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TODD GROUNDWATER

GROUNDWATER CHARACTERIZATION AND RECHARGE STUDY

MODESTO LGA PROJECT

June 2016

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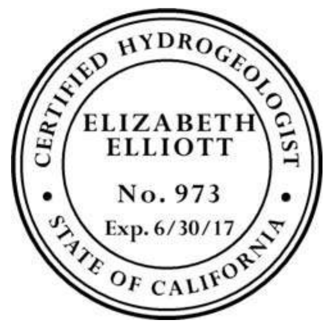

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EXECUTIVE SUMMARY

The City of Modesto (City) is exploring opportunities to improve conjunctive management of its groundwater and surface water resources in the Modesto Subbasin, including managed aquifer recharge (MAR). As a first step in a potential MAR program, the City has conducted this study to characterize the local aquifer system and identify potential target areas to focus MAR strategies. Specifically, this study included a hydrogeologic characterization, identification of potential recharge locations, and numerical model simulations of recharge alternatives. In order to fund this study, the City received a Local Groundwater Assistance (LGA) program grant from the California Department of Water Resources (DWR).

A hydrogeologic conceptual model was developed based on geologic cross sections throughout the City of Modesto Service Area. The cross sections include hydrofacies textures at more than 80 percent of the City wells in recent production and show that the eastern and southeastern regions of the Study Area may be the most promising areas for subsurface recharge methods. Sand beds are thicker in the eastern Study Area. The greatest production from the City's wells from July 2014 to June 2015 was from intermediate and deep aquifer wells along the eastern edge of the Study Area and from the southern edge of the Study Area, immediately north of the Tuolumne River. The area of greatest groundwater production is also the area with the best overall groundwater quality, with relatively fewer detections of arsenic, nitrate, and uranium above their respective MCLs. Groundwater flow direction is to the west and southwest along the eastern and southeastern regions of the Study Area. Therefore, recharged water could be recovered from existing downgradient production wells.

Potential recharge locations were identified based on the hydrogeologic conceptual model, a previous surface recharge analysis, and existing infrastructure, land use, and well locations. Seven potential MAR locations were identified and evaluated: Creekside Golf Course, Sutton Park, South of Mary Grogan Community Park, Sanders Park, Freedom Park, Orchard Park, and Ustach Park. The potential recharge method (i.e., surface and/or subsurface recharge) and recharge rates were estimated at each location. The City estimated that up to 13,850 AFY will be available for MAR.

A numerical model was used to simulate recharge alternatives. A refined local model was created from a regional steady-state USGS model and used to simulate a "No Project" Baseline scenario and three alternative scenarios with both surface recharge (i.e., ponds) and subsurface recharge (i.e., injection wells). Alternative A simulated recharge from ponds and injection wells at seven potential locations identified as part of this Study. Alternative B simulated recharge from an additional 10 injection wells along the eastern edge of the Study Area. Alternative C simulated recharge from an additional five injection wells in the eastern Study Area, but without ponds. Alternative A simulated 8,294 AFY of recharge, while Alternatives B and C simulated 13,850 AFY of recharge.

Simulations show groundwater mounding resulting from recharge at the ponds and injection wells. The maximum simulated mounding is approximately 15 meters (49 feet) in the vicinity of Grogan Park and Sanders Park in Alternatives B and C. Based on April 2015 measurements, the depth to water in this region is between 50 and 55 feet. Due to the observed mounding relatively close to the ground surface, results indicate that subsurface storage may be a limiting factor for large recharge volumes and/or closely-spaced wells. It appears that recharge volumes of about 8,294 AFY could be accommodated. Enhanced recharge of 13,850 AFY results in excessive mounding for the distribution of recharge ponds and wells simulated. However, simulations were conservative in that recovery pumping was not simulated in the recharge wells as would occur for Aquifer Storage and Recovery (ASR) strategies. The MODPATH particle tracks show that most of the recharge water is extracted by City wells, or, in some cases, by nearby wells operated by Modesto Irrigation District (MID). Most of the water is recovered within 25 years, while some of the water remains in the aquifer for longer time periods. The simulated particle pathlines and travel times are conservative (e.g., less recovery); injected water travels farther than would occur with operation of the injection wells as ASR wells. In addition, ASR operations would result in more available aquifer storage, as the injection wells also extract recharge water.

Overall, this study indicates that MAR is feasible and that the eastern and southeastern portions of the Study Area are most promising, with significant potential for recharge and for recovery by City wells.

1. INTRODUCTION

The City of Modesto (City) is exploring opportunities to improve conjunctive water management in the Modesto Subbasin where the City operates about 125 wells for municipal and industrial water supply. Through an agreement with Modesto Irrigation District (MID), the City also receives surface water that is treated at the Modesto Regional Water Treatment Plant (MRWTP). Use of these two sources can be optimized by storing excess surface water, when available, in the groundwater basin for subsequent recovery and use.

