WILDERMUTH ENVIRONMENTAL, INC.

Technical Memorandum	
To:	**Ground-Level Monitoring Committee, Chino Basin Watermaster**
From:	**Wildermuth Environmental, Inc. (WEI)**
Date:	**December 13, 2017**
Subject:	**Task 3 and Task 4 of the Work Plan to Develop a Subsidence Management Plan for the Northwest MZ-1 Area:** ***Development and Evaluation of Baseline and Initial Subsidence-Management Alternatives***

Executive Summary

Objectives: This memorandum describes the construction, calibration, and use of a numerical, one-dimensional aquifer-system compaction model in the northwestern portion of the Chino Basin (Northwest MZ-1)—an area that has experienced gradual and persistent subsidence[1] for decades. The objective of this memo is to explore the future occurrence of subsidence in Northwest MZ-1 under various basin-operation scenarios of groundwater production and artificial recharge and to identify potential subsidence mitigation strategies.

Results: The modeling results indicate that over seven feet of subsidence occurred in Northwest MZ-1 from 1930 to 2015, and that the deep aquifer system is more susceptible to additional aquifer-system compaction (compared to the shallow aquifer system) if heads decline in the future. Under the basin-operation scenario that was used in the 2013 recalculation of the Safe Yield, an additional 1.6 feet of subsidence is projected to occur from 2015 to 2045 based on model results. Alternative basin-operation scenarios that include reduced production and/or increased recharge in Northwest MZ-1 can mitigate the future occurrence of subsidence—a goal of the Chino Basin Optimum Basin Management Program.

Recommendations: The one-dimensional model was constructed and calibrated with limited available data and hydrogeologic information. Hence, the use of the model and the interpretation of its results are limited by significant uncertainties. The construction

[1] The Ground-Level Monitoring Committee defines the term "subsidence" as "permanent or non-recoverable sinking or settlement of the land surface."

of the Pomona Extensometer and subsequent monitoring and testing will provide additional information that can be used to construct and calibrate new and improved numerical models of groundwater flow and subsidence. The new models can be used to build upon the subsidence-management strategies evaluated in this memorandum and to develop a final subsidence-management plan for Northwest MZ-1. These recommendations are consistent with the Watermaster-approved *Work Plan to Develop a Subsidence Management Plan for the Northwest MZ-1 Area.*

Background and Objectives

Land subsidence and the potential for ground fissuring in Northwest MZ-1 were first identified as a concern in the MZ-1 Summary Report[2] and the MZ-1 Subsidence Management Plan.[3] The issues of land subsidence and the potential for ground fissuring in Northwest MZ-1 has been discussed at Ground-Level Monitoring Committee (GLMC) meetings, and the subsidence has been documented and described as a concern in past State of the Basin Reports[4] and annual reports of the GLMC.[5]

Figure 1 shows the location of Northwest MZ-1 and land subsidence that has occurred in this area during the period 1992 to 2016. The land subsidence on Figure 1 was estimated using a remote-sensing technique called interferometric synthetic aperture radar (InSAR). Figure 2 is a time-series chart that shows the long-term history of vertical ground motion at a location of maximum subsidence in Northwest MZ-1 using the InSAR-derived estimates. Figure 2 indicates that a maximum of about 1.25 ft of subsidence has occurred in this area from 1992 through 2016—an average rate of about 0.05 ft/yr. The chart also shows hydraulic heads measured at wells in the area from 1930-2016. From about 1930 to 1978, heads in Northwest MZ-1 declined by about 175 feet. Since then, heads have recovered, but have remained below the levels of 1930. The observed and continuous subsidence that occurred between the 1992 and 2016 period cannot be explained entirely by the concurrent changes in head. A plausible explanation for the subsidence is that thick, slow-draining aquitards are compacting in response to the historical head declines that occurred from 1930 (or before 1930) to 1978.

Figure 1 depicts a steep subsidence gradient across the San Jose Fault in Northwest MZ-1. This steep subsidence gradient is referred to as "differential" subsidence—the same

[2] Chino Basin Watermaster. (2006). *MZ-1 Summary Report*. Prepared by WEI. February 2006.

[3] Chino Basin Watermaster. (2007). *Management Zone 1 Subsidence Management Plan*. Prepared by WEI. October 2007.

[4] Chino Basin Watermaster. (2017). *2016 State of the Basin Report*. Prepared by WEI. June, 2017.

[5] Chino Basin Watermaster. (2014). *2013 Annual Report of the Land Subsidence Committee*. Prepared by WEI. July, 2014.

pattern of differential subsidence that occurred in the Managed Area during the time of ground fissuring. Differential subsidence causes an accumulation of horizontal strain in the shallow sediments and creates the potential for ground fissuring to occur.

Watermaster, consistent with the recommendation of the GLMC, has determined that the Chino Basin Subsidence Management Plan (SMP) needs to be updated to include a *Subsidence Management Plan for the Northwest MZ-1 Area* with the long-term objective of minimizing or abating the occurrence of the land subsidence.[6]

Development of a subsidence management plan for Northwest MZ-1 requires answering the following questions:

1. What are the mechanisms driving the observed subsidence?

   Available evidence indicates that the most likely mechanism behind observed subsidence in Northwest MZ-1 is the compaction of fine-grained sediment layers within the aquifer system. If so, the following questions need to be answered:

   a. What are the depth intervals within the aquifer system that are compacting? The answer to this question will guide the development of management strategies that target the compacting layers.

   b. How does pumping from wells in Northwest MZ-1 influence heads within the aquifer system? The answer to this question will help characterize the hydrogeology that controls subsidence, and will guide the development of the management strategies via groundwater production.

   c. How does wet-water recharge via spreading and/or injection influence heads? The answer to this question will help characterize the hydrogeology that controls subsidence, will guide the development of the management strategies via artificial recharge.

   d. What is the pre-consolidation head[7] within the compacting intervals of the aquifer system? The answer to this question will identify the hydraulic heads necessary to abate the occurrence of subsidence.

2. What is the appropriate method to manage the land subsidence in Northwest MZ-1?

[6] Chino Basin Watermaster. (2015). *Chino Basin Subsidence Management Plan*. Prepared by WEI. July 23, 2015.

[7] In lay terms, the pre-consolidation head is a hydraulic head "threshold." When heads are above the threshold, subsidence is abated. When heads are below the threshold, subsidence occurs.

> First, the future occurrence of land subsidence and its potential consequences under a currently projected basin-operational scenario needs to be estimated as a "baseline." Then, depending on the answers to Question 1, there may be multiple strategies to manage land subsidence, such as modification of pumping patterns, in-lieu recharge, wet-water recharge via spreading, injection, or a combination of methods. For example, one method may be to increase wet-water recharge in MZ-1 beyond the minimum contractual obligation of the Peace II Agreement (6,500 acre-ft/yr through 2030). These strategies might necessitate the modification of water-supply plans for purveyors in the Chino Basin. The strategies need to be described and evaluated and eventually formulated into land subsidence management alternatives.

A hydrogeologic investigation of Northwest MZ-1 is necessary to answer these questions. The investigation will include the installation of piezometers and extensometers, the implementation of a monitoring and testing program, and numerical modeling of aquifer-system deformation.

The Watermaster developed a multi-year work plan to answer these questions and develop the *Subsidence Management Plan for the Northwest MZ-1 Area*.[8] The work plan includes the following tasks:

- Task 1 – Describe Initial Hydrogeologic Conceptual Model & the Monitoring and Testing Program
- Task 2 – Implement the Initial Monitoring and Testing Program
- Task 3 – Develop and Evaluate the Baseline Management Alternative
- Task 4 – Develop and Evaluate the Initial Subsidence-Management Strategies
- Task 5 – Design and Install the Pomona Extensometer Facility
- Task 6 – Design and Conduct Aquifer-System Stress Tests
- Task 7 – Update Hydrogeologic Conceptual Model and Prepare Summary Report
- Task 8 – Update Chino Basin Groundwater Model
- Task 9 – Refine and Evaluate Subsidence-Management Alternatives
- Task 10 – Update the Chino Basin Subsidence Management Plan

This memorandum describes the methods and results for Tasks 3 and 4, which were designed to begin to answer Question 2 above and to explore strategies to manage land subsidence in Northwest MZ-1.

[8] Chino Basin Watermaster. (2015). *Work Plan, Develop a Subsidence-Management Plan for the Northwest MZ-1*. Prepared by WEI. July 25, 2015.

The objective of Task 3 is to describe the future occurrence of land subsidence under recently-projected basin-operation scenario, which includes production and replenishment plans of the Chino Basin parties. This baseline condition is called the Baseline Management Alternative (BMA) and is used for comparison with potential subsidence-management strategies.

The objective of Task 4 is to develop an initial set of management strategies that will minimize or abate the ongoing subsidence in Northwest MZ-1. To minimize or abate this subsidence, heads will need to increase; specifically, to the pre-consolidation head. There are several strategies to increase groundwater levels, such as the modification of pumping patterns, in-lieu recharge, wet-water recharge via spreading, injection, or a combination of methods. Strategies that increase and hold heads above the estimated pre-consolidation head will be described and evaluated and will be called Initial Subsidence-Management Strategies (ISMSs).

Methods

The following methods were used to complete Task 3 and Task 4:

- Research and document the historical subsidence in Northwest MZ-1 since the 1930s.[9]
- Build and calibrate a numerical, one-dimensional, aquifer-system compaction model (1D Model) for a location in Northwest MZ-1 that has experienced the near maximum magnitude of historical subsidence. Estimates of historical subsidence across Northwest MZ-1 (first bullet above) were used in the 1D Model calibration process. The 1D Model calibration generated estimates of current (2015) pre-consolidation head in each model layer at its location.
- Describe the BMA, which includes planning projections of the Chino Basin parties for groundwater production, replenishment, and recharge.
- Project head responses in each model layer to the BMA using the updated 2013 Chino Basin groundwater-flow model.
- Use the projected heads for the BMA in each model layer for the 1D Model boundary conditions, and project the vertical deformation of the aquifer system with the 1D Model.

[9] Water-level data at wells is scarce in Northwest MZ-1 prior to the 1930s. This report assumes that the significant lowering of heads in Northwest MZ-1 began after 1930. Task 8 of the Work Plan, which includes the construction and calibration of a new 1D Model, will include a task to investigate historical production and water-level measurements in Northwest MZ-1, and include any newly-discovered water-level data in the calibration.

- Describe the ISMSs. The ISMSs include revised production, replenishment, and recharge plans for the Chino Basin parties in Northwest MZ-1. The intent of these strategies is to raise head in Northwest MZ-1 above the 2015 pre-consolidation head to minimize or abate the ongoing occurrence of subsidence.
- Project the response of heads in each model layer to the ISMSs using the updated 2013 Chino Basin groundwater-flow model, and compare the projected time-series of heads at the location of the 1D Model to the 2015 pre-consolidation head by layer to predict the effectiveness of the ISMSs to minimize or abate future land subsidence.

Results and Interpretations

Characterization of Historical Subsidence in Northwest MZ-1

Figures 1 and 2 display InSAR-derived estimates of vertical ground motion in Northwest MZ-1 for 1992-2016. These figures indicate that a maximum of about 1.25 ft of gradual and persistent subsidence has occurred in Northwest MZ-1 during this period—an average rate of about 0.05 ft/yr. The area of maximum subsidence is generally aligned along San Bernardino Avenue between Holt Avenue and Interstate 10 in the City of Pomona.

Prior to 1992, InSAR estimates of vertical ground motion are non-existent. Ground elevations published on USGS quadrangle maps are generally sparse, discontinuous, and lack the accuracy necessary for this study. Specifically:

- Spot elevations shown on historical USGS topographic quadrangle maps are accurate to within one-half of one contour interval, which corresponds to a vertical accuracy ± 2.5 to 5 feet—errors too great to be useful in this study since the magnitudes of subsidence that have occurred in this area are of the same order.
- The benchmark elevations shown on the USGS Claremont and Ontario topographic quadrangle maps published between 1928 and 1982 are based on plane table surveys no more recent than 1939, and are therefore not useful in this study.

An effort was made to augment the InSAR-derived estimates of vertical ground motion in Northwest MZ-1 with historical ground-elevation data from repeated leveling surveys performed by the National Geodetic Survey (NGS) and the Metropolitan Water District of Southern California (MWD). Both the NGS and MWD leveling surveys are classified as First Order, Class II surveys with vertical accuracies of 5 cm (0.16 feet) or better. The NGS and MWD survey data are the most accurate and best available historical estimates of vertical ground motion in Northwest MZ-1. These estimates were used to check the reasonableness of the 1D Model calibration, which utilized the InSAR-derived estimates of vertical ground motion at one specific location as calibration targets.

Parsons Brinckerhoff[10] obtained the results for 17 repeated, unadjusted[11] leveling surveys performed by the NGS in Northwest MZ-1 between 1923 and 1978 and for 10 adjusted[12] leveling surveys performed by MWD between 1994 and 2011. Figure 3 shows the locations of the benchmarks.[13] Two additional benchmarks DX2942 and EV3027, shown on the inset of Figure 3, were located outside the study area in locations where vertical ground motion was assumed to be negligible, and were used to adjust NGS benchmark elevations within the study area.[14] Table 1 summarizes the adjusted NGS and MWD benchmark elevation data and the calculated elevation changes at the benchmarks, which are displayed and labeled on the map in Figure 3.

The following observations and interpretations are apparent from inspecting Table 1 and Figure 3:

- Subsidence occurred in Northwest MZ-1 between 1923 and 1978, as shown by the leveling surveys at the NGS benchmarks. This was a period of gradual and persistent decline in heads, as shown on Figure 2. Heads declined gradually and persistently across Northwest MZ-1 by more than 100 feet during this period, and maximum subsidence was estimated to be 3.541 ft at EV3052 from 1923-1974.

- The two east-west lines of NGS benchmarks do not overlie the areas of greatest recent subsidence estimated by InSAR during 1992-2016; this area of greatest recent subsidence is between the two lines of NGS benchmarks. This suggests that the areas between the two lines of NGS benchmarks also experienced subsidence during 1923-1978 and likely at rates greater than the subsidence rates measured at the NGS benchmarks.

- The spatial distribution and magnitude of subsidence as measured by the MWD surveys is similar to the InSAR-derived estimates of subsidence, which supports

[10] The historical NGS and MWD leveling data used in this study were collected and analyzed by a California-licensed Professional Land Surveyor at Parsons Brinckerhoff.

[11] "Unadjusted" refers to the NGS raw benchmark elevations determined during the differential leveling process that have not been adjusted or corrected for leveling closure error.

[12] "Adjusted" refers to the MWD benchmark elevations that have been corrected for leveling closure error.

[13] NGS benchmarks are located along the Union Pacific Railroad corridor south of Holt Avenue and along the BNSF railroad corridor just north of Arrow Highway. The MWD benchmarks are located along the Upper Feeder imported water pipeline.

[14] BM EV3027 served as the "stable" benchmark for Line Numbers 82328/1 and L386/A; BM DX2942 served the "stable" benchmark for Line Numbers L991/10 to L24301/17.

the use of InSAR-derived estimates as calibration targets for the 1D Model (described below).

- The NGS and MWD leveling datasets may be useful in a future update of the Chino Basin groundwater-flow model that includes the calibration of the SUB package to simulate regional aquifer-system deformation.

1-Dimensional Aquifer-System Compaction Model

The numerical 1D Model was constructed and calibrated to simulate the vertical deformation of aquifer-system sediments at a specific location in Northwest MZ-1. The 1D Model was used to hind cast estimates of vertical deformation of the aquifer system over a historical period, and it was used to predict aquifer-system deformation under the BMA. The objectives of the 1D Model effort included:

- Estimate the total historical compaction that has occurred since 1930 at one location in Northwest MZ-1.
- Estimate the hydraulic and mechanical properties of the aquifer-system sediments that control their elastic and inelastic deformation at one location in Northwest MZ-1.
- Estimate the current (2015) pre-consolidation heads of the aquifer-system sediments by layer at one location in Northwest MZ-1.
- Estimate future compaction of the aquifer-system sediments under the BMA at one location in Northwest MZ-1.

Based on the estimates of the 2015 pre-consolidation heads of the aquifer-system sediments derived from the 1D Model calibration, the updated 2013 Chino Basin groundwater-flow model was then used to project the response of heads in each model layer to the ISMSs. Comparison of the projected heads at the location of the 1D Model to the 2015 pre-consolidation head by layer predicts the effectiveness of the ISMSs to minimize or abate future land subsidence.

The *Work Plan to Develop a Subsidence Management Plan for the Northwest MZ-1 Area* recommends that a new 1D Model be constructed and calibrated to simulate vertical aquifer-system deformation at the Pomona Extensometer (PX) site following its construction and a period of monitoring and testing. The information obtained from this original 1D Model will be useful in developing a new 1D Model at the PX site. The new model (1D Model at the PX site) will be used to estimate aquifer-system properties and the pre-consolidation heads within the aquifer system at the PX site. In turn, this new information will be used to update the Chino Basin groundwater-flow model with the addition of the Subsidence and Aquifer-System Compaction (SUB) Package to simulate regional subsidence, which will be used to support the development and evaluation of a final subsidence management alternative(s) for Northwest MZ-1.

Model Code

MODFLOW-2000,[15] the USGS's modular finite-difference ground-water flow model, with the Interbed-Storage (IBS) Package was used to construct and calibrate the 1D Model in Northwest MZ-1 for the following reasons:

- Watermaster has already developed and calibrated a groundwater model based on MODFLOW 2000 and plans to refine it and recalibrate it by 2020. Watermaster is also developing new planning scenarios to evaluate future groundwater management and will be investigating these scenario in 2018 and 2019.
- MODFLOW-2000 and the IBS Package have extensive publicly-available documentation.
- For one-dimensional simulations of vertical aquifer-system deformation, there are no differences between the IBS package and the newer SUB package, which was improved to simulate delays in the release of groundwater from interbed storage and delays in aquifer-system compaction.
- MODFLOW-2000 and the IBS Package have undergone rigorous USGS and academic peer review and have a long history of development and use.
- MODFLOW-2000 and the IBS Package can easily operate with additional simulation tools published by others due to its availability and robust framework.

Conceptual Model

The MVWD-28 well site (shown on Figure 3) was chosen for the 1D Model location. This site was chosen for the following reasons:

1. The well site is located within the area of greatest subsidence as estimated by InSAR from 1992-2016.
2. The well borehole was drilled to a total depth 1,317 ft-bgs, which is deeper than most production wells in the area, and penetrates all three aquifer layers as currently conceptualized in the Chino Basin groundwater-flow model.
3. The borehole lithology was described and is consistent with the borehole resistivity logs. This is important because the borehole lithology is the basic information used to construct and discretize the 1D Model into "aquifer" and "aquitard" layers.

