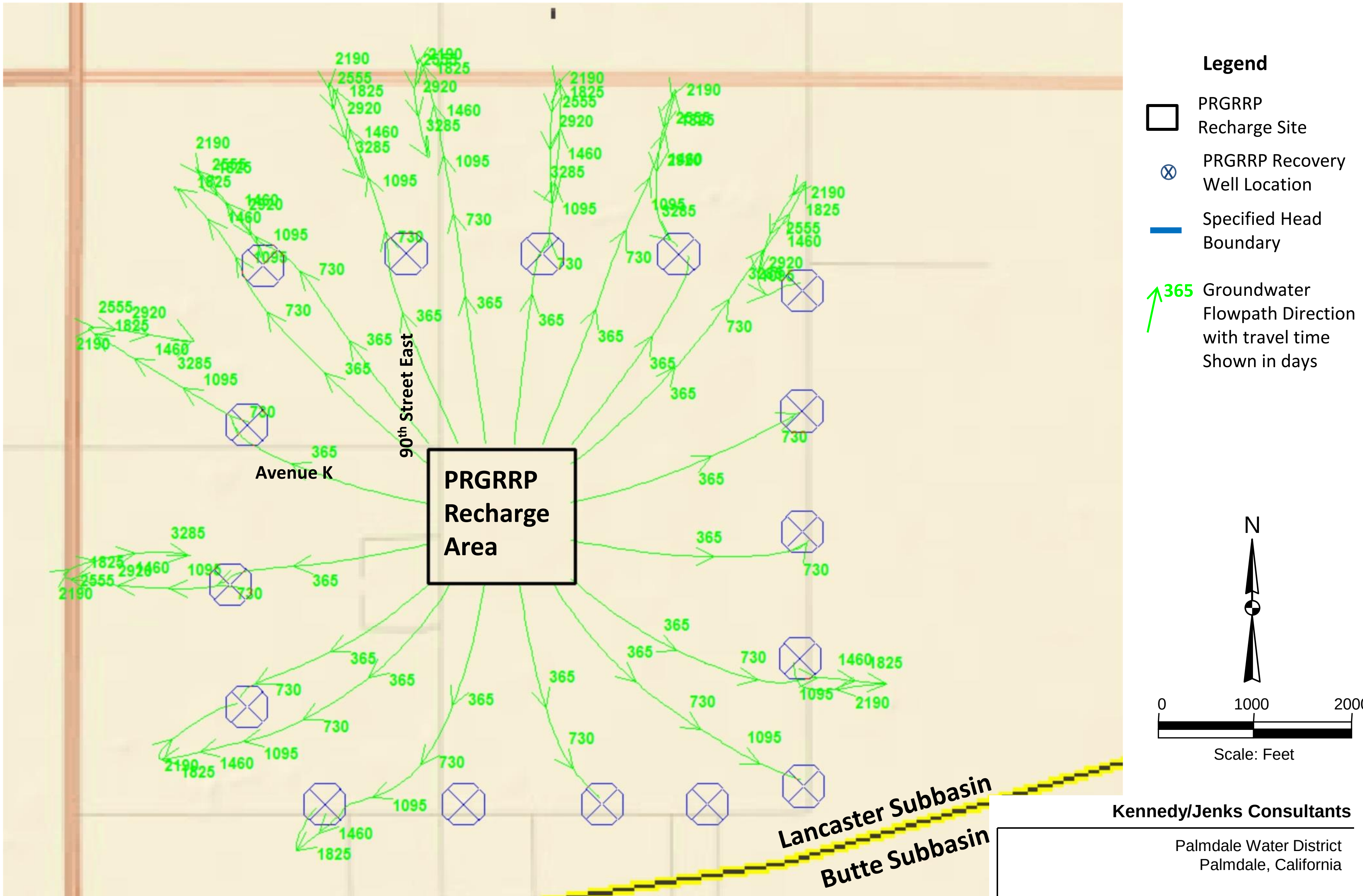
Scenario 4 – Change in Groundwater Levels after 9 Years (maximum drawdown)

K/J 1344505*01
September 2015

Figure 16

Note: Contours represent change in groundwater levels as drawdown, so negative are increase in groundwater levels whereas positive are decreased groundwater levels relative to initial groundwater elevations shown on Figure 10



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Scenario 4 – Flowpaths with Travel Times over 10 years of Operations

K/J 1344505*01
September 2015

Figure 17

Note: Flowpaths represent flow direction of water from recharge area. Distance between arrowheads represents one year of travel time (shown as total days)