In order to implement optimization strategies for managed aquifer recharge (MAR), a more detailed understanding is needed of the local aquifers and groundwater flow system. To address these knowledge gaps, the City has conducted a groundwater characterization and recharge study; the methods, analyses, and results of the study are provided in this project report. The study was funded by a grant under the Local Groundwater Assistance (LGA) program, which is administered by the California Department of Water Resources (DWR).

1.1. PROJECT OBJECTIVES AND METHODOLOGY

The objective of the project is to characterize the aquifer systems beneath the City of Modesto Service Area (Study Area) and evaluate the potential for implementation of MAR strategies. Such strategies could involve surface recharge methods using spreading basins or ponds or subsurface recharge methods using injection wells and/or aquifer storage and recovery (ASR) wells. Any variation or combination of these methods requires many similar attributes, including a hydrogeologic characterization capable of identifying target aquifers and favorable locations.

In order to achieve this objective, detailed cross sections were constructed and interpreted to delineate hydrostratigraphic units. Groundwater quality data were used to refine the hydrogeologic characterization and identify potential problem areas for MAR activities. Groundwater occurrence and flow data were interpreted in the context of available subsurface storage and the fate and transport of recharged water. These analyses were then used to identify general target areas for potential MAR project development.

Land use, existing infrastructure, permitting considerations and other factors were combined with the results of the hydrogeologic characterization to develop conceptual MAR projects. These conceptual projects were analyzed using a steady-state model released in 2007 by the United States Geological Survey (USGS) (Phillips et al., 2007) to evaluate performance at a preliminary level. The model was used to simulate recharge alternatives, analyze groundwater mounding associated with recharge, and evaluate flow paths of the recharged water.

1.2. STUDY AREA

Several study areas were incorporated into the project: the Modesto Service Area, a larger area that extends several miles beyond the Service Area, and an even larger area that was used for the groundwater modeling evaluation. Based on discussions with the City, it was determined that MAR strategies could best be developed within the current Modesto Service Area where existing infrastructure and city-owned land may facilitate project implementation. This area also contains data from more than 100 City monitoring and municipal wells, representing the best opportunity for aquifer characterization. However, a larger area was identified to include data and analysis from other nearby municipal wells; this larger Study Area extended for several miles beyond the Modesto Service Area boundaries. The Modesto Service Area and the larger Study Area for data compilation are shown on Figure 1.

A third Study Area was defined for development of a local-scale groundwater model to assist with preliminary evaluation of potential MAR strategies. The model area needed to be sufficiently large to ensure that MAR strategies analyzed in the Modesto Service Area were not significantly affected by model boundary conditions. The local-scale model area is presented in Section 4 of this report.

The Modesto Service Area (Service Area) lies between the Stanislaus River to the north and the Tuolumne River to the south (Figure 1), and between the San Joaquin River to the west and the Sierra Nevada foothills to the east. Figure 1 shows the Modesto Service Area and the larger data compilation area, along with the surrounding communities of Ripon, Riverbank, Oakdale, Ceres, and Hughson. The ground surface of the Study Area is relatively flat and slopes gently from an elevation of approximately 100 feet above mean sea level (msl) on the eastern edge of the Service Area to approximately 15 feet msl on the western edge.

The City of Modesto Service Area includes 125 production wells, 100 of which were actively pumping within the last year of available data (i.e., from July 2014 to June 2015). In addition, the USGS installed 23 nested monitoring wells at 10 sites in the northeastern portion of the Study Area as part of a separate investigation (Jurgens et al., 2008). The City provided information and data from the Modesto wells to support the project. Data from surrounding wells outside of the Modesto Service Area, including wells from the City of Riverbank, were also compiled by the City and incorporated into the study. The Study Area wells are shown on Figure 2.

2. HYDROGEOLOGIC CHARACTERIZATION

2.1. AQUIFER CHARACTERIZATION

The regional geology and hydrogeology of the Modesto Subbasin and Study Area have been investigated and described by the USGS in several studies, most recently by Burow, et al. (2004) and by Jurgens, et al. (2008). Hydrogeologic conditions also have been examined locally in connection with focused studies including groundwater contamination investigations. However, a comprehensive hydrogeologic framework that incorporates a detailed aquifer analysis had not been systematically developed for the Study Area. Our characterization, described below, focused on development of this framework to support potential MAR projects.

2.1.1. Hydrogeologic Setting

The Study Area is in the western region of the Modesto Subbasin of the San Joaquin Valley Groundwater Basin as defined by DWR (Bulletin 118 basin designation 5-22.02) (DWR, 2006). DWR has categorized the Modesto Subbasin as high priority in the 2014 prioritization ranking of groundwater basins. The ranking was conducted under the California Statewide Groundwater Elevation Monitoring (CASGEM) Program and finalized in 2015 as required by the recently-adopted Sustainable Groundwater Management Act (SGMA) of 2014. The high priority designation was based primarily on the amount of irrigated land in the subbasin and reliance on groundwater use.