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[15] A.W. Harbaugh, E.R. Banta, M.C. Hill, and M.G. McDonald. (2000). *MODFLOW-2000, the U.S. Geological Survey modular ground-water model—User guide to modularization concepts and the Ground-Water Flow Process*. USGS Open-File Report 00-92.

The lithology at MVWD-28 consists of coarse-grained "aquifers," comprised of silty sands, sands, and gravels, interbedded with fine-grained "aquitards," comprised of silts, silty clays, and clays. Figure 4 shows the generalized borehole lithology for MVWD-28,[16] its short-normal resistivity log, and the hydrostratigraphic layer divisions of the Chino Basin groundwater-flow model. Layer 1 is representative of the shallow aquifer system and is generally characterized by unconfined to semi-confined groundwater conditions. Layers 2 and 3 are representative of the deep aquifer system and are characterized by confined groundwater conditions, lower permeability sand and gravel layers (compared to Layer 1), and a greater abundance of interbedded fine-grained sediments.

Model Discretization

The borehole lithology at MVWD-28 was discretized into a stacked column of two-foot thick aquifer or aquitard cells starting from 280 ft-bgs to the bottom of Layer 3 at 1,290 ft-bgs (505 model cells). The uppermost 280 feet of sediments were not included in the 1D Model because the sediment was unsaturated during the calibration period and therefore not subject to deformation caused by changes in head. The inset in Figure 4 shows an example of the 2-foot cell discretization. Each model cell was assigned to its corresponding 1D Model layer and identified as either an "aquifer" or "aquitard."

Calibration Period and Time Discretization

The calibration period is July 1, 1992 to July 1, 2015, which was chosen based on the availability of InSAR-derived estimates of vertical ground motion at the MVWD-28 location. The calibration of the 1D Model requires initial estimates of head, pre-consolidation head, and compaction for each model cell for July 1, 1992. To obtain these initial estimates, the 1D Model was simulated over a historical period prior to the calibration period, from July 1, 1930 (a time that is assumed to pre-date significant head declines and compaction of aquifer-system sediments in Northwest MZ-1) to June 30, 1992.

The stress period of the 1D Model is three months because the Chino Basin groundwater-flow model, which was used to provide the boundary conditions of head for the 1D Model, runs on a three-month stress period.

Boundary Conditions

The boundary conditions for the "aquifer" layers in the 1D Model are the heads within each model layer. Historical measured heads at wells near MVWD-28 were inspected and charted on Figure 5 to construct a long-term time-series of heads that are representative of the shallow (Layer 1) and deep (Layers 2 and 3) aquifer systems. From about 1930 to 1978, head data were only available from wells screened across Layer 1, which showed a gradual decline of about 175 feet. Heads in Layer 1 increased by about 50-60 feet after

[16] The well driller's log that describes the borehole sediments is attached to this memorandum.

1978. Beginning in the early 1980s, new production wells were drilled deeper and began producing from the deep confined aquifers, which caused lowering of heads in Layers 2 and 3 to elevations lower than heads in Layer 1.

Prior to the 1980s, there is a lack of measured heads in the deep aquifer system. To estimate heads in the deep aquifer system prior to 1980 and to supplement head data after 1980 in all layers, quarterly simulated heads for all layers at the MVWD-28 location were extracted from the calibrated Chino Basin groundwater-flow model to help construct a long-term quarterly time-series of head in all three layers from 1930-2014.

Figure 6 displays the long-term quarterly time-series of heads used as the boundary conditions for Layers 1, 2, and 3 for the period 1930-2014 in the 1D Model (solid line curves). From 1930-1960, the measured water levels at MVWD-15 were used as head estimates in Layer 1; heads in Layers 2 and 3 were assumed to closely follow the heads in Layer 1 during this period because little groundwater, if any, was being pumped from these layers during this period. From 1960-2014, measured and simulated heads were used to construct time-series of heads in all three layers.

The Flow and Head Boundary (FHB) Package[17] was used to assign the estimated time-series of heads in Figure 6 to the 1D Model cells.

Initial Conditions

The 1D Model requires assignment of initial conditions for head, pre-consolidation head, and compaction for each model cell. An initial head of 750.5 ft-amsl for July 1, 1930 was assigned to each model cell in each layer based on the estimated heads shown in Figure 6. Assuming that 1930 was before significant head declines and compaction of the aquifer-system sediments in Northwest MZ-1, the initial pre-consolidation head was also set at 750.5 ft-amsl, and the initial compaction was set to zero for all model cells.

The initial conditions for the start of the calibration period (July 1, 1992) for hydraulic head, pre-consolidation head, and compaction were derived from the 1D Model simulation of July 1, 1930 to June 30, 1992. This process of deriving the initial conditions for the start of the calibration period is described in more detail below.

Initial Aquifer/Aquitard Properties

Table 2a lists the initial estimates of vertical hydraulic conductivity and inelastic and elastic skeletal specific storage that were assigned to all aquifer and aquitard cells by layer. These initial estimates were adopted from the final calibrated Ayala Park 1D Model (WEI, 2005) and were adjusted during calibration.

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[17] Leake, S.A. and Lilly, M.R. (1997). *Documentation of computer program (FHB1) for assignment of transient specified-flow and specified-head boundaries in applications of the modular finite-difference ground-water flow model (MODFLOW).* USGS Open-File Report 97-571.

1D Model Calibration

The calibration of the 1D Model was conducted in an iterative process:

1. Run the 1D Model from July 1, 1930 to June 30, 1992 (historical period) using the specified boundary conditions and the initial aquifer and aquitard properties in Table 2a to derive the distribution of head and pre-consolidation head in all model cells and estimates of total compaction for June 30, 1992.[18] For subsequent iterations, the aquifer and aquitard properties are based on updated values developed in the calibration process.
2. Run the 1D Model from July 1, 1992 to June 30, 2015 (calibration period) using the specified boundary conditions and the distribution of head and pre-consolidation head in all model cells derived from the simulation of the historical period in step 1 above.
3. Compute the time-series of vertical aquifer-system deformation over the calibration period and compare to the InSAR-derived estimates of vertical ground motion at the 1D Model location.
4. Adjust the model's aquifer and aquitard properties to achieve a better match between the simulated aquifer-system deformation and the InSAR-derived estimates of vertical ground motion for the next iteration.

Every model run for calibration was guided by a sensitivity analysis. Parameter sensitivity measures the impact of a small parameter change on the calculated system response. If a small parameter change results in a large change in the simulated compaction of the 1D Model cells, the parameter is regarded as sensitive. Based on these sensitivity analyses, aquitard compaction was sensitive to the inelastic skeletal specific storage, elastic skeletal specific storage, and the vertical hydraulic conductivity. As such, each of these parameters was adjusted during model calibration.

During the calibration process, the 1D Model parameters were adjusted (within expected reasonable bounds) through manual and automatic parameter-estimation techniques to match the simulated aquifer-system deformation to the InSAR-derived estimates of vertical ground motion between July 1992 and June 2015. The computer code PEST (Model-Independent Parameter Estimation and Uncertainty Analysis)[19] was used to conduct the sensitivity analysis and to optimize the 1D Model calibration. The objective function used to calibrate the 1D Model was the sum of the squared weighted residuals. PEST uses the Marquardt-Levenberg method to minimize the objective function. There

[18] A code was developed to sum up the compaction estimates from each saturated model cell for each stress period over the simulation period. Unsaturated cells were excluded from the summations.

[19] Doherty, J. 1994. *PEST*. Watermark Computing, Corinda, Australia, 122p.

are several strategies for updating model parameters, as discussed by Neuman,[20] Carrera and Neuman,[21,22,23] Finsterle and Najita,[24] and Sun and Yeh[25], and in the PEST User Manual.[26] The value of the objective function decreases iteratively with the progress of calibration. The iterative calibration process described above was repeated until a good match between model-simulated aquifer-system deformation and the InSAR-derived estimates of vertical ground motion was obtained within the reasonable bounds for the aquifer and aquitard properties.

Figure 7 shows the time history over the calibration period (1992 to 2015) of InSAR-derived estimates of vertical ground motion and 1D Model estimates of vertical aquifer-system deformation. This figure also shows the gaps in the availability of InSAR-derived estimates of vertical ground motion. Comparison of the two time series indicates that the 1D Model estimates track the time series of the InSAR-derived estimates very well as the time series are nearly identical.

Figure 8 is a scatter plot comparing the InSAR-derived estimates of vertical ground motion to the 1D Model estimates of vertical aquifer-system deformation. The points are distributed closely around the diagonal line. The coefficient of determination is 0.987 which means the 1D Model can explain 98 percent of the variance on the historical data. Another statistical tool to measure model calibration is the Nash-Sutcliffe Efficiency (NSE) index.[27] The NSE index is a normalized statistic, similar to the coefficient of determination, that determines the relative magnitude of the residual variance ("noise") compared to the measured data variance ("information"). The NSE index indicates how well the plot of observed versus simulated data fits the "perfect-fit" line. The NSE index

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[20] Neuman, S.P. (1973). Saturated-unsaturated seepage by finite elements. *ASCE J. Hydraulics Division, 2233-2251*.

[21] Carrera, J., and S. P. Neuman. (1986a). Estimation of Aquifer Parameters Under Transient and Steady State Conditions: 1. Maximum Likelihood Method Incorporating Prior Information. *Water Resources Research, Vol. 22, No. 2*, p 199-210.

[22] Carrera, J., and S. P. Neuman. (1986b). Estimation of aquifer parameters under steady state and transient condition: 2. Uniqueness, Stability, and Solution Algorithms. *Water Resources Research, Vol. 22, No. 2,* p 211 – 227.

[23] Carrera, J., and S. P. Neuman. (1986c). Estimation of Aquifer Parameters Under Transient and Steady State Conditions: 3. Application to Synthetic and Field Data. *Water Resources Research, Vol. 22, No. 2,* p. 228-242, 1986c.CDM. 1995. 1990-94 Groundwater Conditions. November 1, 1995.

[24] Finsterle, S. and Najita, J. (1998). Robust estimation of hydrogeologic model parameters. *Water Resources Research, Vol. 34, No. 11,* p. 2939-2947.

[25] N-Z Sun, N-Z. and Yeh, WW-G. (1992). A stochastic inverse solution for transient groundwater flow: Parameter identification and reliability analysis. *Water Resources Research, Vol. 28, No. 12.*

[26] Doherty, J. 1994. *PEST*. Watermark Computing, Corinda, Australia, 122p.

[27] Nash, J. E., and J. V. Sutcliffe. (1970). River flow forecasting through conceptual models: Part 1. A discussion of principles. J. *Hydrology 10(3): 282-290*. Parker, R., J. G. Arnold.

ranges between negative infinity and 1.0, with the NSE index equal to 1.0 being the optimal value. Values between 0.5 and 1.0 are generally viewed as acceptable levels of performance, whereas values less than 0.0 indicate that the mean observed value is a better predictor than the model-estimated value, which indicates unacceptable performance. The characterization of calibration performance using the NSE index is reported by Moriasi[28] as follows: negative infinity to 0.5 as unsatisfactory; 0.5 to 0.65 as satisfactory; 0.65 to 0.75 as good; 0.75 to 1.0 as very good. The NSE index for the 1D Model is 0.987, indicating a very good calibration.

Table 2b shows the final calibrated aquifer-system properties that are within reasonable bounds (other areas where these properties have been estimated, such as at Ayala Park).

Model Errors and Limitations

In general, a groundwater model is a simplified mathematical representation of a complex hydrogeologic system. Because of this, there are limits to the accuracy of the model and the use and interpretation of the model results. There are various sources of error and uncertainty. Model error commonly stems from the conceptual model, practical limitations of grid cell size and time discretization, parameter structure, insufficient calibration data, and the effects of processes not simulated by the model. These factors, along with error in observations, result in uncertainty in model results.

The potential errors and limitations associated with the 1D Model and its calibration include:

- The 1D Model was based on the limited resolution, depth, and accuracy of the description of the aquifer-system sediments, as documented on the MVWD-28 well driller's log.
    - The resolution by depth interval of the geologic descriptions in this log are typically greater than five feet, which may not be a fine enough resolution to characterize any thinner interbedding of aquifer and aquitard layers that are an important control on aquifer-system deformation.
    - The borehole did not penetrate the semi-consolidated bedrock formations; there may be deforming sediments at depths below the borehole bottom that are responsible for some of the vertical ground motion estimated by InSAR.
    - The borehole sediments were not described by a registered geologist or hydrogeologist. There is less confidence in lithologic descriptions that are not prepared using a standard classification system or under the

[28] Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Binger, r. l., Harmel, R. D., Veith, T. L. 2007. *Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations.* Vol. 50(3): 885−900 2007 American Society of Agricultural and Biological Engineers ISSN 0001−2351.

supervision of a licensed professional (e.g., professional geologist, certified hydrogeologist, or geotechnical engineer) with adequate training and experience in logging sediments.

- Most wells in Northwest MZ-1 have well screens that only penetrate the shallow aquifer system or penetrate both the shallow and deep aquifer systems. There are no wells that are screened only across the deep aquifer system, meaning that there are no historical measured water-level data for only the deep aquifer system. As such, there is some uncertainty in the long-term time-series of heads for Layers 2 and 3 that were used as the boundary conditions for the 1D Model calibration, which creates uncertainty in the model results.
- Water-level data at wells is scarce in Northwest MZ-1 prior to the 1930s. This 1D Model effort assumes that the significant lowering of heads in Northwest MZ-1 began after 1930, which may not be an accurate assumption. If head declines began before 1930, then this could impact the 1D Model calibration and add uncertainty in the model results.
- The 1D Model used InSAR-derived estimates of vertical ground motion as calibration targets for aquifer-system compaction. The limitations of using InSAR-derived estimates as calibration targets are: (i) the InSAR record is from 1992 to 2016, which limits the length of the calibration period; (ii) there are multiple data gaps in the InSAR record because of satellite malfunctions and satellite replacement; and (iii) InSAR produces an aggregate estimate of aquifer-system deformation and therefore provides no depth-specific calibration targets. Due to the lack of depth-specific calibration there is greater uncertainty in the depth-specific estimates for the aquifer and aquitard properties, and hence, the model results.

Continued monitoring and enhanced understanding of hydrogeologic conditions is crucial to minimizing model error and uncertainty, especially the construction and monitoring of the PX in Northwest MZ-1. Monitoring and testing can identify local anomalies associated with geologic complexity that are not currently represented in the model. Model error and uncertainty can be reduced by incorporating new monitoring information into future models. For example, Task 8 of the Work Plan, which includes the construction and calibration of a new 1D Model, will include a task to research and identify historical water-level measurements in Northwest MZ-1 prior to 1930, and include any newly-discovered water-level data in the calibration.

Historical Subsidence Simulation

The final calibration run for the 1D Model indicated a total of about 7.6 feet of aquifer-system compaction at the 1D Model location from 1930 to 2015. Figure 9 shows the time-series of the simulated compaction and indicates that most of the historical compaction (about 6.7 feet) occurred between 1930 and 1978—the period of gradual and persistent lowering of groundwater levels by about 190 feet in Northwest MZ-1.

There are no historical leveling data near the MVWD-28 site to confirm the 1D Model results. That said, Figure 3 and Table 1 show that 3.5 feet of subsidence occurred between 1923 and 1974 at benchmark EV3052 and 1.64 feet of subsidence occurred between 1968 and 1978 at benchmark EV3054, which are both consistent with the timing and magnitude of the compaction that was estimated by the 1D Model at its location over the historical simulation period.

The final calibration run also generated end-of-calibration (2015) estimates of the pre-consolidation head by layer at the 1D Model site, which are displayed on Figure 10. Note that the 2015 heads for layers 2 and 3 are equal to or marginally greater than their respective 2015 pre-consolidation heads, while the 2015 head for layer 1 is about 25 feet higher than its 2015 pre-consolidation head. This suggests that the deep aquifer system is more susceptible to compaction compared to the shallow aquifer system should heads decline in the future.

Estimates of Future Subsidence in Northwest MZ-1

Baseline Management Alternative (BMA)

The objective of projecting aquifer-system compaction for the BMA is to estimate the future occurrence of subsidence in Northwest MZ-1 using a recently developed and investigated planning scenario that was used by the Watermaster to recalculate Safe Yield. The BMA used herein is Planning Scenario 5A. Planning Scenario 5A contains the projected groundwater pumping and managed artificial recharge plans for the period 2011 through 2050. Scenario 5A was developed in 2011 for the 2013 Amendment to the 2010 Recharge Master Plan Update and was subsequently used in 2014 to recalculate Safe Yield. Watermaster used the 2013 Chino Basin groundwater model to project the basin response to Scenario 5A, and specifically the period 2011 through 2020 to estimate the Safe Yield. Scenario 5A has also been used as a pre-project or baseline scenario to evaluate the groundwater basin response to proposed recharge projects and storage management plans. A complete description of Planning Scenario 5A and the model projection of future groundwater conditions is published on Watermaster's website.[29]

Model-Predicted Estimates of Future Subsidence associated with the BMA

Figure 10 shows the projected changes in heads by model layer at the 1D Model site for the BMA from 2015 to 2045.[30] Under the BMA, heads in all layers begin to gradually decline after about 2020 and decline at a greater rate after 2025.

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[29] http://www.cbwm.org/docs/engdocs/WEI 2013 CBWM Recalculation Model Update/

[30] The initial heads for the BMA were adjusted to match the final heads from the final calibration run for the 1D Model.

Figure 10 displays the 2015 model-predicted estimates of the pre-consolidation head by layer at the 1D Model location. At the beginning of the simulation, the initial heads for all three layers are near or above the initial pre-consolidation heads, which indicates that aquifer-system compaction should be relatively minor from 2015-2025. After about 2025, heads in layers 2 and 3 are projected to fall below their respective 2015 pre-consolidation heads, which indicates that aquifer-system compaction will occur at higher rates. After about 2032, head in layer 1 is projected to fall below its 2015 pre-consolidation head, which indicates that rates of aquifer-system compaction will further increase.