Groundwater flow within the subbasin is to the southwest, generally following the geologic dip of the basement rock and sedimentary units (DWR, 2006). Groundwater occurs within both consolidated and unconsolidated units within the subbasin. The deeper consolidated units include the Ione, Valley Springs, and Mehrten formations. The shallower unconsolidated units include the Laguna, Turlock Lake, Riverbank, and Modesto formations. The Corcoran Clay is present in the western portion of the Study Area at the base of the Upper Turlock Lake Formation. This unit represents a well-defined, regional confining layer separating shallow unconfined aquifers from deeper confined aquifers (Burow et al., 2004).

The aquifer system in the Study Area includes unconfined to semiconfined aquifers above and east of the Corcoran Clay and confined aquifers beneath the Corcoran Clay. The unconfined aquifer system includes the Modesto, Riverbank, and Upper Turlock Lake formations. East of the Corcoran Clay, unconfined conditions transition to semiconfined conditions with depth due to clay lenses and extensive paleosols (Burow et al., 2004). The confined aquifer is composed of the Turlock Lake and upper Mehrten formations (Burow et al., 2004).

The Modesto, Riverbank and Turlock Lake formations form sequences of overlapping terrace and alluvial fan deposits in response to cycles of alluviation, soil formation and channel incision influenced by changes in climate and glacial stages in the Sierra Nevada (Jurgens et al., 2008). The Modesto Formation forms a thin veneer at the surface, approximately 20 feet thick (Jurgens et al., 2008) throughout most of the Modesto Study Area (except east of Modesto where it is absent) (Burow et al., 2004). The Modesto Formation is composed of fluvially-deposited arkosic sand, gravel and silt and its lithology is similar to the underlying Riverbank, Turlock Lake, and Laguna formations (Burow et al., 2004). Where saturated, the Modesto Formation yields moderate amounts of water (Burow et al., 2004).

The Riverbank Formation is also composed of fluvial arkosic sand, gravel and silt and varies in thickness from approximately 150 to 250 feet (Burow et al., 2004). Its depositional dip is slightly steeper than the Modesto Formation, resulting in westward thickening of the deposits. The formation yields moderate quantities of water. A reddish clay-rich duripan, or paleosol, exists at the top of the unit, below the Modesto Formation (Burow et al., 2004).

The Turlock Lake Formation is the most developed aquifer in the Modesto area, yielding up to 2,000 gallons per minute (gpm) from gravel and sand units (Burow et al., 2004). Similar to the Modesto and Riverbank formations, the Turlock Lake Formation is composed of a coarsening-upward sequence of silt, arkosic sand, and gravel layers (Burow et al., 2004). Where present, the blue lacustrine Corcoran Clay is up to 100 feet thick and lies within the Turlock Lake Formation, dividing the formation into upper and lower aquifer units. The Corcoran Clay occurs locally at depths ranging from 80 to 210 feet (Burow et al., 2004). The Corcoran Clay is generally well sorted clay to silty clay, but becomes siltier and grades into coarser textures along the edges (Burow et al., 2004). Paleosols separate the Turlock Lake Formation from the overlying Riverbank Formation and are also present between the Upper and Lower Turlock Lake formations (Burow et al., 2004).

The Laguna Formation is composed of alluvial deposits of gravel, sand, and silt in at least two coarsening-upwards sequences (Burow et al., 2004). Laguna Formation sediments are more consolidated than the younger overlying formations (Jurgens et al., 2008) and yield variable amounts of water (Burow et al., 2004). The Laguna Formation is not clearly identifiable from adjacent units in areas to the east where it crops out at the surface (Burow et al., 2004).

The underlying consolidated Mehrten Formation is most distinguished by its black sands, composed of andesitic fluvial deposits eroded from the Sierra, and yields moderate to large quantities of good to excellent quality water in some areas (DWR, 1974). However, most Modesto wells are not sufficiently deep to encounter the Mehrten Formation beneath the Study Area.

2.1.2. Cross Section Development

Nine geologic cross sections (A-A’ through I-I’) were developed to delineate the geologic formations and aquifer units described above throughout the Study Area. Geologic units and textures are based on drillers’ reports and geophysical logs. Ground surface elevations were generated from the National Elevation Dataset (NED, 10m) developed by the USGS. Cross section locations are shown on Figure 3 and the cross sections are presented on Figures 4 through 12. As shown on Figure 3, cross sections were developed along the approximate depositional dip direction (B-B’, C-C’, F-F’ and H-H’) and depositional strike direction (A-A’, D-D’, E-E’, G-G’, and I-I’).

The cross sections include 84 City of Modesto wells, representing more than two-thirds of the City wells and more than 80 percent of the City wells that were in production over the last year. The sections also include 9 of the 10 USGS-installed monitoring wells now owned by the City. These wells are nested wells, providing multiple monitoring points at various depths for each monitoring well location. The lithology is based on information from available drillers’ reports for 79 Modesto wells, 14 of which also have geophysical logs. Drillers’ reports are not available for five of the Modesto wells on the cross sections. Lithology for the nested USGS wells, shown on cross sections B-B’, G-G’, H-H’, and I-I’, is based solely on geophysical logs (including resistivity logs, referred to as electric logs). In general, electric logs, when calibrated with descriptions on drillers’ reports, represent more accurate and detailed information on thickness and textures of various aquifer units than can be developed from drillers’ reports alone. If an electric log (e-log) is available, it is noted on the cross sections below the well number. Screened intervals are shown on the cross sections as dark shading. If known, the base of casing is indicated as a hash mark for wells without screened intervals.