The time-series of heads by model layer shown on Figure 10 were used as input data for boundary conditions of the 1D Model to simulate aquifer-system compaction and predict timing and magnitude of future subsidence under the BMA. Figure 11 shows the 1D Model results for aquifer-system compaction under the BMA. A minor seasonal elastic deformation of the aquifer-system sediments is shown by the “wavy” form of the time-series curve. From 2015-2025, total compaction is projected to be about 0.1 ft at the 1D Model location. From 2025 to 2045, the 1D Model predicts increasing rates of aquifer-system compaction and about 1.65 ft of total compaction at the 1D Model location.

The preliminary conclusions of the 1D Model results for the BMA are:

- The deep aquifer system (layers 2 and 3) is most susceptible to aquifer-system compaction if future head declines occur in Northwest MZ-1 on the order of 70 ft, as projected under the BMA.
- Future head declines in Northwest MZ-1 on the order of 70 ft, as projected under the BMA, may cause aquifer-system compaction and differential land subsidence in Northwest MZ-1 on the order of at least 1.6 ft by 2045.
- If heads in all layers in Northwest MZ-1 remain relatively stable in the future, aquifer-system compaction may occur at rates of approximately 0.01 ft/yr.
- Heads in the deep aquifer system need to increase by at least 10 ft and remain above the current pre-consolidation head to abate ongoing subsidence in Northwest MZ-1.

Initial Subsidence-Management Strategies (ISMSs)

The objective of developing and evaluating the ISMSs is to develop preliminary information on the efficacy of various recharge and production schemes that could be used to develop a full-scale subsidence management plan for Northwest MZ-1. The ISMSs described and evaluated herein are modifications to the BMA that include either increased wet-water recharge in Northwest MZ-1 or decreased production in Northwest MZ-1. The assumptions of the ISMSs are outlined in the table below. Refinements to the

ISMSs will likely occur after the construction of the PX, updates to the modeling tools, and input from the Chino Basin parties and the GLMC.[31]

Description of the Initial Subsidence-Management Strategies (ISMSs) and Associated Chino Basin Groundwater Model Scenarios

ISMS Scenario	Description
S5P	Increase wet-water recharge in Northwest MZ-1 to 50 percent of the production volume of the cities of Pomona and Upland, SAWCo, and MVWD.
S5Q	Decrease production by the Cities of Pomona and Upland, SAWCo, and the MVWD by 50 percent.
S5R	Increase wet-water recharge in Northwest MZ-1 to 66 percent of the production volume of the Cities of Pomona and Upland, SAWCo, and the MVWD.
S5S	Decrease production by the Cities of Pomona and Upland, SAWCo, and the MVWD by 66 percent.

Estimates of Future Subsidence associated with the ISMSs

Figures 12a, 12b, and 12c show the projected heads under the ISMSs at the 1D Model location for each model layer from 2015 to 2045. Also shown are the 2015 pre-consolidation heads for each layer that were determined from 1D Model calibration. If heads fall below the pre-consolidation head, permanent compaction of the aquifer-system sediments and land subsidence are predicted to occur.

The preliminary conclusions of the 1D Model results for the ISMSs shown on Figures 12a, 12b, and 12c are:

- Heads in all layers can be elevated and maintained above the 2015 estimates of pre-consolidation head through 2045 under each ISMS. This suggests that future subsidence can be minimized or eliminated over the next 30 years under management strategies that are no more aggressive than ISMS Scenarios S5P and S5Q.
- In the deep aquifer system (layers 2 and 3 in Figures 12b and 12c), the ISMSs that include decreased production (S5Q and S5S) are more effective at increasing heads, immediately and over the long-term, than the ISMSs that include increased

[31] See Task 9 in *Work Plan to Develop a Subsidence Management Plan for the Northwest MZ-1 Area*. http://www.cbwm.org/docs/engdocs/Land%20Subsidence/20150724%20-%20Chino%20Basin%20Subsidence%20Management%20Plan%202015/FINAL_CBSMP_Appendix_B.pdf

recharge at basins (S5P and S5R). This is an important conclusion because this modeling effort indicates that the deep aquifer system is more susceptible to aquifer-system compaction compared to the shallow aquifer system if heads decline in Northwest MZ-1 in the future.

- In the shallow aquifer system (layer 1 in Figure 12a), the ISMSs that include increased recharge at basins (S5P and S5R) are just as or more effective at increasing heads than the ISMSs that include decreased production (S5Q and S5S), particularly over the long-term.

Recommendations

The 1D Model was constructed and calibrated with limited data and hydrogeologic information. The use of the 1D Model and interpretation of its results is limited by significant but un-quantified uncertainty—uncertainty that is likely too great to provide sufficient confidence for use of the 1D Model to develop and evaluate a final subsidence management plan for Northwest MZ-1. Information, had it existed, that would have been useful in its construction and calibration are:

- Descriptions of the aquifer-system sediments deeper than 1,300 ft-bgs. These sediments could be compacting but were excluded from the 1D Model because there are no boreholes that penetrate these depths in Northwest MZ-1.
- Geologic and hydrogeologic data to constrain the depth-specific values of aquifer-system properties that control compaction, including vertical hydraulic conductivity and elastic and inelastic skeletal specific storage. These data will hopefully be obtained from the drilling and construction of the PX and by monitoring for depth-specific changes in head at the monitoring wells and depth-specific aquifer-system deformation at the extensometers.
- Water-level data at wells is scarce in Northwest MZ-1 prior to the 1930s. This report assumes that the significant lowering of heads in Northwest MZ-1 began after 1930, which may not be an accurate assumption. Task 8 of the Work Plan, which includes the construction and calibration of a new 1D Model, will include a task to investigate historical production and water-level measurements in Northwest MZ-1, and include any newly-discovered water-level data in the calibration

The construction of the Pomona Extensometer to a planned depth of 1,500 ft-bgs, subsequent monitoring and testing, and investigation to identify additional historical water-level measurements at wells, will provide additional information that can be used to construct and calibrate new and improved numerical models of groundwater flow and subsidence. These new models, along with updated pumping projections, may be used to update estimates of pre-consolidation head by aquifer-system layer, and build upon the ISMSs evaluated in this memorandum to ultimately develop a subsidence-management plan for Northwest MZ-1. These recommendations are consistent with the Watermaster-approved *Work Plan to Develop a Subsidence Management Plan for the Northwest MZ-1 Area*.

Attachments

1. Well driller's log for MVWD Well 28.
2. Responses to comments from the GLMC.

Tables and Figures

Table 1
Adjusted Benchmark Elevations and Elevation Change Across Northwest MZ-1 -- *1923-2011*

Benchmark Name	Latitude	Longitude	1923	1932	1934	1961	1968	1969	1974	1978	1994	2011	1923-1974	1968-1974	1969-1974	1968-1978	1969-1978	1994-2011
			Elevation (ft)										Elevation Change (ft) and Annual Rate of Change (ft/year)*					
NGS Surveys (1923 to 1978)																		
EV2715	34°03'30"N	117°45'30"W					849.060		849.045	849.016				-0.014 *-0.002*		-0.044 *-0.004*		
EV2716	34°03'27"N	117°45'13"W	855.302	855.283														
EV3044	34°03'34"N	117°41'18"W						957.196	956.860						-0.336 *-0.067*			
EV3045	34°03'34"N	117°41'49"W						946.193	945.590						-0.603 *-0.121*			
EV3048	34°03'35"N	117°42'57"W					907.858		907.097	906.512				-0.760 *-0.127*		-1.346 *-0.135*		
EV3049	34°03'33"N	117°43'24"W					898.711		897.861	897.288				-0.850 *-0.142*		-1.423 *-0.142*		
EV3050	34°05'39"N	117°40'10"W				1,223.103		1,222.987										
EV3052	34°03'31"N	117°45'09"W	862.201	862.186	862.172				858.660				-3.541 *-0.069*					
EV3054	34°03'35"N	117°43'54"W					885.194		884.215	883.550				-0.979 *-0.163*		-1.644 *-0.164*		
EV3056	34°03'31"N	117°44'26"W					875.556		874.849	874.189				-0.707 *-0.118*		-1.367 *-0.137*		
EV3057	34°03'29"N	117°44'45"W					861.800		861.382					-0.417 *-0.070*				
EV3059	34°05'38"N	117°42'23"W						1,169.386	1,169.435	1,169.348					0.049 *0.010*		-0.038 *-0.004*	
EV3060	34°05'38"N	117°41'55"W						1,183.997	1,184.032	1,183.944					0.035 *0.007*		-0.052 *-0.006*	
EV3061	34°05'38"N	117°41'16"W						1,202.498	1,202.544	1,202.482					0.047 *0.009*		-0.016 *-0.002*	
EV3063	34°05'38"N	117°40'48"W		1,204.366		1,204.438												
EV3071	34°05'58"N	117°42'23"W						1,225.571		1,225.565							-0.006 *-0.001*	
EV3162	34°03'34"N	117°41'50"W	944.940	944.943														
MWD Surveys (1994 to 2001)																		
AB8243	34°5'38.00"N	117°44'56.60"W									1,071.20	1,071.20						0.00 *0.000*
AB8241	34°5'25.10"N	117°44'10.00"W									1,074.18	1,074.16						-0.02 *-0.003*
AB8240	34°5'26.00"N	117°43'29.20"W									1,099.45	1,099.34						-0.11 *-0.016*
AB8239	34°5'19.20"N	117°43'20.00"W									1,094.16	1,093.97						-0.19 *-0.027*
AB8238	34°5'12.00"N	117°42'55.00"W									1,082.91	1,082.46						-0.45 *-0.064*
AB8237	34°5'4.00"N	117°42'41.00"W									1,087.57	1,086.86						-0.71 *-0.101*
AB8234	34°4'54.10"N	117°41'22.00"W									1,095.01	1,094.96						-0.05 *-0.007*
AB8233	34°4'53.60"N	117°40'52.20"W									1,106.34	1,106.34						0.00 *0.000*
AB8232	34°4'53.60"N	117°40'15.50"W									1,115.60	1,116.60						1.00 *0.143*
EV3031	34°4'40.00"N	117°40'14.00"W									1,089.17	1,089.17						0.00 *0.000*

Blank cells = No data

*Elevation change is not italicized. Annual rate of elevation change is italicized.

Table 2a
Initial Estimates of Aquifer-System Properties for the 1D Model

Model Layer	Depth	Aquifer Code*	Kv	Sskv	Sske
	ft-bgs		ft/day	1/ft	
1	280 - 800	1	5.00E-01	1.00E-06	1.00E-06
		2	7.22E-05	6.11E-05	1.11E-05
2	800 - 1,140	1	1.00E-01	1.00E-06	1.00E-06
		2	5.65E-05	3.22E-05	7.22E-06
3	1,140 - 1,290	1	1.00E-01	1.00E-06	1.00E-06
		2	5.65E-05	3.33E-05	4.63E-06

Table 2b
Final Calibrated Estimates of Aquifer-System Properties for the 1D Model

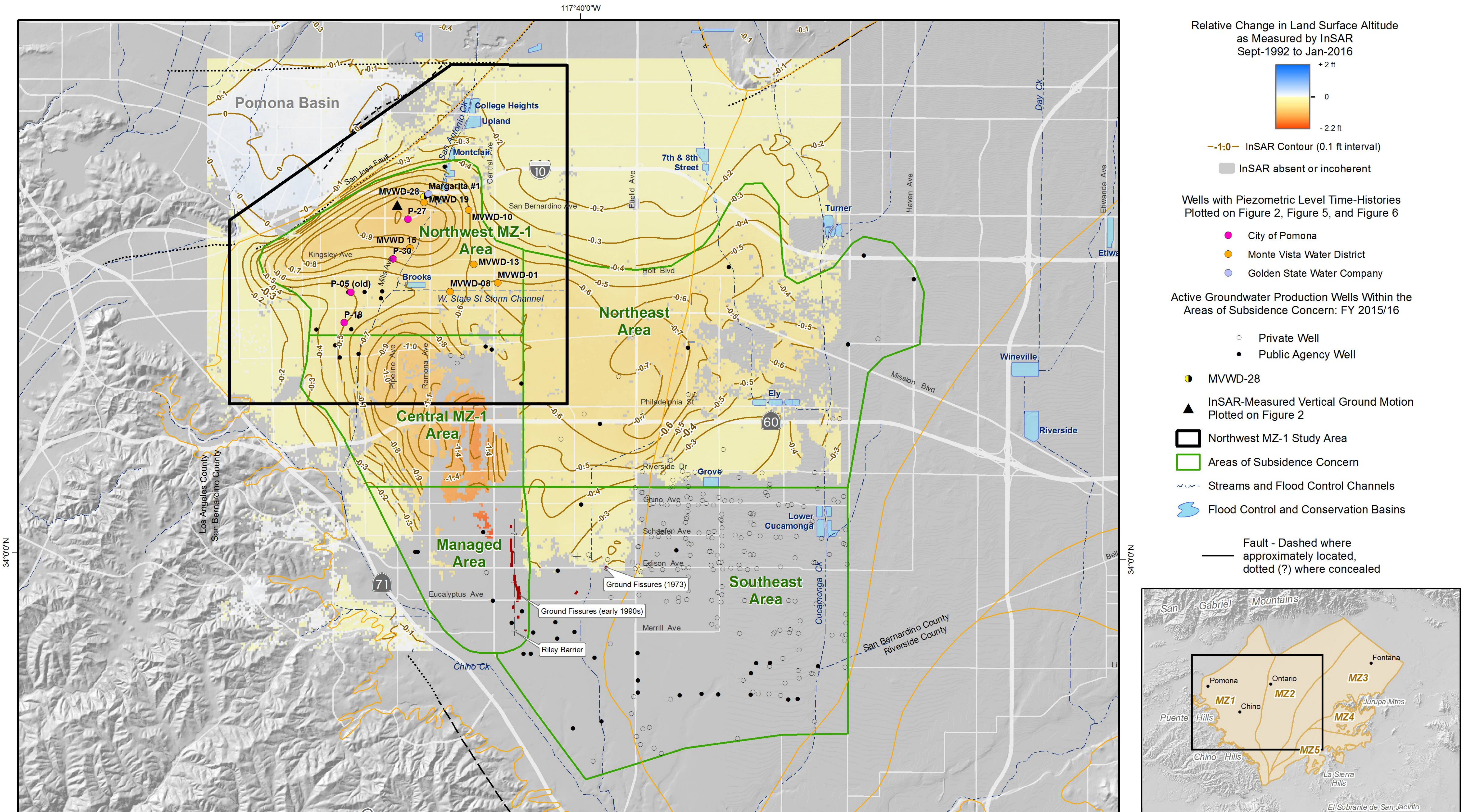
Model Layer	Depth	Aquifer Code*	Kv	Sskv	Sske
	ft-bgs		ft/day	1/ft	
1	280 - 800	1	5.00E-01	1.00E-06	1.00E-06
		2	7.22E-05	1.05E-04	4.50E-06
2	800 - 1,140	1	1.00E-01	1.00E-06	1.00E-06
		2	2.65E-05	1.05E-04	4.50E-06
3	1,140 - 1,290	1	1.00E-01	1.00E-06	1.00E-06
		2	2.65E-05	1.05E-04	4.50E-06

*Aquifer Code 1 = Aquifer; 2 = Aquitard

Kv = Vertical hydrualic conductivity

Sskv = Inelastic, or virgin skeletal specific storage

Sske = elastic skeletal specifc storage



Prepared by:

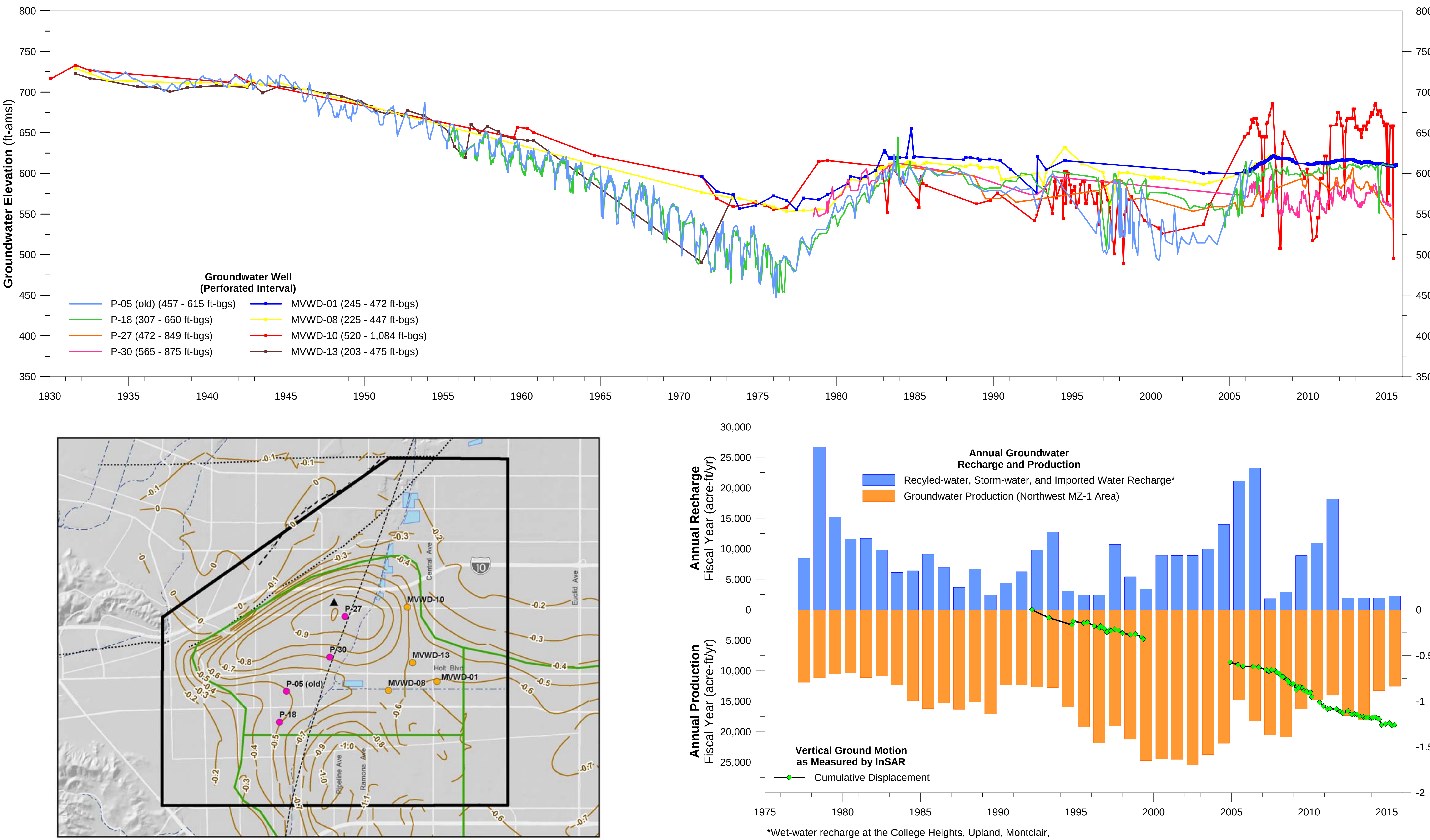
WEI
WILDERMUTH ENVIRONMENTAL, INC.