The cross sections were developed based on hydrofacies textures. Descriptions on the drillers’ reports were used to categorize the lithology into four textures: gravel, sand, silt, and clay. Where available, the electric logs were used to validate or correct lithology and unit thickness provided on the drillers’ reports. For this project, the focus was on the coarse-grained units of gravel and sand. These units are more likely targets for MAR development. In general, intervening silts and clays were undifferentiated on the sections and are assumed to represent aquitards throughout the overall aquifer system.

The texture analysis was conducted for all of the wells shown on the cross sections for which drillers’ reports were available. The texture categories were defined on the cross sections at the same scale for which they were described on the drillers’ reports. For example, the drillers’ report for Well 62, located in the eastern edge of the Study Area and shown on cross sections C-C’ (Figure 6) and I-I’ (Figure 12), describes a sand layer from a depth of 225 to 226 below ground surface. Consequently, a one-foot “sand” layer was placed on the cross section at this corresponding depth and elevation. The quality of the drillers’ reports varies, and therefore, lithology was not described at a one-foot scale for each well. However, the detail provided on each drillers’ report is preserved, to the extent feasible, on the cross sections.

Once hydrofacies textures were interpreted and recorded at each well location, geologic formation boundaries were estimated to determine the overall hydrogeologic framework. As discussed previously, the geologic formations underlying the Study Area include the Modesto, Riverbank, Upper Turlock Lake, Corcoran Clay, Lower Turlock Lake, and Laguna formations. Sequence boundaries (i.e., formation boundaries) developed by the USGS in a portion of the Study Area were used as a starting point for estimating sequence boundaries on the cross sections (Jurgens et al., 2008). The elevations of the sequence boundaries approximated by the USGS were interpreted across the cross sections based on several sources of information, including surface geology, depositional dip, and marker beds, such as the Corcoran Clay and paleosols. A map of the surface geology published by the USGS (Burow et al., 2004) was used to approximate the extent of the Modesto Formation on the cross sections.

The presence and extent of the Corcoran Clay was estimated based on information provided on drillers' reports and geophysical logs. The Corcoran Clay is typically described as blue clay on the drillers' reports and corresponds with very low resistivity (~10 OHM-M) on the electric logs. The extent of the Corcoran Clay was corroborated with the extent mapped by the USGS (Burow et al., 2004), as shown on Figure 3. Since the Corcoran Clay is located at the base of the Upper Turlock Lake Formation, its location was used to delineate the sequence boundary between the Upper and Lower Turlock Lake formations beneath the western Study Area.

Paleosols, which are oxidized and buried soil surfaces, were used to estimate the boundaries between the Riverbank and the Upper and Lower Turlock Lake formations. Paleosols have been used to identify formation boundaries throughout the San Joaquin Valley and were typically described in the drillers' reports as reddish clay-rich layers (Jurgens et al., 2008).

Once the sequence boundaries were approximated on each cross section, textures were correlated within each formation. The cross sections honor the texture information from the drillers' reports and geophysical logs at the well locations. Between well locations, the sand bodies were correlated within each formation based on elevation and thickness. Thick sand bodies were assumed to be more continuous and more likely to be interconnected with nearby thick sand bodies than thinner sand bodies.

The cross sections were used to categorize the wells by the aquifer in which the base of the screen interval is located; aquifers were grouped into a shallow aquifer, an intermediate aquifer, and a deep aquifer. Wells without a screened interval were categorized based on the aquifer at the base of the casing. Aquifer categories for wells not on the cross sections were based on wells with similar screen depths that were on the cross sections. "Shallow aquifer" wells were defined as wells with screens extending into the Riverbank and Upper Turlock Lake formations (19 wells). "Intermediate aquifer" wells were defined as wells with screens extending into the Lower Turlock Lake Formation and through the Corcoran Clay, where present (70 wells). "Deep aquifer" wells were defined as extending into the Laguna Formation (or deeper) (34 wells). Most of the wells in the Study Area are intermediate aquifer wells, with screens that extend into the Lower Turlock Lake Formation.

Summary information and data for City of Modesto wells are provided in Table A-1 in Appendix A of this report. The table includes well construction data, whether the wells are on a cross section prepared for this report, the formation in which each well is screened, the aquifer category, specific capacity data (if available) and recent production information.

2.1.3. Aquifer Evaluation

2.1.3.1. Hydrogeologic Framework

The cross sections depict the hydrogeologic framework within the Study Area. The project is focused on recharge potential, and therefore, it is critical to identify areas with the most extensive sands. Consequently, the focus of cross section correlations was sand units. As shown on the cross sections, there are portions of some well screens that are outside of sand, likely in silts or sandy silts. Although silts and sandy silts have the potential to yield and store water, they have less recharge potential than more coarse-grained textures.

The dip direction cross sections (B-B’, C-C’, H-H’, and F-F’) show the gently westerly sloping Modesto, Riverbank, Upper Turlock Lake, Lower Turlock Lake, and Laguna formations. As shown on the cross sections, the Modesto Formation is exposed at the surface throughout most of the Study Area. A hydrogeologic characterization of the Modesto Area completed by the USGS (Burow et al., 2004) illustrates that the older Riverbank Formation crops out immediately east of the City. The thinning of the Modesto Formation in the east and exposure of the Riverbank Formation at the surface is illustrated most clearly on the dip direction cross sections.

The Corcoran Clay is present in the western region of the Study Area as illustrated on cross sections A-A’, B-B’, C-C’, D-D’ and F-F’. These cross sections show that the Corcoran Clay ranges in thickness from approximately 5-10 feet, in the vicinity of Well 281 located in the northwest region of the Study Area and shown on cross section A-A’, to approximately 120 feet in the southwestern region of the Study Area, as shown on cross sections C-C’ and D-D’. As described by Burow et al. (2004), and evident in the southwestern region of the Study Area on cross sections B-B’, C-C’, and F-F’, the edges of the Corcoran Clay grade into coarser material. Cross section A-A’ shows that the Corcoran Clay is continuous throughout most of the western Study Area and its thickness undulates, varying from approximately 5 to 10 feet in the northwestern region of the Study Area to approximately 50 feet along the western edge of the Study Area.

Based on lithologic interpretations, the Corcoran Clay on sections A-A’, C-C’, and D-D’ does not appear to extend as far east in some areas as mapped by USGS (compare the edge of the Corcoran Clay on these sections to the line of extent shown on Figure 3). This could indicate that the extent is more irregular than previously mapped or extends farther than indicated by well data on these sections. Because the cross section interpretation is based only on a few logs, the unit may have been too thin to be identified (or not recorded) on several geologic logs from drillers’ reports. In general, the extent mapped by USGS appears to be corroborated by interpretations from the remaining cross sections, and no modifications to the USGS mapped extent are recommended based on this assessment. However, any future local groundwater investigation should consider the cross section interpretations.

The characteristic black sands of the Mehrten Formation are identified in the drillers’ report for two wells: Wells 48 and 65. Well 65, located in the central eastern region of the service are and shown on cross section F-F’ (Figure 9), contains black sands at an elevation of approximately -325 msl. Well 65 is the deepest well on cross section F-F’ and black sands are not evident at any other well on this section. Well 48, located in the northern central region of the Study Area and shown on cross sections B-B’ and G-G’ (Figures 5 and 10), contain black sands at approximately the same elevation (-325 feet msl). There are three other wells on cross section B-B’ (Wells 61, 51, and 54) that extend to this elevation, but their drillers’ reports do not identify black sands. Therefore, the Mehrten Formation could not be correlated throughout cross section B-B’.

2.1.3.2. Textures

The cross sections show the interbedded nature of the sands and clays beneath the Study Area, but reflect a higher percentage of fine grained material throughout the Study Area. This is consistent with the findings of a texture analysis conducted by the USGS as part of their Modesto area hydrogeologic characterization (Burow et al., 2008). The USGS found that the mean percentage coarse-grained texture within their study region was 39.6 percent, indicating a prevalence of fine-grained texture (Burow et al., 2008).

The USGS texture analysis methodology was similar to the methodology followed during cross section development, as described in Section 2.1. 2. The USGS evaluated 3,504 well logs from a large multi-county region that also included the Modesto Study Area. The USGS study region spanned from Manteca in the northwest to Merced in the southwest, and included most of the Turlock and Modesto subbasins. The USGS methodology used a binary texture classification of either “coarse grained” (100 percent coarse) or “fine grained” (0 percent coarse) to categorize each interval on the well logs. Coarse-grained texture was defined as consisting primarily of sand or gravel while fine grained texture was defined as consisting primarily of silt or clay (Burow, et al., 2004). Once this binary texture classification was complete, the coarse-grained percentage was averaged on a 1-meter basis along the depth of the well log.

The dip direction cross sections (B-B’, C-C’, H-H’, and F-F’) indicate relatively thick connected sand beds throughout parts of the Upper and Lower Turlock Lake formations. Thick sand layers are also evident in the Laguna Formation, as illustrated on cross section H-H’, especially in the eastern region of the Study Area (Figure 11). However, fewer wells have been drilled into the Laguna Formation, so data are relatively limited.

The strike direction cross sections (A-A’, D-D’, E-E’, G-G’, and I-I’) suggest less sand connectivity than the dip direction cross sections, which is expected for this alluvial-fluvial depositional environment. By comparing cross section A-A’ on the western edge of the Study Area to cross section I-I’ on the eastern edge of the Study Area, it is evident that sand beds are thicker in the eastern region of the Study Area. This is also consistent with the alluvial depositional environment. As runoff flows from the Sierra Nevada toward the west, water bodies lose energy on the flatter alluvial plain, and systematically deposit the heavier load of sands and gravels. As the rivers continued to flow westward, the sediment load becomes finer.