Author: MAB
Date: 12/13/2017
Document Name: 20170504_NWMZ1_LocationMap11x17

Baseline Management Alternative
for the Northwest MZ-1 Area

Historical Vertical Ground Motion in the Western Chino Basin
1992 to 2016

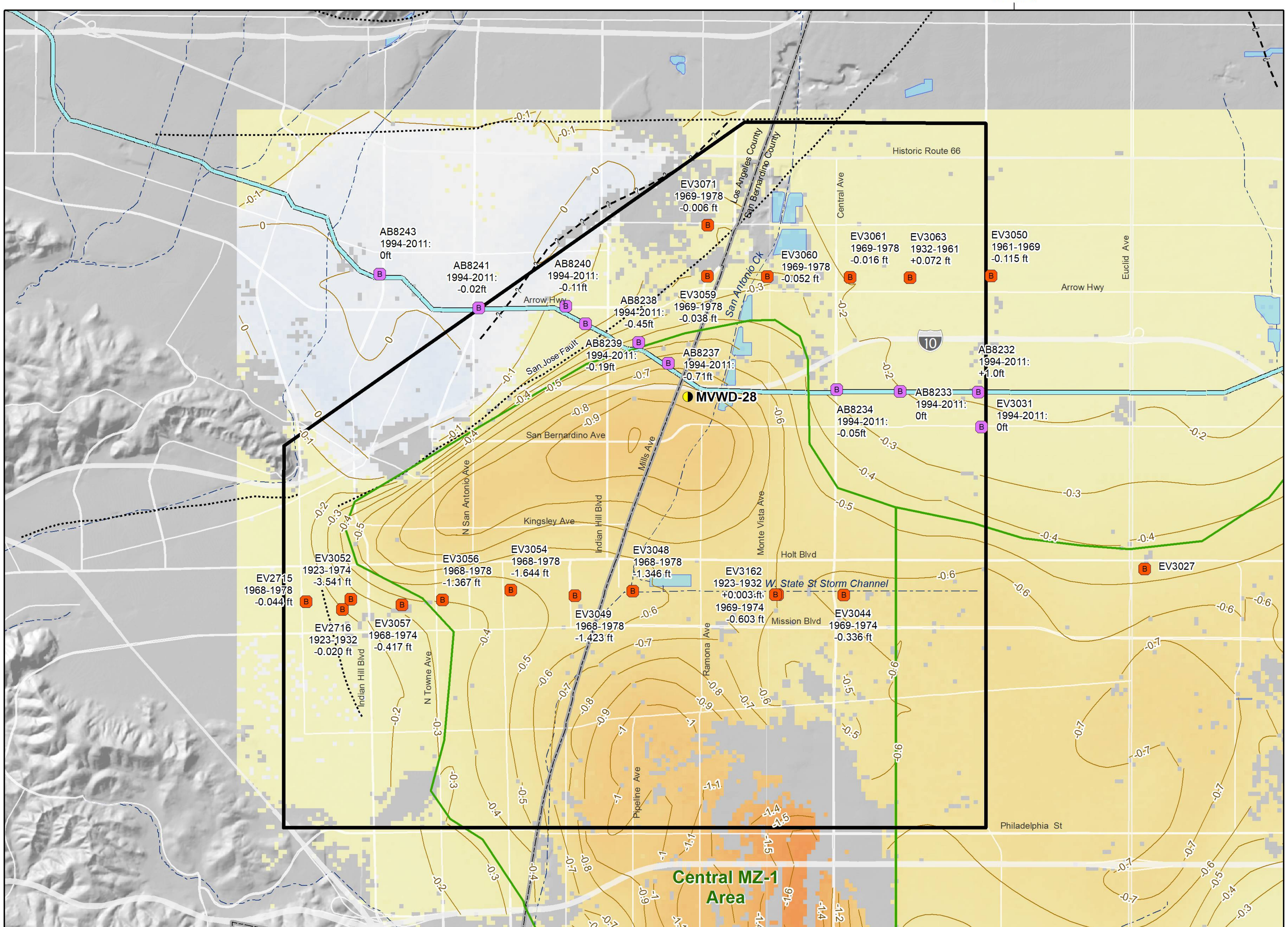
Figure 1



*Wet-water recharge at the College Heights, Upland, Montclair, and Brooks Basins; and at MVWD ASR wells

Time-History of Recharge, Production, Piezometric Levels, and Ground Motion in the Northwest MZ-1 Area

Figure 2



Relative Change in Land Surface Altitude as Measured by InSAR Sept. 1992 to Jan. 2016

+ 2.0 ft
0
- 2.2 ft

InSAR data absent (incoherent)

-0.1 InSAR Contour (0.1 ft interval)

NGS Historic Benchmarks

MWD Benchmarks

Location of 1D Model at MVWD Well 28

Northwest MZ-1 Study Area

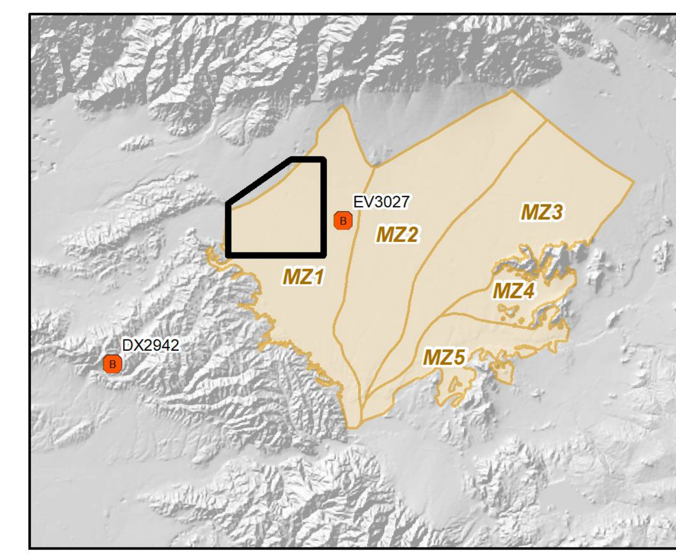
Areas of Subsidence Concern

MWD Upper Feeder

Streams and Flood Control Channels

Flood Control and Conservation Basins

Fault - Dashed where approximately located, dotted (?) where concealed



WILDERMUTH ENVIRONMENTAL, INC.

Author: MAB
Date: 9/6/2017
Document Name: 20161220_HistrBenchmarkReview_v2_11x17

0 1 2 Miles
0 1 2 Kilometers

Subsidence Management Alternatives
for the Northwest MZ-1 Area

Historical Elevation Surveys at Benchmarks in Northwest MZ-1
1923 to 1978 and 1994 to 2011

Figure 3

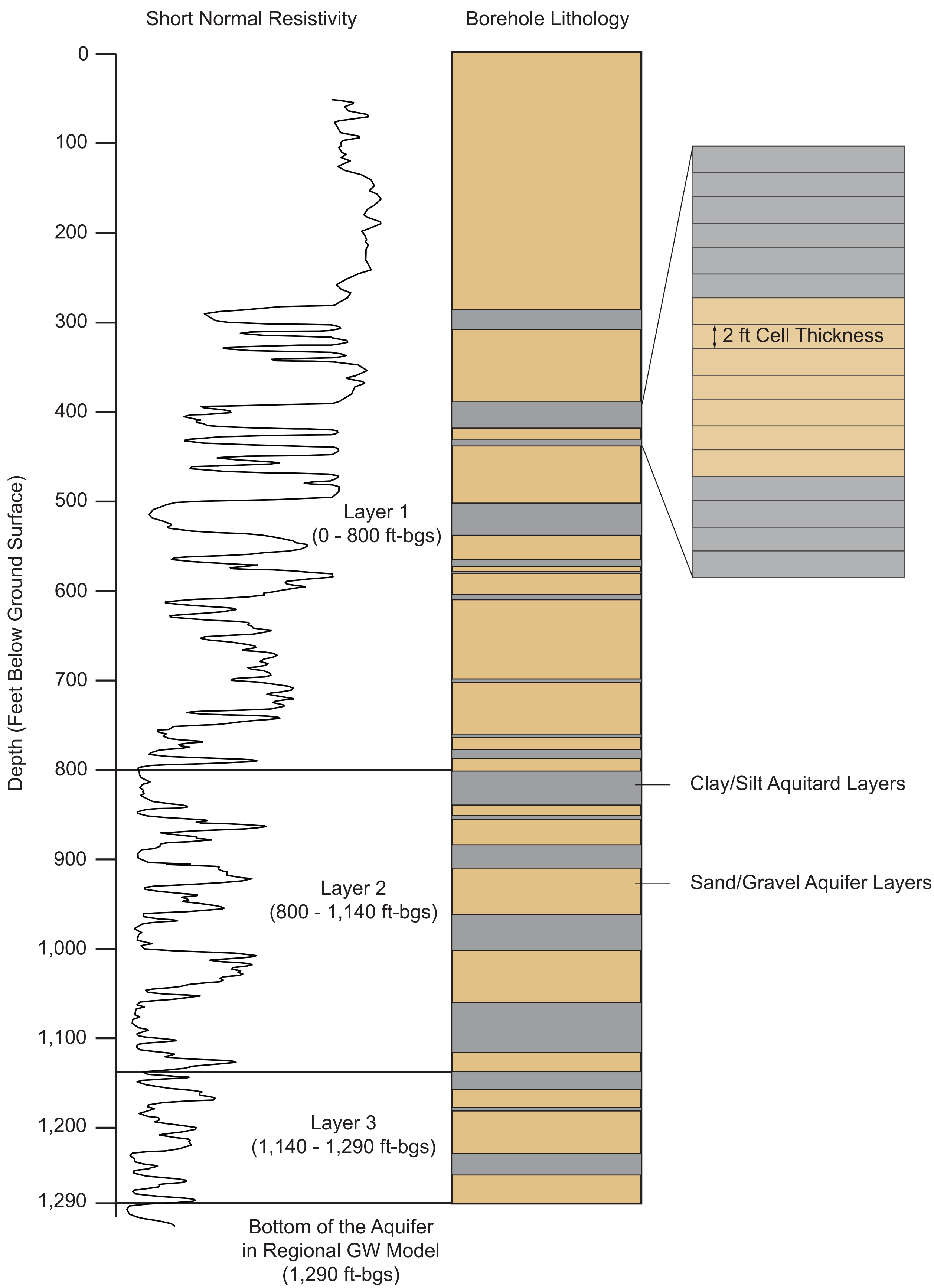
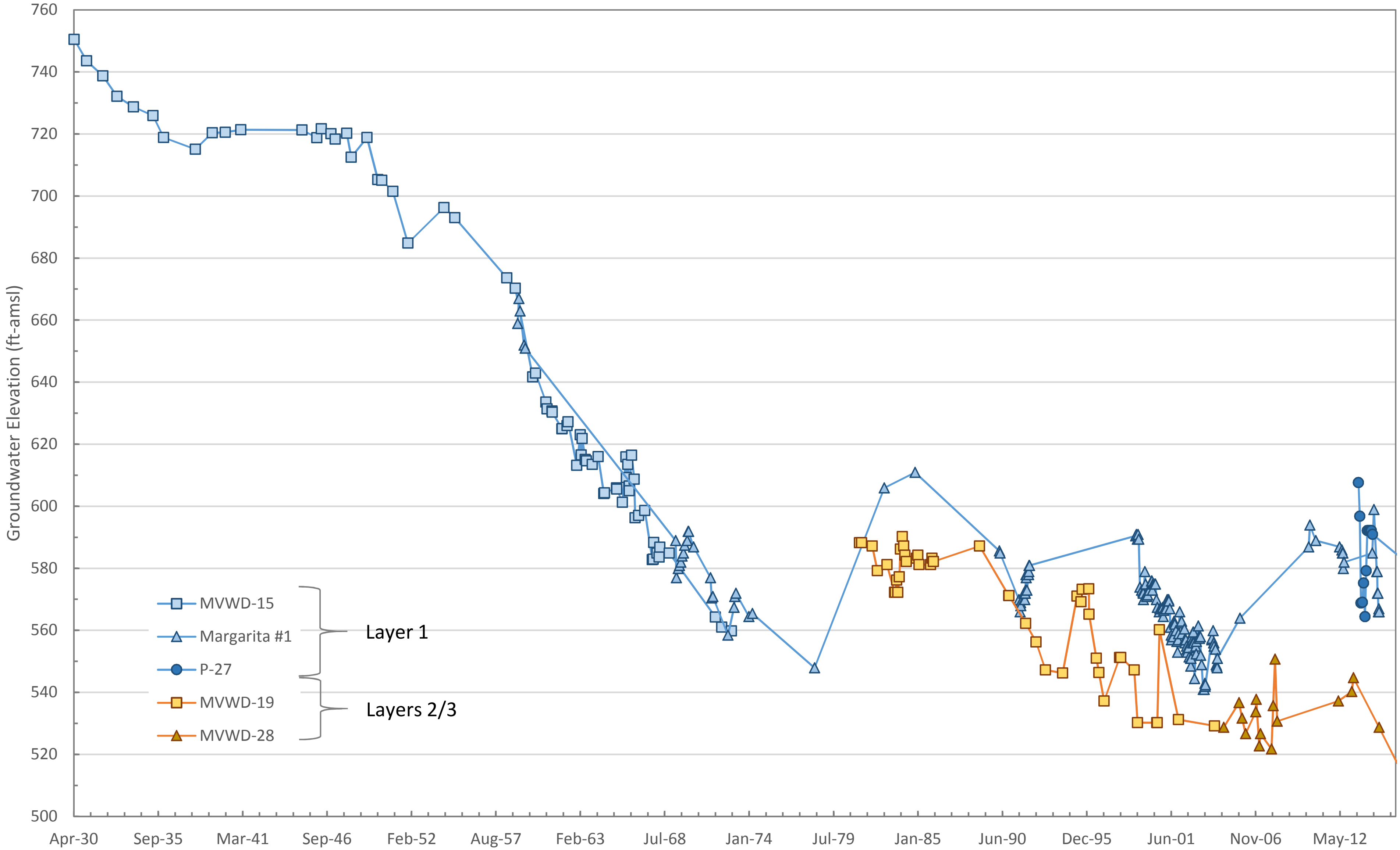


Figure 4. Generalized hydrogeology of the 1D aquifer-system compaction model and grid based on the MVWD-28 lithologic and resistivity logs. Inset shows the 2-foot cell spacing used throughout the entire model.

Figure 5

Time Series of Measured Groundwater Elevations at Wells

Near the 1D Model Location within the Shallow (Layer 1) and Deep (Layers 2 and 3) Aquifer Systems

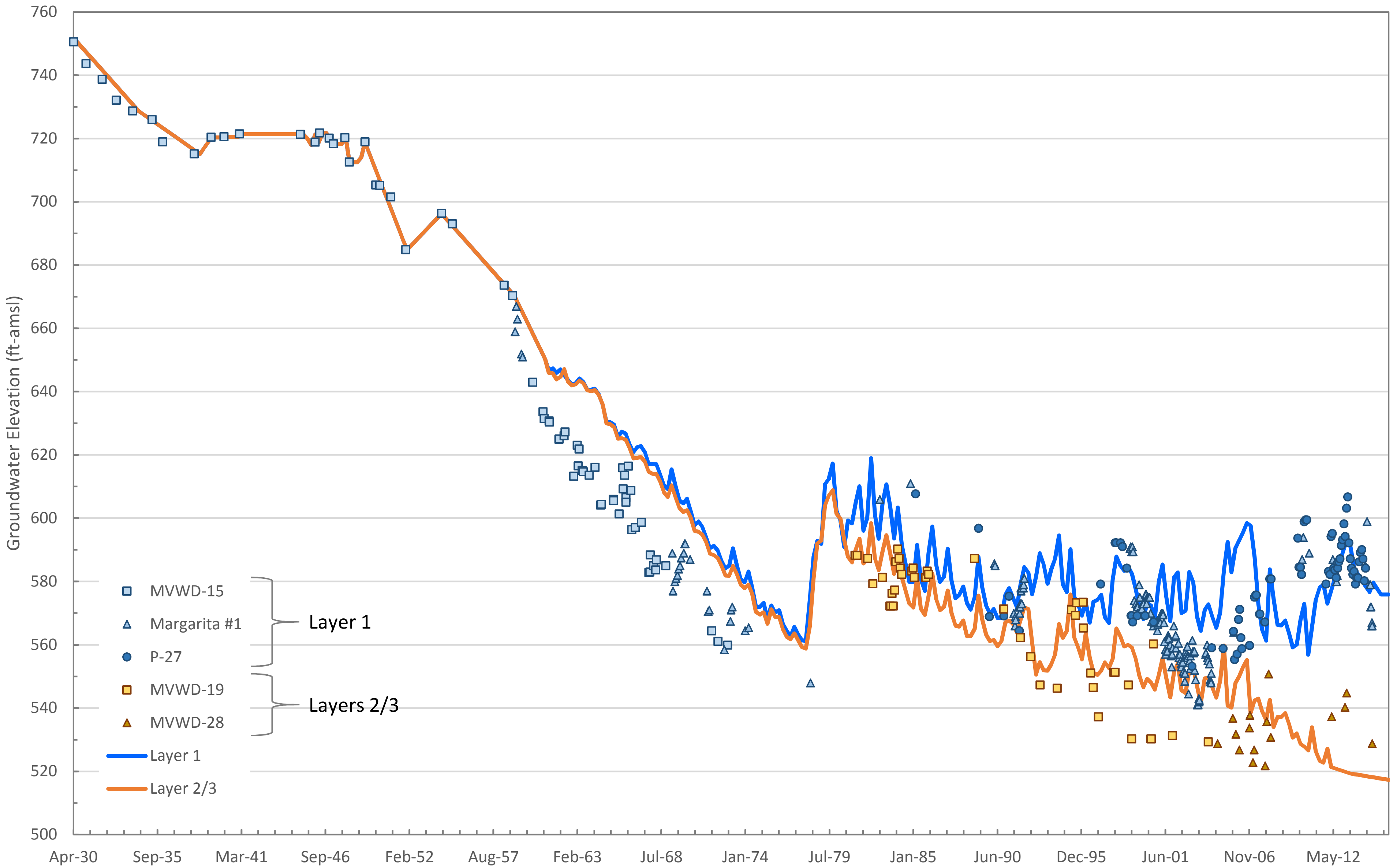


10/9/2017 -- 10:42 AM

Figure 5_Figure 6_WaterLevels_BC -- Figure5_MV28wells_WL

Figure 6

Time Series of Groundwater Elevations by Model Layer Used to Calibrate the 1D Model