As described in more detail below, many of the more productive wells are screened in the intermediate and deep aquifer sand units in the eastern and southeastern regions of the Study Area where sand units appear thicker and more continuous.

2.1.3.3. Well Production

The City provided monthly production data for their service area wells from July 2002 to June 2015. Annual production for 2003 to 2014 (i.e., years with complete data) are illustrated on Figure 13. During this twelve year period, annual pumping decreased approximately 33 percent, from a maximum of approximately 47,200 acre-feet per year (AFY) in 2003 to approximately 31,500 AFY in 2013. The rate of decline was gradual between 2003 and 2008, but then the rate of decline increased between 2009 and 2013. Total pumping rebounded slightly in 2014 to approximately 39,700 AF.

Figure 14 illustrates average annual production for each well from July 2014 to June 2015, the most recent year of pumping data. During this time, 100 wells were pumping and production averaged 378 AFY per well. Production ranged from 3 AFY (Well 306) to 1,655 AFY (Well 52).

Figure 15 illustrates the relationship between production (AFY) and aquifer. As described above, aquifers are categorized as either shallow, intermediate, or deep according to the deepest aquifer in which they are screened. The wells are color-coded: shallow aquifer wells are yellow, intermediate aquifer wells are green, and deep aquifer wells are blue. As indicated on the graph, wells with screens into the deep aquifers are pumped more than wells in the shallow aquifer: shallow aquifer wells averaged 221 AFY, intermediate aquifer wells averaged 349 AFY, and deep aquifer wells averaged 516 AFY from July 2014 to June 2015. This correlation alone does not necessarily indicate that the deep aquifers are associated with higher transmissivity; the City operates its wellfield based on groundwater quality as well as quantity and wells are often taken offline due to unacceptable levels of certain constituents. It is noted that both groundwater quality and quantity are also key considerations for MAR projects.

Figure 16 illustrates (in map view) the production magnitude and aquifer for each well that was pumping between July 2014 and June 2015. There are 12 wells that produced over 1,000 AFY during this time. Well 57, located in the central region of the Study Area immediately north of the Tuolumne River, is the only shallow aquifer well that pumped at a rate of over 1,000 AFY. In general, the greatest production occurred in intermediate aquifer and deep aquifer wells along the eastern edge of the Study Area (generally from north to south: Wells 39, 54, 52, 62, 41, and 59) and in the southern edge of the Study Area immediately north of the Tuolumne River (generally from west to east: Wells 225, 279, 277, and 312). Intermediate aquifer Well 56 is the only well in the western side of the Study Area that produced over 1,000 AFY from July 2014 to June 2015. Because the City pumping operations are heavily influenced by groundwater quality, high production along the eastern and the southern portion of the Study Area, roughly between Route 132 and the Tuolumne River, may reflect regions with better water quality.

2.1.3.4. Specific Capacity

Specific capacity is the amount of water produced by a well per foot of drawdown (drop in water level) and is often used as a measure of well performance or aquifer transmissivity. Drillers' reports for 51 of the City of Modesto wells (approximately 40 percent) included pumping test information. However, there are significant limitations for the use of these pumping test data. In many cases, the length of the test was unavailable; for those with available data, test durations varied considerably – a factor that can affect specific capacity. Further, only the basic information is provided and water levels recorded during the test are unavailable. Nonetheless, in the absence of aquifer tests or adequate data collected during testing of well pumps, these data represent the best opportunity for evaluating hydraulic properties of Study Area aquifers. For wells with pumping test information, values of specific capacity and transmissivity have been estimated.

Based on the reported pumping rate (Q in gallons per minute (gpm)) and drawdown (s in ft), specific capacities (Q/s in gpm/ft) ranged from 8 gpm/ft to 263 gpm/ft of drawdown (dd) and averaged 48 gpm/ft dd. Data for five wells indicate specific capacity values greater than 90 gpm/ft. Some of these specific capacities seem unreasonably high for sustained groundwater pumping.

Figure 17 illustrates the relationship between specific capacity and depth for the 51 wells with pumping data. The figure shows that there is not a strong relationship between specific capacity and depth, and that most wells are clustered in the 200 to 350 foot depth range with specific capacities less than 65 gpm/ft dd. The intermediate aquifer wells have the highest average specific capacity (56 gpm/ft dd) followed by the shallow aquifer wells (40 gpm/ft dd) and deep aquifer wells (35 gpm/ft dd).

Figure 18 shows the location of wells with pumping test data and illustrates both the color-coded aquifer and specific capacity magnitude. The shallow aquifer wells with specific capacity data are clustered around the central region of the Study Area and, with the exception of Wells 1 and 223, have specific capacities less than 50 gpm/ft dd. The intermediate aquifer wells and deep aquifer wells with pumping test data are, in general, outside of the central region of the Study Area. The highest specific capacity values outside of the center of the Study Area are from intermediate aquifer Wells 281 (263 gpm/ft dd) and 290 (215 gpm/ft dd) in the northwest corner of the Study Area, deep aquifer Well 310 (73 gpm/ft dd) in the southeast corner of the Study Area, deep aquifer Well 245 (114 gpm/ft dd) to the east of the Study Area (off the map) near the Tuolumne River, and intermediate aquifer Well 49 (138 gpm/ft dd) south of Tuolumne River.

Transmissivity (T) values were estimated from specific capacity using coefficients provided by Driscoll (1986):

T = 2,000 * specific capacity (confined aquifer)

T = 1,500 * specific capacity (unconfined aquifer)

Based on these relationships, average T values are estimated at approximately 72,000 gallons per day per foot (gpd/ft) (unconfined conditions) and 96,000 gpd/ft (confined conditions). Both unconfined and confined groundwater conditions are present in the Study Area. As discussed previously, unconfined to semiconfined conditions are present above and east of the Corcoran Clay, while confined conditions are present below the Corcoran Clay (Burow et al., 2004). Published T values above or east of the Corcoran clay range between 60,000 to 80,000 gpd/ft (Page and Balding, 1973), which is consistent with the average unconfined T value estimated from Study Area specific capacity data.

2.2. Water Levels and Groundwater Flow

The City of Modesto provided water level measurements for their Study Area production wells from January 2000 to April 2015. Water level measurements were also provided for the City for Riverbank wells in March 1998, February 2005, and May 2010, and Oakdale wells, from January 2009 to November 2011. In addition, water level measurements were available from August 2003 to September 2006 for the USGS monitoring wells. The USGS monitoring well water level measurements were provided in two forms: 1) continuous water level data were provided directly from files of USGS personnel, and 2) hand-measured water level data were downloaded from USGS National Water Information System (NWIS).

Groundwater elevation contour maps were developed based on water levels measured in July 2000, the oldest and most complete set of water level data, and April 2015, the most recent set of water level measurements. These groundwater elevation contour maps are illustrated on Figures 19 and 20.

In July 2000, as shown on Figure 19, groundwater generally flows from east to west from an elevation of approximately 70 feet msl along the eastern edge of the Study Area to 30 feet msl along the northwestern edge of the Study Area. There are localized cones of depression within the Study Area, the largest of which is in the northern region of the Study Area in the vicinity of Wells 25, 48, and 50. In this area, drawdowns of approximately 10 to 15 feet are evident. Wells 25 and 48 are deep aquifer wells with screens extending into the Laguna Formation and Well 50 is an intermediate aquifer well screened in the Lower Turlock Lake Formation. Groundwater in the southeastern region of the Study Area flows to the southwest towards the Tuolumne River.

Groundwater elevation contours in April 2015, as shown on Figure 20, illustrate that water levels declined approximately 5 to 10 feet throughout the Study Area since July 2000. Groundwater flows from an elevation of approximately 55 feet msl along the eastern Study Area to approximately 25 feet msl in the northwestern region of the Study Area. The largest cone of depression, with approximately 20 feet of drawdown, is centered on Well 16, an intermediate aquifer well located in the north-central region of the Study Area and screened in the Upper and Lower Turlock Lake formations. A localized cone of depression with drawdown of approximately 5 to 10 feet is evident in the northern region of the Study Area around Well 43, an intermediate aquifer well screened in the Upper Turlock Lake and Lower Turlock Lake formations. Groundwater flow direction in the southern region of the Study

Area is predominantly to the south, toward the Tuolumne River. This represents a slight southward shift in flow direction from July 2000, when the flow direction in the southern region of the Study Area was to the southwest. This shift may be a result of the high production from wells along the southern periphery of the Study Area and immediately north of the Tuolumne River, as described above and illustrated on Figure 16, or as a result of the lower flows along the Tuolumne River due to the drought.

Water level hydrographs were plotted for select USGS wells (Figure 21) and City of Modesto production wells presented on the cross sections (Figures 22 through 30). In general, water levels follow similar cyclic patterns based on seasonal pumping, with annual drawdown and recovery cycles. These cycles correlate well with monthly pumping data provided by the City. Overall, water levels show a slight decline of approximately 5 to 10 feet from 2000 to 2015. The hydrographs show that on dip direction cross sections (B-B', C-C', F-F', and H-H'), water levels decrease to the west, which is consistent with the groundwater flow direction illustrated on the contour maps (Figures 19 and 20).

Figure 22 shows hydrographs for select wells on cross section A-A'. Slight differences in water levels between Well 63 (a deep aquifer well screened in the Lower Turlock Lake and Laguna formations) and adjacent Well 42, (screened in the Upper Turlock Lake, Corcoran Clay, and Lower Turlock Lake formations) suggest a downward gradient through the Corcoran Clay. Water levels in shallow aquifer Wells 2, 3, and 8 follow similar patterns to one another, but exhibit less of a pumping response than nearby shallow aquifer Well 57. This is a result of higher pumping rates in Well 57, but also suggests, as shown on the cross section, that Wells 2, 3, and 8 are in a sand body that may be disconnected from Well 57.