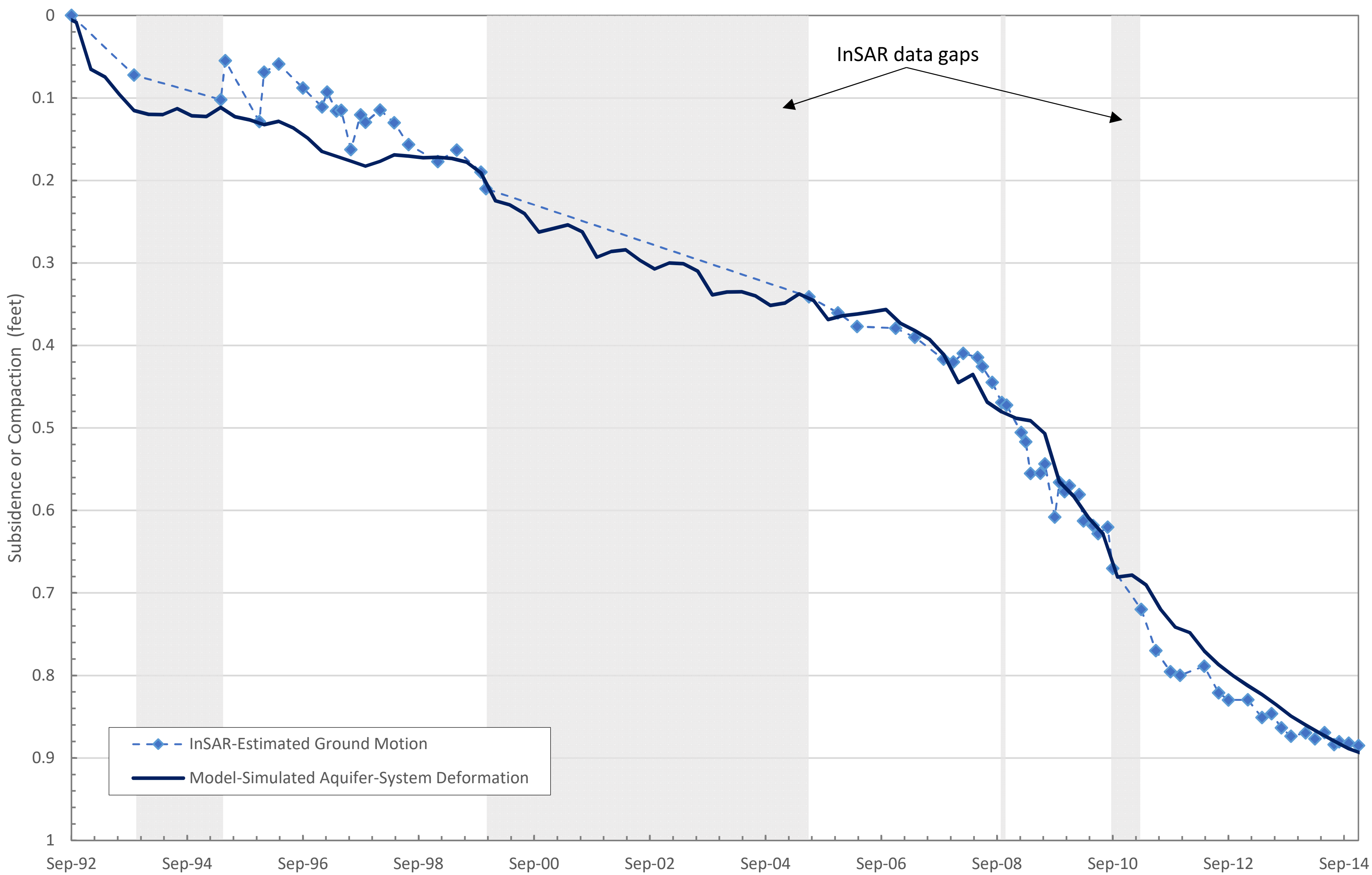


10/9/2017 -- 10:43 AM

Figure 5_Figure 6_WaterLevels_BC -- Figure6_L1_L2_WL

Figure 7

Model-Simulated Aquifer-System Deformation versus InSAR-Estimated Ground Motion at the MVWD-28 Well Location for Final Calibration of the 1D Model



10/11/2017 - 10:27 AM
Figure 7_Figure 8_Figure 9_Model_results_v4b

Figure 8

Model-Simulated Compaction vs. InSAR-Estimated Subsidence for Final Calibration of the 1D Model

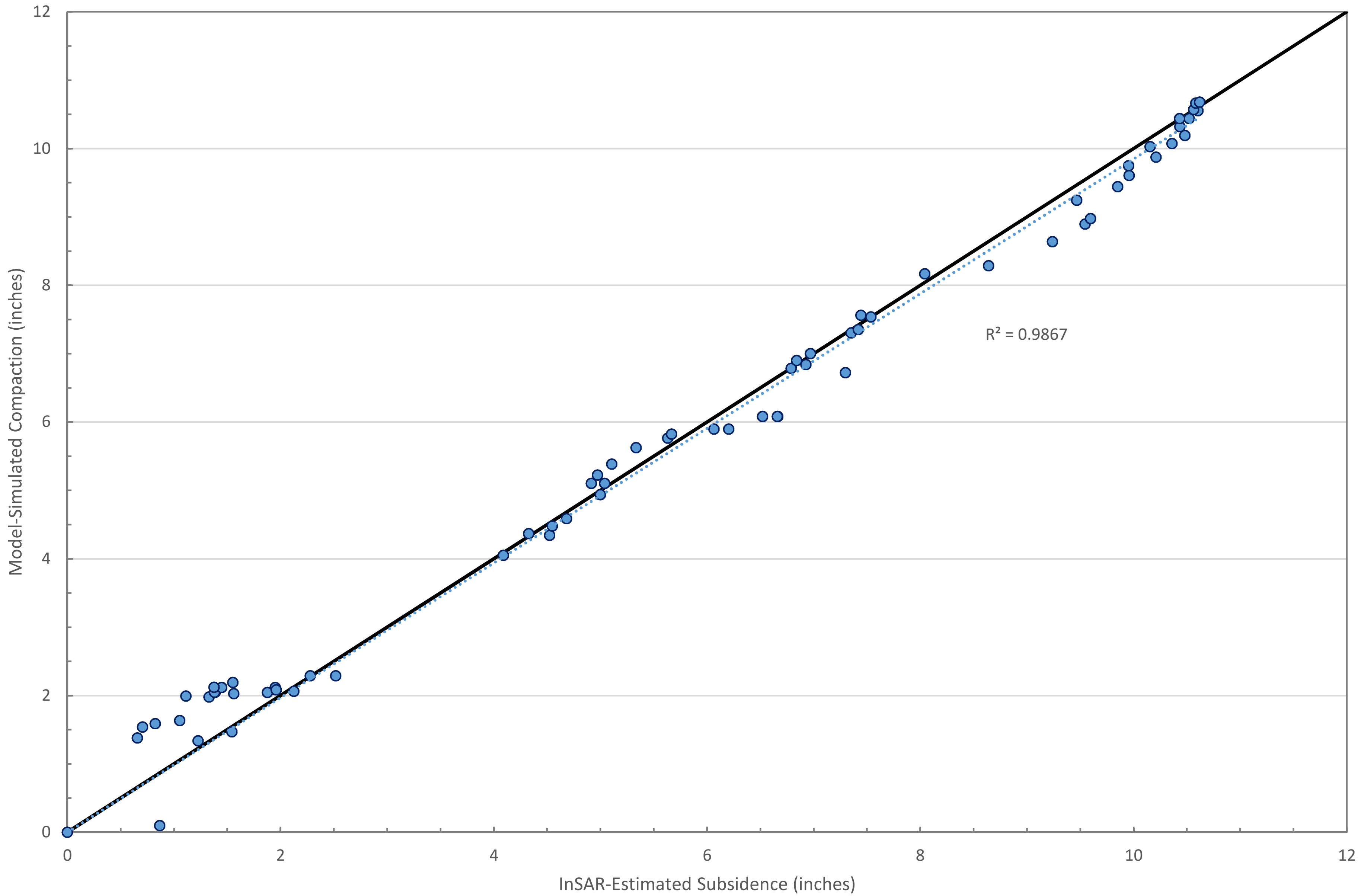
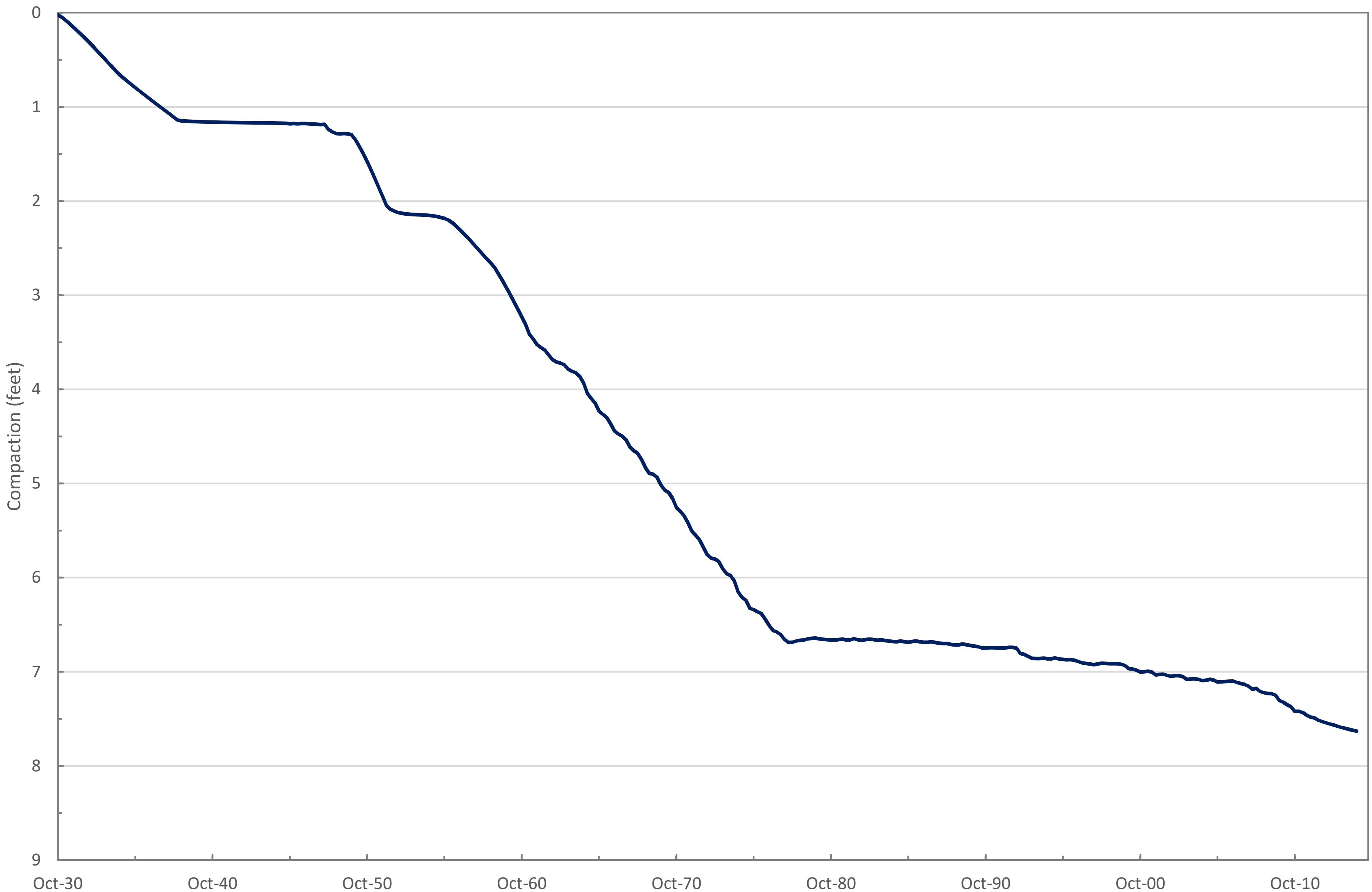


Figure 7_Figure 8_Figure 9_Model_results_v4b -- Figure8_Measured_Observed_Cmpr
10/11/2017

Figure 9

1D Model Simulated Compaction at the MVWD-28 Well Location

1930-2015



10/11/2017 - 11:01 AM

Figure 7_Figure 8_Figure 9_Model_results_v4b

Figure 10

Projected Heads by Layer at the 1D Model Location under the Baseline Management Alternative
Compared to Estimated 2015 Preconsolidation Heads

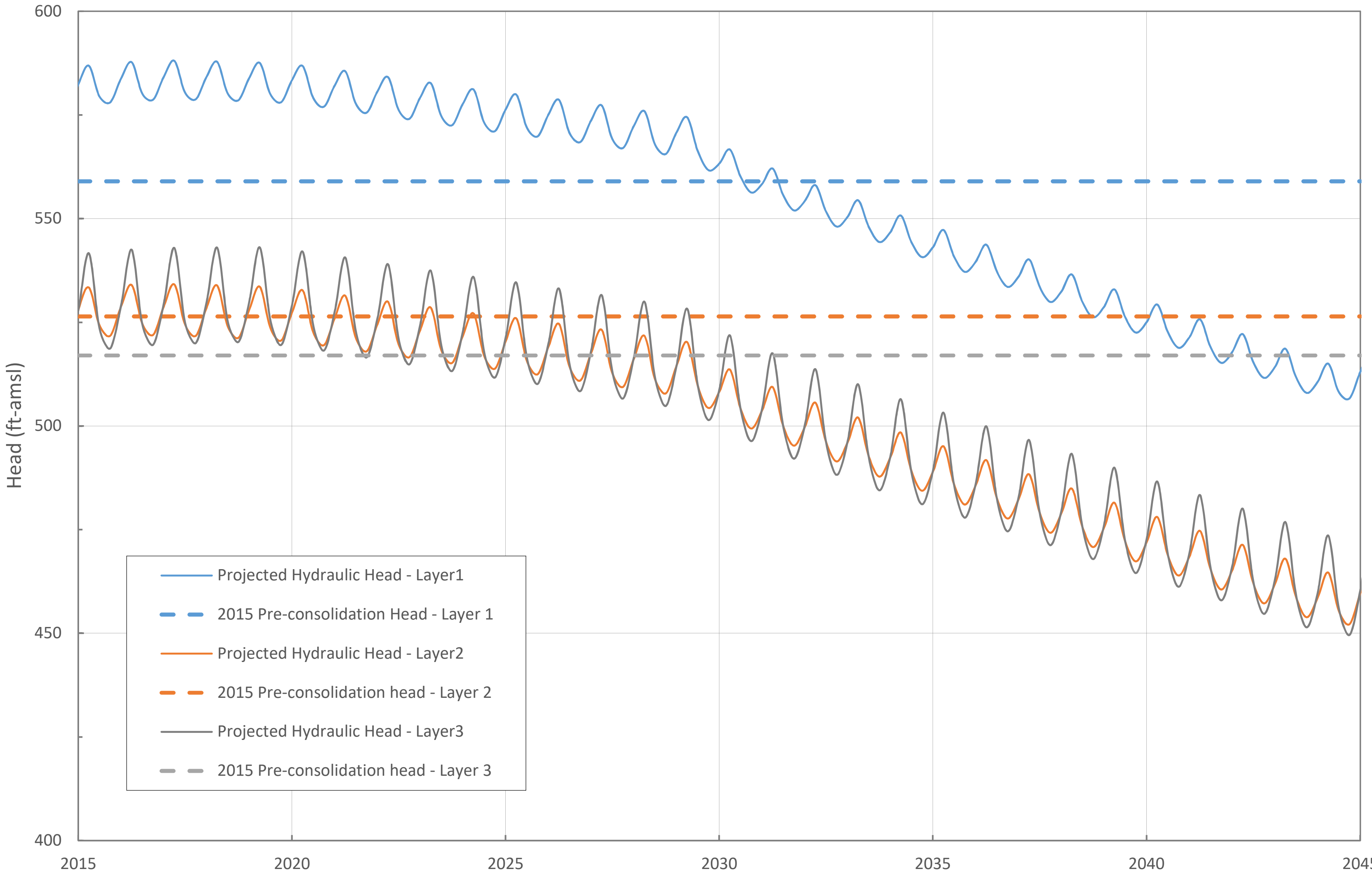


Figure 10_11_12abc_rev --Fig 10 WL_BMA
10/11/2017

Figure 11

Projected Aquifer-System Compaction at the 1D Model Location under the Baseline Management Alternative

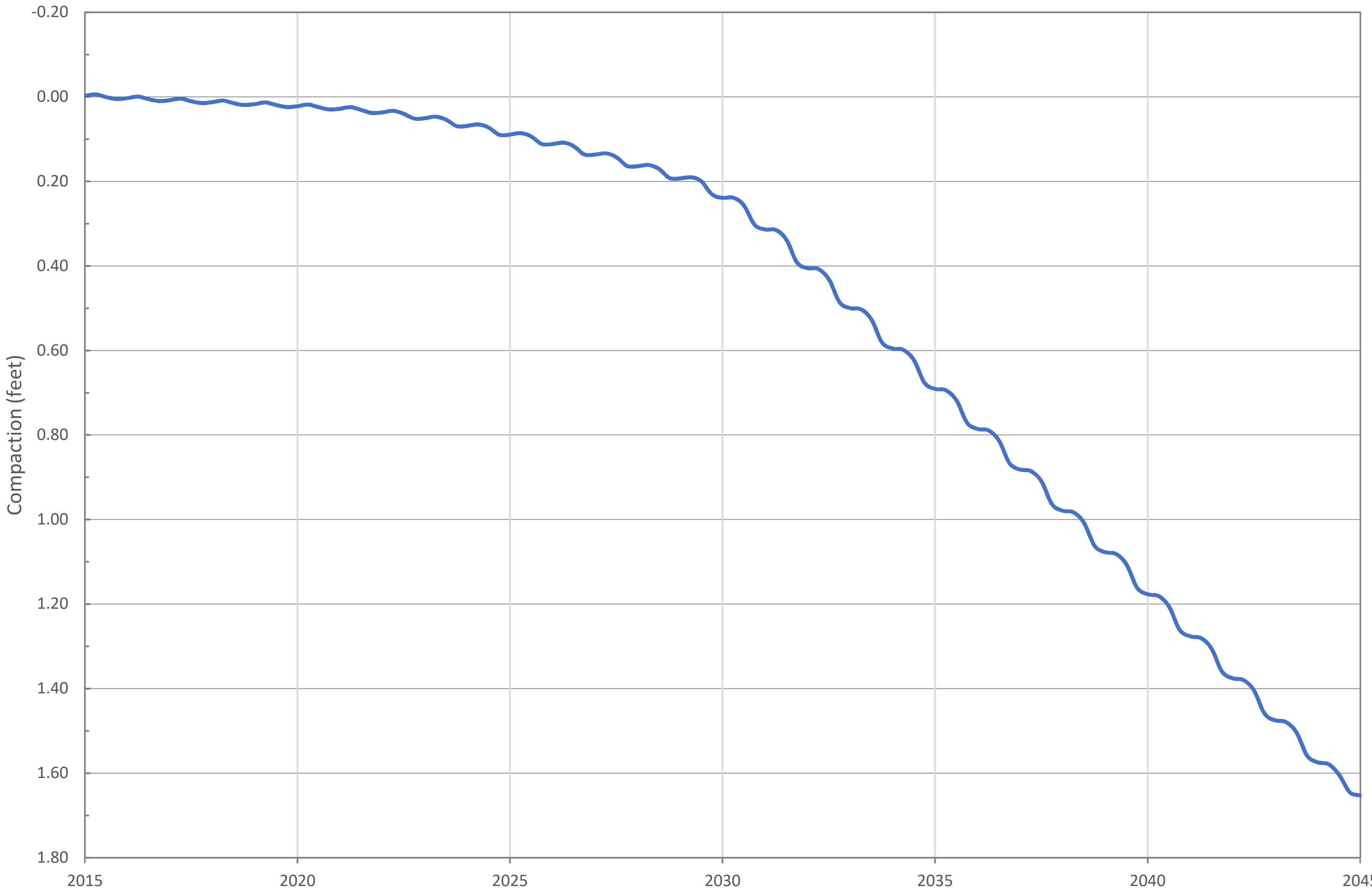


Figure 10_11_12abc_rev -- Fig-11 COMPCT_FINAL
10/11/2017

Figure 12a

Projected Heads in Layer 1 at the 1D Model Location under the ISMAs versus the 2015 Pre-Consolidation Head for Layer 1

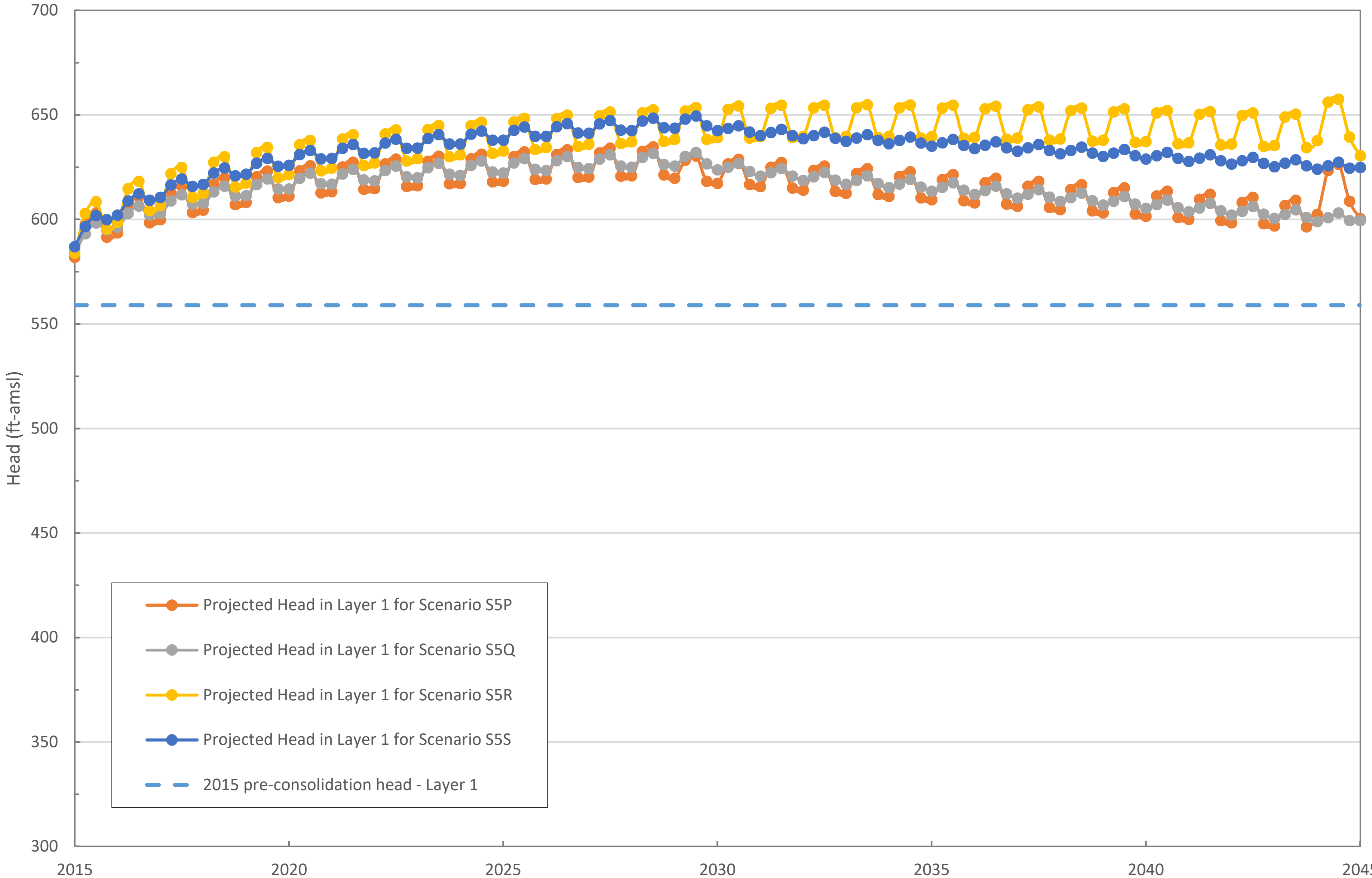


Figure 10_11_12abc_rev --Fig 12a Layer1_WL
10/11/2017

Figure 12b

Projected Heads in Layer 2 at the 1D Model Location under the ISMAs
versus the 2015 Pre-Consolidation Head for Layer 2

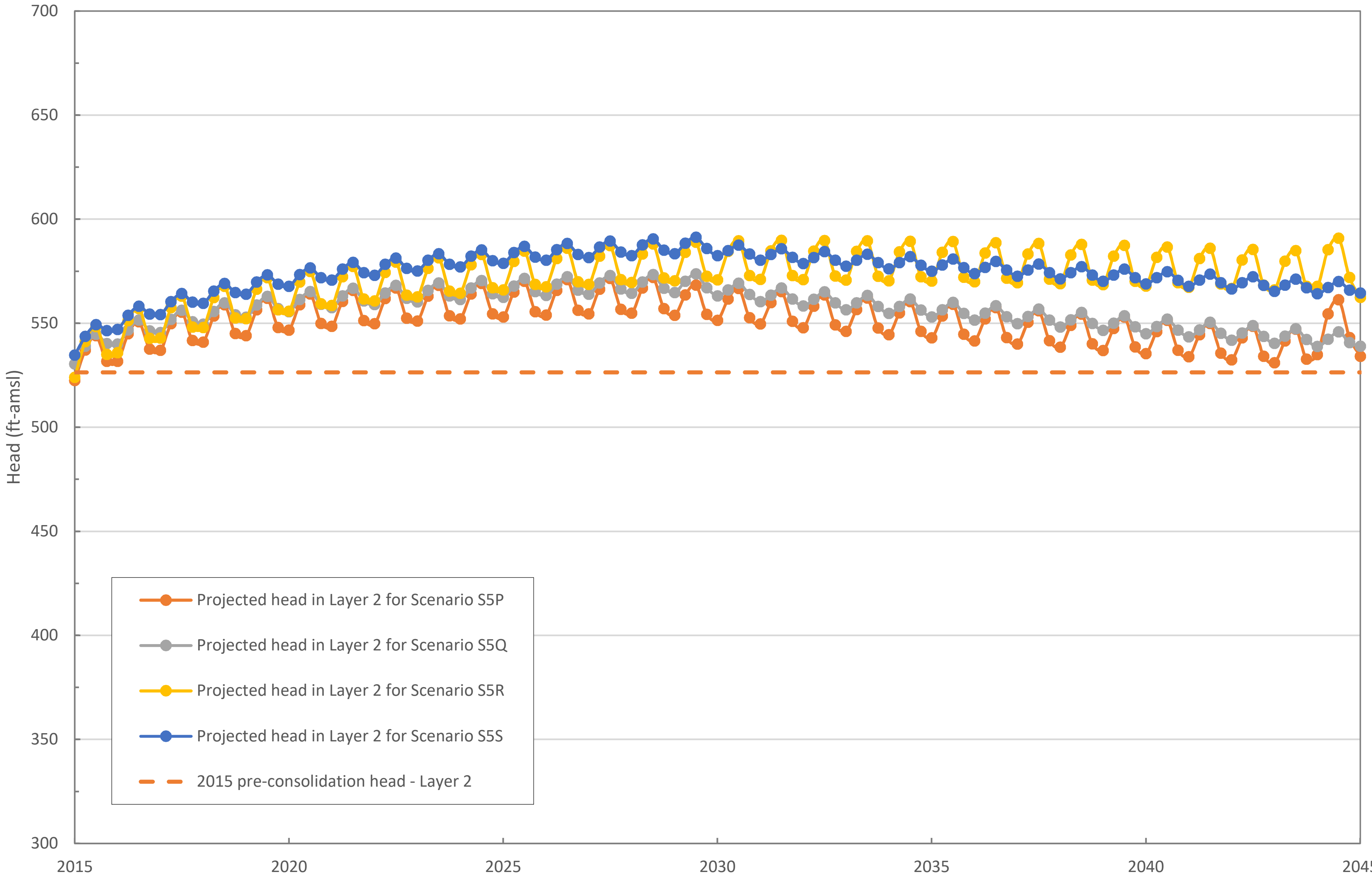


Figure 10_11_12abc_rev --Fig 12b Layer2_WL
10/11/2017

Figure 12c
Projected Heads in Layer 3 at the 1D Model Location under the ISMAs
versus the 2015 Pre-Consolidation Head for Layer 3

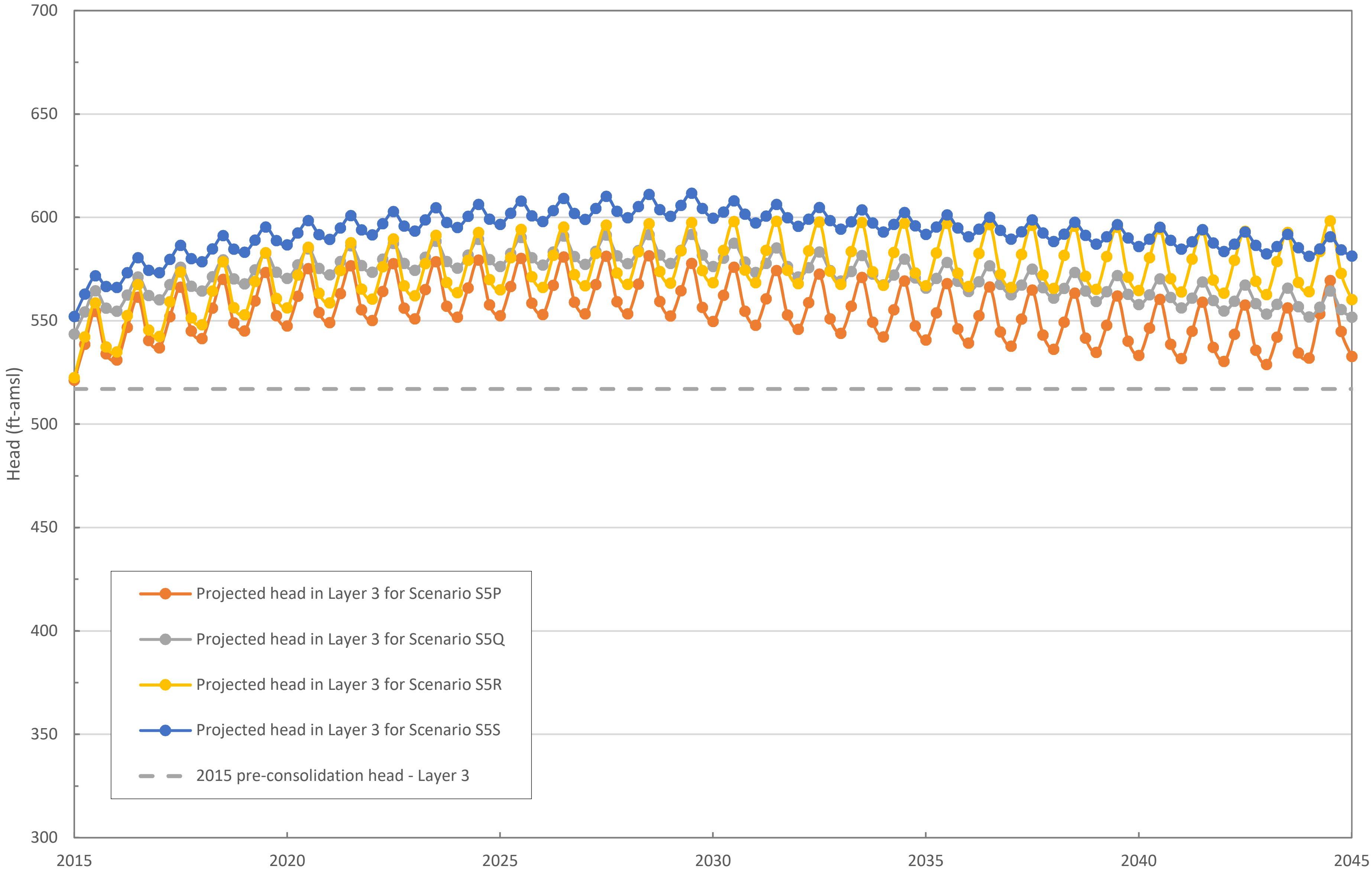


Figure 10_11_12abc_rev -- Fig 12c Layer3_WL
10/11/2017

Attachments

ORIGINAL
File with DWR

Page 1 of 3
Owner's Well No. 28
Date Work Began 01/01, Ended 04/01
Local Permit Agency San Bernardino
Permit No. 2000120871 Permit Date 12/11/00

STATE OF CALIFORNIA
WELL COMPLETION REPORT
Refer to Instruction Pamphlet

No. 770402

STATE WELL NO./STATION NO.
LATITUDE LONGITUDE
APN/TRS/OTHER

GEOLOGIC LOG

ORIENTATION (✓) X VERTICAL ___ HORIZONTAL ___ ANGLE ___ (SPECIFY)
DRILLING METHOD Reverse FLUID Water

DEPTH FROM SURFACE Ft.	to Ft.	DESCRIPTION *Describe material, grain size, color, etc.*
50	240	Sand & Gravel
240	250	Sand, Gravel & Rock
250	260	Sand, Gravel & Cobbles
260	280	Sand & Gravel
280	320	Sand, Gravel & Rock
320	350	Sand & Gravel
350	360	Sand, Gravel & Clay
360	390	Sand & Gravel
390	400	Sand, Gravel & Rock
400	436	SAnd, Gravel, Rock & Clay
436	470	Sand, Silt, Gravel & Clay
470	490	Sand, Gravel & Clay
490	520	Clay
520	560	Clay, Sand & Gravel
560	568	Silt, Gravel & Sand
568	576	Silt
576	581	Silt & Sand
581	584	Silt, Sand, Gravel & Clay
584	606	Gravel & Silt
606	690	Sand, Gravel & Clay
690	707	Sand, Gravel, Clay & Silt
707	735	Sand & Silt
735	763	Sand, Gravel & Silt
763	768	Silt, Clay & Sand
768	778	Silt, Clay & Gravel
778	783	Sandy Silt & Gravel
783	785	Silt, Clay & Gravel
785	791	Clay & Sand
791	799	Sand & Gravel
799	809	Clay

TOTAL DEPTH OF BORING 1310 (Feet)
TOTAL DEPTH OF COMPLETED WELL 1245 (Feet)

WELL OWNER

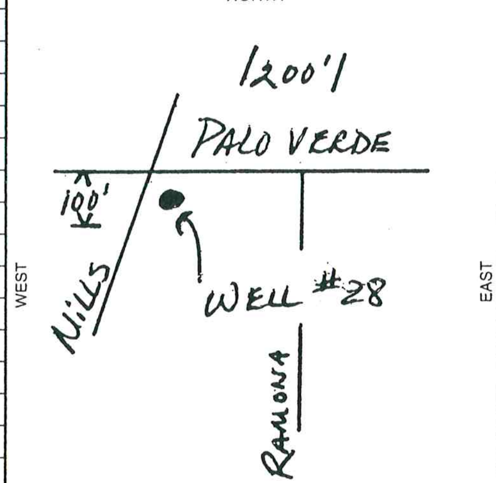
Name Monte Vista Water District
Mailing Address 10575 Central Avenue
Montclair Calif. 91763
CITY STATE ZIP

WELL LOCATION

Address S/O Palo Verde, E/O Mills
City Montclair
County San Bernardino
APN Book ___ Page ___ Parcel ___
Township 1S Range 8W Section 15
Latitude ___ NORTH DEG. MIN. SEC. Longitude ___ WEST DEG. MIN. SEC.

LOCATION SKETCH

NORTH



WEST EAST
SOUTH

Illustrate or Describe Distance of Well from Roads, Buildings, Fences, Rivers, etc. and attach a map. Use additional paper if necessary. PLEASE BE ACCURATE & COMPLETE.

ACTIVITY (✓)

X NEW WELL
MODIFICATION/REPAIR
___ Deepen
___ Other (Specify)
___ DESTROY (Describe Procedures and Materials Under "GEOLOGIC LOG")

PLANNED USES (✓)

WATER SUPPLY
___ Domestic X Public
___ Irrigation ___ Industrial
MONITORING ___
TEST WELL ___
CATHODIC PROTECTION ___
HEAT EXCHANGE ___
DIRECT PUSH ___
INJECTION ___
VAPOR EXTRACTION ___
SPARGING ___
REMEDIATION ___
OTHER (SPECIFY) ___

WATER LEVEL & YIELD OF COMPLETED WELL

DEPTH TO FIRST WATER 530 (Ft.) BELOW SURFACE
DEPTH OF STATIC WATER LEVEL 530 (Ft.) & DATE MEASURED 4-13-01
ESTIMATED YIELD * 3000 (GPM) & TEST TYPE Pump
TEST LENGTH 24 (Hrs.) TOTAL DRAWDOWN 79 (Ft.)
** May not be representative of a well's long-term yield.*

CASING (S)

DEPTH FROM SURFACE Ft.	to Ft.	BORE-HOLE DIA. (Inches)	TYPE (✓) BLANK	SCREEN	CON-DUCTOR	FILL PIPE	MATERIAL / GRADE	INTERNAL DIAMETER (Inches)	GAUGE OR WALL THICKNESS	SLOT SIZE IF ANY (Inches)
0	50	48"			x		139-B	35¼"	.375	
+2	635	32"	x				"	18"	"	
* 635	1225	28"		x			SS 304	"	.312	.070"
1225	1245	"	x				"	"	"	

* Multiple Screens

ANNULAR MATERIAL

DEPTH FROM SURFACE Ft.	to Ft.	CE-MENT (✓)	BEN-TONITE (✓)	FILL (✓)	FILTER PACK (TYPE/SIZE)
0	50	x			
0	530	x			
530	1245				6x12

ATTACHMENTS (✓)

___ Geologic Log
___ Well Construction Diagram
___ Geophysical Log(s)
___ Soil/Water Chemical Analyses
___ Other ___

ATTACH ADDITIONAL INFORMATION, IF IT EXISTS.

CERTIFICATION STATEMENT

I, the undersigned, certify that this report is complete and accurate to the best of my knowledge and belief.

NAME Beylik Drilling, Inc.
(PERSON, FIRM, OR CORPORATION) (TYPED OR PRINTED)

555 S. Harbor Blvd. La Habra Calif. 90631
ADDRESS CITY STATE ZIP

Signed T. Caldwell 5/7/01 306291
WELL DRILLER/AUTHORIZED REPRESENTATIVE DATE SIGNED C-57 LICENSE NUMBER

DWR 188 REV. 11-97

IF ADDITIONAL SPACE IS NEEDED, USE NEXT CONSECUTIVELY NUMBERED FORM

ORIGINAL
File with DWR

STATE OF CALIFORNIA

WELL COMPLETION REPORT

Refer to Instruction Pamphlet

No. 770403

Owner's Well No. 28

Date Work Began 01/01, Ended 04/01

Local Permit Agency San Bernardino

Permit No. 2000120871 Permit Date 12/11/00

DWR USE ONLY — DO NOT FILL IN

STATE WELL NO./STATION NO.

LATITUDE LONGITUDE

APN/TRS/OTHER

GEOLOGIC LOG

ORIENTATION (✓) X VERTICAL ___ HORIZONTAL ___ ANGLE ___ (SPECIFY)

DRILLING METHOD Reverse FLUID Water

DEPTH FROM SURFACE Ft.	to Ft.	DESCRIPTION *Describe material, grain size, color, etc.*
809	819	Clay & Sand
819	839	Clay
839	855	Clay & Sand
855	859	Clay
859	873	Sand & Gravel
873	876	Clay & Silt
876	886	Sand & Gravel
886	906	Clay & Silt
906	912	Clay
912	924	Sand & Gravel
924	926	Sand
926	936	Sand & Gravel
936	940	Silty Clay
940	950	Sand
950	965	Sand
965	973	Sandy Clay & Silt
973	976	Sand & Silt
976	986	SAnd & Clay
986	993	SAnd
993	996	Sand with color change
996	999	Sand & Silt
999	1005	Sandy Clay & Silt
1005	1015	Sand & Silt
1015	1017	Silt
1017	1027	Sand & Silt
1027	1050	Sand
1050	1055	Clay
1055	1064	Silty Sand
1064	1074	Silt & Clay
1074	1080	Silt

TOTAL DEPTH OF BORING ________ (Feet)

TOTAL DEPTH OF COMPLETED WELL ________ (Feet)

WELL OWNER

Name Monte Vista Water District

Mailing Address 10575 Central Avenue

Montclair Calif. 91763

CITY STATE ZIP

WELL LOCATION

Address S/O Palo Verde, E/O Mills

City Montclair

County San Bernardino

APN Book ____ Page ____ Parcel ____

Township 1S Range 8W Section 15

Latitude ___ NORTH DEG. MIN. SEC. Longitude ___ WEST DEG. MIN. SEC.

LOCATION SKETCH

NORTH

WEST EAST

SOUTH

Illustrate or Describe Distance of Well from Roads, Buildings, Fences, Rivers, etc. and attach a map. Use additional paper if necessary. PLEASE BE ACCURATE & COMPLETE.

ACTIVITY (✓)

___ NEW WELL

MODIFICATION/REPAIR

___ Deepen

___ Other (Specify)

___ DESTROY *(Describe Procedures and Materials Under "GEOLOGIC LOG")*

PLANNED USES (✓)

WATER SUPPLY

___ Domestic ___ Public

___ Irrigation ___ Industrial

MONITORING ___

TEST WELL ___

CATHODIC PROTECTION ___

HEAT EXCHANGE ___

DIRECT PUSH ___

INJECTION ___

VAPOR EXTRACTION ___

SPARGING ___

REMEDIATION ___

OTHER (SPECIFY) ___

WATER LEVEL & YIELD OF COMPLETED WELL

DEPTH TO FIRST WATER ______ (Ft.) BELOW SURFACE

DEPTH OF STATIC WATER LEVEL ______ (Ft.) & DATE MEASURED ______

ESTIMATED YIELD * ______ (GPM) & TEST TYPE ______

TEST LENGTH ______ (Hrs.) TOTAL DRAWDOWN ______ (Ft.)

* *May not be representative of a well's long-term yield.*

CASING (S)

DEPTH FROM SURFACE Ft. to Ft.	BORE-HOLE DIA. (Inches)	TYPE (✓) BLANK	SCREEN	CON-DUCTOR	FILL PIPE	MATERIAL / GRADE	INTERNAL DIAMETER (Inches)	GAUGE OR WALL THICKNESS	SLOT SIZE IF ANY (Inches)

ANNULAR MATERIAL

DEPTH FROM SURFACE Ft. to Ft.	CE-MENT (✓)	BEN-TONITE (✓)	FILL (✓)	FILTER PACK (TYPE/SIZE)

ATTACHMENTS (✓)

___ Geologic Log

___ Well Construction Diagram

___ Geophysical Log(s)

___ Soil/Water Chemical Analyses

___ Other ______

ATTACH ADDITIONAL INFORMATION, IF IT EXISTS.

CERTIFICATION STATEMENT

I, the undersigned, certify that this report is complete and accurate to the best of my knowledge and belief.

NAME Beylik Drilling, Inc.
(PERSON, FIRM, OR CORPORATION) (TYPED OR PRINTED)

555 S. Harbor Blvd. La Habra Calif. 90631
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Signed [signature] 5/7/01 306291
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File with DWR

Page 3 of 3

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Permit No. 2000120871 Permit Date 12/11/00

STATE OF CALIFORNIA

WELL COMPLETION REPORT

Refer to Instruction Pamphlet

No. 770404

STATE WELL NO./STATION NO.

LATITUDE | LONGITUDE

APN/TRS/OTHER

GEOLOGIC LOG

ORIENTATION (✓) x VERTICAL ___ HORIZONTAL ___ ANGLE ___ (SPECIFY)

DRILLING METHOD Reverse FLUID Water

DEPTH FROM SURFACE Ft.	to Ft.	DESCRIPTION *Describe material, grain size, color, etc.*
1080	1086	Clay
1086	1092	Silt
1092	1096	Silt & Sand
1096	1104	Silt
1104	1106	Sand & Silt
1106	1109	Sand
1109	1119	Sandy Clay & Silt
1119	1123	Silty Sand
1123	1126	Clay & Silt
1126	1128	Silty Sand
1128	1135	Sand
1135	1137	Silt & Sand
1137	1141	Sand & Gravel
1141	1146	Silt & Clay
1146	1150	Sand & Gravel
1150	1160	Sandy Clay & Silt
1160	1170	Sand
1170	1179	Sand
1179	1185	Silt
1185	1232	Sand & Silt
1232	1242	Clay
1242	1256	Silt
1256	1274	Sand & Silt
1274	1280	Sandy Silt with Clay
1280	1291	SAnd, Silt & Gravel
1291	1310	Silty Clay

TOTAL DEPTH OF BORING ______ (Feet)

TOTAL DEPTH OF COMPLETED WELL ______ (Feet)

WELL OWNER

Name Monte Vista Water District

Mailing Address 10575 Central Avenue

Montclair Calif. 91763

CITY STATE ZIP

WELL LOCATION

Address S/O Palo Verde, E/O Mills

City Montclair

County San Bernardino

APN Book ___ Page ___ Parcel ___

Township 1S Range 8W Section 15

Latitude ___ DEG. MIN. SEC. NORTH Longitude ___ DEG. MIN. SEC. WEST

LOCATION SKETCH

NORTH

WEST EAST

SOUTH

Illustrate or Describe Distance of Well from Roads, Buildings, Fences, Rivers, etc. and attach a map. Use additional paper if necessary. PLEASE BE ACCURATE & COMPLETE.

ACTIVITY (✓)

___ NEW WELL

MODIFICATION/REPAIR

___ Deepen

___ Other (Specify)

___ DESTROY (*Describe Procedures and Materials Under "GEOLOGIC LOG"*)

PLANNED USES (✓)

WATER SUPPLY

___ Domestic ___ Public

___ Irrigation ___ Industrial

MONITORING ___

TEST WELL ___

CATHODIC PROTECTION ___

HEAT EXCHANGE ___

DIRECT PUSH ___

INJECTION ___

VAPOR EXTRACTION ___

SPARGING ___

REMEDIATION ___

OTHER (SPECIFY) ___

WATER LEVEL & YIELD OF COMPLETED WELL

DEPTH TO FIRST WATER ______ (Ft.) BELOW SURFACE

DEPTH OF STATIC WATER LEVEL ______ (Ft.) & DATE MEASURED ______

ESTIMATED YIELD * ______ (GPM) & TEST TYPE ______

TEST LENGTH ______ (Hrs.) TOTAL DRAWDOWN ______ (Ft.)

* *May not be representative of a well's long-term yield.*

CASING (S)

DEPTH FROM SURFACE Ft. to Ft.	BORE-HOLE DIA. (Inches)	TYPE (✓) BLANK	SCREEN	CON-DUCTOR	FILL PIPE	MATERIAL / GRADE	INTERNAL DIAMETER (Inches)	GAUGE OR WALL THICKNESS	SLOT SIZE IF ANY (Inches)

ANNULAR MATERIAL

DEPTH FROM SURFACE Ft. to Ft.	CE-MENT (✓)	BEN-TONITE (✓)	FILL (✓)	FILTER PACK (TYPE/SIZE)

ATTACHMENTS (✓)

___ Geologic Log

___ Well Construction Diagram

___ Geophysical Log(s)

___ Soil/Water Chemical Analyses

___ Other ______

ATTACH ADDITIONAL INFORMATION, IF IT EXISTS.

CERTIFICATION STATEMENT

I, the undersigned, certify that this report is complete and accurate to the best of my knowledge and belief.

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Response to GLMC Comments

City of Chino Hills, City of Pomona, and Monte Vista Water District – Comments provided by Dennis Williams and Johnson Yeh of GEOSCIENCE Support Services, Inc.

Comment 2.0 – General Observations.

The 1-D Model was developed by WEI to simulate historical land subsidence at a specific location in the northwestern portion of the Chino Basin. The model structure was largely based on the driller's log for well MVWD-28. A combination of measured and simulated groundwater level time series were used as boundary conditions for the shallow (model layer 1) and deep (model layers 2 and 3) aquifer systems of the 1-D Model. For the period from 1930 through 1978, only measured groundwater level data from wells screened in model layer 1 (MVWD-15 and Margarita #1) were available. To generate head for model layers 2 and 3 during this early time period and to supplement observed water levels in all model layers for the remaining model calibration period, head data for boundary conditions were extracted from the calibrated Chino Basin groundwater flow model previously developed by WEI.

The calibrated 1-D Model was then used to predict future land subsidence patterns under projected recharge and discharge conditions. Given the model design, the simulation results are only really applicable at this specific site. In general, the simulated land subsidence matched historical July 1992 to July 2015 In-SAR-derived estimates of vertical ground motion at this site. However, more confidence would be given to model results if the model were also calibrated against historical elevations from land leveling surveys as well as In-Sar, as In-Sar is still somewhat untested or unproven for this use on its own.

Upon reviewing the technical memorandum, several key weaknesses in the assumptions and structure of the 1-D Model developed by WEI were observed, and are discussed in greater detail in the following section. To improve the reliability of the subsidence modeling results, we recommend:

- Incorporating the ability to simulate delayed subsidence with the MODFLOW Subsidence and Aquifer-System Compaction (SUB) Package, and
- Improving model calibration to match recent groundwater level trends.

Response:

We agree that the 1D Model is site specific by design in an effort to represent the main subsiding areas in Northwest MZ-1, and that this may not be a perfectly accurate assumption. We also agree that the model was constructed and calibrated with limited available data and hydrogeologic information, and hence, the use and interpretation of the model results are limited by uncertainties. In particular, the only ground-motion data available for calibration of the 1D Model is derived from InSAR. Historical ground-motion data from leveling surveys at the 1D-Model site is non-existent.

To mitigate these limitations, the Work Plan includes subsequent tasks to: (i) construct the Pomona Extensometer (PX) and perform monitoring and testing to provide additional information on the depth-specific aquifer and aquitard properties, and (ii) use this additional information to construct and calibrate new and improved numerical models of groundwater flow and subsidence. The new models will include a new 1D Model located at the PX site and a regional MODFLOW model with the SUB package. During calibration, the new models will use historical and the most recent groundwater-level and ground-motion data from all available sources. These models will be used in projection mode to build upon the subsidence-management strategies evaluated in this memorandum and to develop a final subsidence-management plan for Northwest MZ-1.

Comment 3.0 – Delayed subsidence cannot be simulated properly by the 1-D Model.

As shown on Figure 2 of the WEI technical memorandum (reproduced here as attached Figure 1), observed groundwater levels decline from 1930 to approximately 1978, where they begin to rebound slightly and stabilize through the end of the record. Water levels shown on this figure are primarily from model layer 1, with some screened intervals being completed in model layer 2. However, even the water levels in the deeper screened intervals of model layers 2 and 3 show stabilization beginning around 1996 (WEI Figure 5, Figure 2 attached).

Despite the stabilization in water level trends over the last 20 to 35 years, In-SAR data shows continued subsidence through the model calibration period (WEI Figure 7, Figure 3 attached). This indicates that the subsidence occurring in the Chino Basin is delayed in its response to declining groundwater levels during the period from 1930 through 1978. This delayed subsidence was recognized on page 2 of the technical memorandum, which states that "from about 1930 to 1978, heads in Northwest MZ-1 declined by about 175 feet. Since then, heads have recovered, but have remained below the levels of 1930. The observed and continuous subsidence that occurred between the 1992 to 2016 period cannot be explained entirely by the concurrent changes in head. A plausible explanation for the subsidence is that thick, slow-draining aquitards are compacting in response to the historical head declines that occurred from 1930 (or before 1930) to 1978." Considering the great thickness of the aquitards and the observed time lag between the recovery of groundwater levels and the ongoing occurrence of land subsidence in the study area, simulating subsidence using the 1-D Model is not suitable for this area.

One of the limitations of the 1-D Model is that it relies on the Interbed-Storage (IBS) Package for MODFLOW, which is unable to simulate delayed subsidence. In other words, in order to produce subsidence with the IBS Package, water levels must be declining. As shown on WEI Figure 7 (Figure 3 attached), the calibrated 1 D Model appears to do a decent job at reproducing the observed subsidence despite this modeling limitation. The concern here is that in order to simulate the observed delayed subsidence, an incorrect water level trend is modeled. As shown on WEI Figure 6 (attached Figure 4), the calibrated water level for model layers 2 and 3 shows a declining trend from 1979 through the end of the model period, despite apparently stable water levels in the deeper aquifer from 1996 through 2015. not reflect actual water level trends.

Running future scenarios with an incorrect water level trend, especially at the end of the model calibration period, is not advisable. Instead, we believe that the use of the Subsidence and Aquifer-System Compaction (SUB) Package in the three-dimensional (3-D) Chino Basin groundwater flow model would be more appropriate for evaluating subsidence and running future scenarios. While the advantage of using the 3-D groundwater flow model with the SUB package seems to be acknowledged in the text in reference to future work for regional subsidence modeling (page 8 of the technical memorandum), the inability of the 1-D Model to simulate delayed subsidence should be addressed and recognized in the "Model Errors and Limitations" section.

Response:

We disagree with the comments that:

- the 1D Model cannot properly simulate delayed drainage and compaction of aquitards (i.e. subsidence)
- is therefore "is not suitable"
- an "incorrect water level trend" was used in calibration.

First, the IBS package used in the 1D Model is capable of simulating delay drainage and compaction of aquitards: The 1D Model is discretized into "aquifer" and "aquitard" layers, and each layer is discretized into 2-foot cells (see Figure 4). For example, a 10-foot thick aquitard layer was discretized into five 2-foot cells, and the aquitard layer was typically bounded on the top and bottom by aquifer cells. Each aquitard cell was assigned a relatively low hydraulic conductivity because aquitards are chiefly composed of fine-grained sediments of low permeability. Each aquifer cell was assigned a relatively high hydraulic conductivity because aquifers are chiefly composed of permeable, coarse-grained sediments. As an initial condition for calibration, each aquifer and aquitard cell was assigned the same head. The boundary conditions for head changes during the historical/calibration period were input to the aquifer cells only. The aquitard cells adjacent to the aquifer cells responded to the head changes in the aquifer cells during each time-step. For example, if head declined in the aquifer cell, then water flowed from the higher head in the aquitard cell to the lower heads in the aquifer cells pursuant to Darcy's equation, and the skeletal storage of the aquitard cell declined and caused the cell to compress or compact. In subsequent time steps, the aquitard cells "deeper" in the aquitard layer responded to the head changes in the adjacent aquitard cells, and so on, for subsequent time steps, and for other aquitard cells "deeper" within the aquitard layer. In this manner, the IBS package is capable of simulating the delayed drainage and deformation of the aquitard layers, so we do not recommend adding contrary language to the "Model Errors and Limitations" section.

With regard to the comment that an "incorrect water level trend" was used in calibration, we used measured and model-simulated heads to construct a historical time-series of head changes for the aquifer cells in all three model layers. We achieved a "very good" calibration of the 1D Model using this time-series of head changes as boundary conditions for the aquifers, and the final calibrated aquifer and aquitard properties are within reasonable bounds. That said, the memorandum recognizes the potential errors and uncertainty in the time-series of head changes, and the associated uncertainty in the model results:

> *Most wells in Northwest MZ-1 have well screens that only penetrate the shallow aquifer system or penetrate both the shallow and deep aquifer systems. There are no wells that are screened only across the deep aquifer system, meaning that there are no historical measured head data for only in the deep aquifer system. As such, there is some uncertainty in the long-term time-series of heads for Layers 2 and 3 that were used as the boundary conditions for the 1D Model calibration, which creates uncertainty in the model results* (Page 15; first bullet).

The memorandum includes recommendations for minimizing model error and uncertainty for future models that will be developed and used pursuant to the Work Plan:

> *Continued monitoring and enhanced understanding of hydrogeologic conditions is crucial to minimizing model error and uncertainty, especially the construction and monitoring of the PX in Northwest MZ-1. Monitoring and testing can identify local anomalies associated with geologic complexity that are not currently represented in the model. Model error and uncertainty can be reduced by incorporating new monitoring information into future models. For example, Task 8 of the Work Plan, which includes the construction and calibration of a new 1D Model, will include a task to research and identify historical water-level measurements in Northwest MZ-1 prior to 1930, and include any newly-discovered water-level data in the calibration* (Page 15).

Lastly, we agree with the comment that a regional MODFLOW model with the SUB package be used in future modeling efforts to develop and evaluate a subsidence management plan for Northwest MZ-1. We also contend that the MODFLOW/SUB model be used in conjunction with a new 1D Model at the PX site, as described and justified in the Work Plan.

State of California – Comments provided by Rick Rees of Amec Foster Wheeler

Comment 1, P.1, Executive Summary, Results:

"The modeling results indicate that over seven feet of subsidence occurred in Northwest MZ-1 from 1930 to 2015, and that…"

Suggest considering whether this statement expresses a level of certainty beyond that supportable by the existing preliminary model. Although the stated amount of subsidence is consistent with the modeling results, it may be appropriate to acknowledge the level of uncertainty in historical heads, aquifer/aquitard physical characteristics, and measured ground surface elevations for the area of interpreted greatest subsidence more prominently. Would subsidence of more than seven feet in this relatively localized area be expected result in observable geomorphic features (such as changes in drainage) that have not been apparent?

Response:

The statement is clear that the estimate of seven feet of subsidence is a model result, and the memorandum explicitly recognizes and describes the uncertainty in the model results in the section "Model Errors and Limitations." Therefore, we see no need to modify the memorandum.

With regard to whether or not we should see "observable geomorphic features" associated with the seven feet of subsidence, this topic has not been investigated in detail, and we are unaware of any documented "observable geomorphic features" associated with the subsidence. That said, the modeling indicates that the subsidence occurred gradually over several decades, and across a relatively steep-sloping alluvial fan, which may have obscured and/or mitigated impacts of subsidence on gravitation processes, such as stream flow in channels.

Comment 2, P.7, second paragraph, first bullet:

"… subsidence was estimated to be 3.541 ft…"

Number of significant figures implies a high level of precision that may not be justified.

Response:

The National Geodetic Survey (which was the source of the data) carries three significant figures in their data sheets for 1st order elevation surveys.

Comment 3, P. 10, second paragraph, second sentence:

"The uppermost 280 feet of sediments were not included in the 1D Model because the sediment was unsaturated during the calibration period and therefore not subject to deformation caused by changes in head."

The model is used to simulate deformation extending back to 1930, so if this zone was saturated during this early period it may result in some inaccuracies of the early simulations of deformation. The zone appears to consist primarily of coarse-grained material so if a portion was saturated in the 1930's and subsequently drained there was probably negligible deformation. Suggest including the elevation of the base of the 280-foot depth interval so the reader can compare this number to the simulated groundwater elevations in Figure 6.

Response:

The 280-foot depth interval is never saturated during the simulations. The elevation of the base of the 280-foot depth interval is 773 ft-amsl, which is above the initial condition for head in 1930 and is above the highest head shown on Figure 6. The 280-foot depth interval was a conservative choice made to preserve flexibility for potential future simulations.

Comment 4, P.12, last paragraph, second sentence

"…computed code…."

Should this be "computer code?"

Response:

The memorandum has been updated as suggested. Thank you.

Comment 5, P. 14, bullet items under potential errors and limitations, third bullet in second-order bullets:

"The borehole sediments were not described by a registered geologist or hydrogeologist, which limits the accuracy of the lithologic descriptions."

Suggest that this bullet should mention that a resistivity log was available to support the generalized lithologic descriptions of coarse and fine sediments. Also suggest it may be better to say that there is less confidence in lithologic descriptions that are not prepared using a standard classification system by or under the supervision of a licensed professional (e.g., professional geologist, certified hydrogeologist, or geotechnical engineer) with adequate training and experience in logging sediments.

Response:

The memorandum has been updated as suggested. Thank you.

Comment 6, P.15, last paragraph, Historical Subsidence Simulation, first sentence:

"The final calibration run for the 1D Model indicated a total of about 7.6 feet of aquifer system compaction at the 1D Model location from 1930 to 2015."

Previous text (e.g., P.12, paragraph 1, numbered item 2) defines the calibration period as 1992 through 2015. Suggest clarifying that subsidence indicated by model results for years prior to 1992 are not for the calibration period but are for an extrapolation using the calibrated model, and the pre-calibration period is less certain in terms of heads, especially in the deeper zones.

Response:

We disagree with the comment that the simulation from 1930 to 1992 is an "extrapolation." The simulation from 1930 to 1992 was an important step in the calibration process to establish the distribution of head, pre-consolidation head, and total compaction in all model cells for June 30, 1992, which was the beginning of the calibration period.

We agree that the imperfect understanding of historical heads in the deep aquifer system is a potential source of error and uncertainty in the model results. We believe the discussion in the section "Model Errors and Limitations" is a sufficient description of these potential errors and uncertainties.

Comment 7, P. 17 and 18, general discussion under Initial Subsidence-Management Strategies (ISMSs):

Strategies consist of increasing wet-water recharge or reducing production in the area of concern. Assuming that neither of these strategies will result in a decrease in pumping demand in the basin as a whole and that any wet-water recharge will be credited to a storage account and then pumped in another part of the basin under the efficient market assumption, are these strategies potentially just shifting subsidence related issues to another part of the Chino Basin?

Response:

Not necessarily. For example, the number and thicknesses of aquitard layers in in the eastern portion of the Chino Basin are not as great compared to the western portion of Chino Basin; therefore, the eastern areas are not as prone to pumping-induced subsidence.

Comment 8, P.19, Recommendations:

Suggested noting information that would have been useful if available includes additional head data from early times and deeper aquifer zones. Although it is unlikely additional historical head data will become available, adding this to the text might help remind the reader of an uncertainty inherent in the model and its results.

Response:

Agreed. The memorandum has been updated as suggested. Thank you.

Comment 9, Table 1 and Figure 1:

Consider if significant figures presented are supportable for elevations reported/elevation changes calculated for all data sets.

Response:

The National Geodetic Survey (which was the source of the data) carries three significant figures in their data sheets for 1st order elevation surveys.

Comment 10, Figure 4:

Driller's log does not appear to support occurrence of sedimentary bedrock below 1290 ft-bgs. Driller's log indicates a silty clay from 1291 to 1310 (the bottom of the borehole). If lithology from Watermaster's regional groundwater model is used in the generalized lithology columnar section, it should be separated out from the borehole lithology.

Response:

The 1,290 ft-bgs represents the bottom of the aquifer in the Watermaster's regional MODFLOW groundwater model. A note to this effect has been added to Figure 4.

Monte Vista Water District – Comments Provided by Van Jew

Comment 1, Under Executive Summary, Results:

Instead of "recent", insert "2014" or whichever was the year the recalc occurred.

Response:

The memorandum has been updated with the year 2013 replacing "recent." Thank you.

Comment 2, Under Executive Summary, Results:

Instead of "and" replace with "and/or"

Response:

The memorandum has been updated as suggested. Thank you.

Comment 3, Under Executive Summary, Recommendations:

Insert "as well as the recently received 2017 groundwater pumping projections".

Response:

The construction and calibration of new models do not include future pumping projections. Use the new models in projection mode may utilize the 2017 pumping projections, but by the time these new models are used, there may be updated planning information on pumping projections. Therefore, we do not recommend inserting the suggested text into the memorandum.

Comment 4, Under Background and Objectives:

Does 0.05 ft/yr meet the OBMP definition of tolerable subsidence?

Response:

Program Element 4 of the OBMP Implementation Plan states that the "occurrence of subsidence and fissuring in Management Zone 1 is not acceptable and should be reduced to tolerable levels or abated." The OBMP Implementation Plan does not provide – and neither Watermaster nor WEI have developed to date – a definition of a "tolerable level" of subsidence. The OBMP Implementation Plan called for the development of an interim plan to minimize subsidence and fissuring, the collection of information to assess the causes of subsidence and fissuring, and the development of an effective long-term management plan. Watermaster has and continues to undertake these activities, which will result in the determination of whether and to what extent subsidence and fissuring can be abated or the levels to which it might be reduced.

Comment 5, Under Background and Objectives, third bullet point:

Does the rate of approximately 0.01 ft/yr meet the OBMP definition of tolerable levels of subsidence?

Response:

See prior response above.

Comment 6, Under Table:

Description of the Initial Subsidence-Management Strategies (ISMSs) and Associated Chino Basin Groundwater Model Scenarios, ISMS Scenario - S-5P: What, in AFY, is the approximate magnitude of 50 percent of the production volume of the cities of Pomona and Upland, SAWCo, and MVWD? 3,250 AFY?

Response:

The value changes with year. The 50 percent of the production volume of the cities of Pomona and Upland, SAWCo, and MVWD ranges from 9,923 to 14,434 AFY.

Comment 7, Under Recommendations:

Insert "along with updated pumping projections may" in place of "will."

Response:

The memorandum has been updated as suggested. Thank you.

City of Chino – Comments Provided by Eric Fordham of GeoPentech, Inc.

Comment 1, Under Executive Summary, Results:

"modeling results indicate" – Suggest rewording to indicate that survey data infers over 7 ft of subsidence and modeling results suggest the deep system is more susceptible to compression.

Response:

We contend in the memorandum that the historical survey data: (i) support the use of InSAR-derived data as calibration targets and (ii) are qualitatively consistent with the model results that estimate over seven feet of subsidence occurred in Northwest MZ-1 from 1930-2015. Therefore, we made no modifications to the memorandum.

Comment 2, Under Executive Summary, Results:

"projected to occur" – Change to "projected to occur based on model results".

Response:

The memorandum has been updated as suggested. Thank you.

Comment 3, Under Background and Objectives, Last Paragraph of Section:

Rather than using the term "head" when referring to a groundwater related pressure, it may be helpful to differentiate by using a different term for a groundwater level measurement such as in a well versus a given hydraulic head pressure related to stress applied to an aquitard material.

Response:

The paragraph has been revised to replace "groundwater levels" with "head." Throughout this memorandum, we attempted to use the term "head" or "hydraulic head" as general terms to describe the pore pressure within the aquifer system sediments, whether within an aquifer or an aquitard, and whether under confined or unconfined conditions. We described measurements of head as "water levels" in wells and piezometers.

Comment 4, Under Results and Interpretations, Characterization of Historical Subsidence in Northwest MZ-1:

"3.541 ft" Significant figure to the thousands with accuracy of 5 cm?

Response:

The National Geodetic Survey (which was the source of the data) carries three significant figures in their data sheets for 1st order elevation surveys.

Comment 5, Under Results and Interpretations, 1-Dimensional Aquifer-System Compaction Model, first paragraph:

Change "project" to predict.

Response:

The memorandum has been updated as suggested. Thank you.

Comment 6, Under Results and Interpretations, 1-Dimensional Aquifer-System Compaction Model, Boundary Conditions:

"MVWD-15 "This well is not shown on the either map figure 1 or 2. Do you mean MVWD-13? Also, Well Margarita #1 and MVWD-19 are not shown on either of the maps.

Response:

Figure 1 has been updated to include wells: MVWD-15, MVWD-19, and Margarita #1. Thank you.

Comment 7, Under Results and Interpretations, 1-Dimensional Aquifer-System Compaction Model, 1-D Model Calibration:

In response to "indicating a very good calibration", While I agree the calibration is very good, the model overpredicts compaction early (likely with most compression occurring in layers 1 and 2) and somewhat under-predicts compaction late (likely with most compression occurring in layer 3). This is probably due to the aquitard skeletal specific storage values being the same for all layers. (see next comment).

Comment 8, Under Results and Interpretations, 1-Dimensional Aquifer-System Compaction Model, 1-D Model Calibration:

In response to "Table 2b shows the final calibrated aquifer-system properties", It seems odd that the resulting inelastic and elastic specific storage values for the aquitard are equal for all layers. This generally occurs when a parameter hits a bound that is set for the parameter estimating process, which may be artificial. Is there a reason that can be identified why these values are all the same?

Response to Comments 7 and 8:

The measured compaction values over the calibration period (1992-2015) are from InSAR data, which represents aggregate compaction within aquitards across all three model layers. Without knowledge of depth-specific compaction in this modeling exercise, we assumed that elastic and inelastic skeletal specific storage values were uniform in all aquitard interbeds in each layer to make calibration reasonable and practicable.

In subsequent modeling tasks pursuant to the Work Plan, we will have lithologic and extensometer data available to better constrain the depth-specific variability in the skeletal storage coefficients. These data and information will allow for a more unique model solution.

Comment 9, Under Results and Interpretations, 1-Dimensional Aquifer-System Compaction Model, Model Errors and Limitations:

In response to "The resolution by depth interval of the geologic descriptions in this log are typically greater than five feet, which may not be a fine enough resolution to characterize any thinner interbedding of aquifer and aquitard layers that are an important control on aquifer-system deformation", It may be useful to run a sensitivity analyses on aquitard thicknesses for the 3 layers along with associated skeletal specific storage. Interpretation of drillers' textural description of sediments from the boring log as well as variability in the nature of the fine-grained sediment can result in a range of aquifer/aquitard thicknesses and the sensitivity to a reasonable range in thicknesses of these units should be tested in the model.

Response:

Our primary point here was that the conceptual model can be improved with a higher-resolution description of the borehole sediments. A higher-resolution description will be obtained during the drilling of the Pomona Extensometer boreholes. We do not recommend performing a sensitivity analysis on aquitard thickness at the point, but perhaps during the construction and calibration of the new 1D Model for the Pomona Extensometer site. This recommendation should be discussed by the GLMC.

Comment 10, Under Results and Interpretations, 1-Dimensional Aquifer-System Compaction Model, Historical Subsidence Simulation, Figure 9:

On Figure 9, it would be helpful to better understand the model response to ongoing residual compaction if the modeled groundwater level and pre-consolidation hydraulic head for the layers was presented along with the simulated compaction. That is, has the rate of compaction leveled off since the mid-1970s because groundwater levels have recovered above an established pre-consolidation hydraulic head level?

Response:

Yes. Inspection of Figure 2 shows that water levels at many wells in Northwest MZ-1 declined to an all-time low by 1977, and then recovered by about 100 feet over the next 8-10 years. This is the reason for the break in slope in the model-simulated compaction curve at about 1978 on Figure 9.

Comment 11. Under Estimates of Future Subsidence in Northwest MZ-1, Estimates of Future Subsidence Associated with the BMA:

"Estimates" should be changed to "Model Predicted Estimates".

Response:

The memorandum has been updated as suggested. Thank you.

Comment 12. Under Estimates of Future Subsidence in Northwest MZ-1, Initial Subsidence-Management Strategies (ISMSs):

In response to "The ISMSs described and evaluated herein are modifications to the BMA that include either increased wet-water recharge in Northwest MZ-1 or decreased production in Northwest MZ-1." Do the 50% and 66% increase/decrease in recharge/production have any significance or are these values provided only as an example of how these strategies would influence subsidence? Perhaps, make it clear the relevance of these values, if any.

Response:

The memorandum describes the objective of developing and evaluating the ISMSs is to provide "preliminary" information on the efficacy of various recharge and production schemes at minimizing or abating the subsidence in Northwest MZ-1. It goes on to describe that refinements to the ISMSs will likely occur after the construction of the PX, updates to the modeling tools, and input from the Chino Basin parties and the GLMC, in the effort to develop a full-scale subsidence management plan for Northwest MZ-1.

Comment 13. Under Recommendations:

In response to "The use of the 1D Model and interpretation of its results is limited by significant but un-quantified uncertainty.", It should be noted either here or above that while the model is a good start to understand the effect of groundwater level declines on compaction, the model uncertainties are likely still too large to provide confidence for future ISMS predictions.

Response:

We agree. The text has been revised to address the comment.

Comment 14. Under Recommendations:

Something to consider for planning purposes: In addition to logging the soil type encountered during drilling of the PX, it has been shown by Terzaghi and others that there is a strong correlation between the Plasticity Index/Liquid Limit of fine grained sediments and their compaction coefficient. This parameter can be tested in a disturbed sample that could be collected from the screen of the shaker. It may be a useful property to evaluate to differentiate the consolidation properties of aquitard sediments as they are encountered with depth during drilling.

Response:

Thank you for the suggestion. The text has been revised as suggested. We will investigate the laboratory methods proposed in the comment, the usefulness of the laboratory results in this effort, and the costs, and bring this information to the attention of the GLMC.