Hydrographs for the USGS monitoring wells on cross section B-B' are shown on Figure 23. Water levels in USGS nested well FPC (FPC-1, FPC-2, and FPC-3) illustrate a downward vertical gradient from the Riverbank Formation into the Lower Turlock Lake and Laguna formations. The differences in water levels between USGS Wells FPC-1 and FPC-2 is much greater than the differences between FPC-2 and FPC-3; this suggests that there is a stronger vertical gradient from the Riverbank Formation to the Lower Turlock Lake formation than from the Lower Turlock Lake Formation to the Laguna formation. Although limited in number, water levels from the USGS nested well OFPB also suggest a downward vertical gradient from the Riverbank Formation to the Upper Turlock Lake formation. The water level in OFPB-2 fluctuates, which may reflect pumping in adjacent Well 54, apparently screened in the same sand unit.

This difference in pumping response is also illustrated on Figure 24 for hydrographs on cross section C-C'. Water levels in shallow aquifer Wells 10 and 29 show less of a pumping response than nearby shallow aquifer Well 57. This may be a result of higher pumping rates in Wells 57, but also suggests, as shown on cross section C-C', that Wells 10 and 29 are screened in a sand body that is disconnected from Well 57.

Hydrographs for select wells on cross section D-D' are shown on Figure 25. Differences in water levels between Well 19, completed in the Corcoran Clay, and nearby Well 100, completed in the Upper Turlock Lake Formation, suggest a downward gradient into the

Corcoran Clay. Based on the cross section, Wells 4 and 57 are screened in the same sand unit, but Well 57 has a more pronounced response to pumping. This is likely because Well 57 has higher pumping rates than Well 4 and because Well 4 appears to be screened in separate sand layers.

Figure 26 presents hydrographs for Wells 21 and 300, located on cross section E to E' in the central region of the Study Area. Water levels are slightly higher in Well 21, which is screened in the Upper and Lower Turlock Lake formations, than in nearby Well 300, completed in the Laguna Formation. This suggests a downward gradient between the Lower Turlock Lake and Laguna formations in this portion of the Study Area.

Hydrographs for select wells on cross section F-F' are shown on Figure 27. Water levels in Well 56, located in the western region of the Study Area and screened within the Corcoran Clay and Lower Turlock Lake Formation, show a more dramatic response to pumping than water levels in adjacent Well 8, screened above the Corcoran Clay in the Upper Turlock Lake Formation. This is due to higher pumping in Well 57 than in Well 8. The hydrographs show that when Well 56 is pumping and its water level declines, there is a downwards vertical gradient through the Corcoran Clay. But, when Well 57 is not pumping and its water level is higher than in Well 8, there is an upward vertical gradient through the Corcoran Clay. Water levels in the eastern Study Area decrease consistently with the direction of groundwater flow, from Wells 52, 46, and 37. Well 65, located between Well 37 and Well 46 and screened deeper than these nearby wells, has lower water levels. This suggests a downward gradient from the Upper and Lower Turlock Lake formations into the Laguna Formation in the eastern region of the Study Area.

Hydrographs for the three deep City wells on cross section G-G' (Figure 28), namely Wells 48, 264, and 58, illustrate water levels in the Laguna Formation. Water levels in Wells 48 and 58 have a similar pattern, but are lower than the water levels in Well 264. Water levels in Well 264 have less of a pumping response, likely due to lower pumping rates and the well's open borehole completion (without well screens).

The water levels in the USGS wells on cross section G-G' exhibit similar fluctuations and vertical gradients (Figure 21). Water levels in nested wells FPC and FPB are highest in the shallowest wells (FPC-1 and FPB-1) and decrease with depth. The water levels in FPC-1 and FPB-1, screened in the Riverbank Formation, are at least 10 feet higher than the deeper wells screened in the Upper and Lower Turlock Lake formations (FPC-2 and FPB-2) and the Laguna Formation (FPC-3 and FPB-3). Water levels in the intermediate aquifer wells (FPC-2 and FPB-2) are slightly higher (approximately 1 to 5 feet) than in the deeper wells. These water levels illustrate a strong downward vertical gradient from the Riverbank Formation to the Upper and Lower Turlock Lake formations, and a weaker downward vertical gradient from the Upper and Lower Turlock Lake formations into the Laguna Formation. In addition, Riverbank Formation wells show less of a pumping response because most pumping wells are deeper. Hydrographs for USGS nested wells FPE and OFPA show that water levels in the Riverbank Formation and the shallow portion of the Upper Turlock Lake Formation are similar. Water levels decrease in the base of the Upper Turlock Lake Formation (OFPA-3) and the upper region of the Lower Turlock Lake Formation (FPE-3). This suggests a stronger downward vertical gradient within the Upper Turlock Lake Formation than between the Riverbank and the Upper Turlock Lake formations.

Water levels for select wells on cross section H-H', shown on Figure 29, illustrate the horizontal and vertical gradients in the central / northern portions of the Study Area. Water levels are higher in Well 39 than in Well 25, which is consistent with the groundwater flow direction from east to west. Well 58, located between Wells 25 and 39 and screened in deeper Laguna Formation sands, has lower water levels than either Well 25 or Well 39, which suggests a downward gradient into the Laguna Formation.

Water levels in USGS well FPA, a nested well screened in the Riverbank (FPA-1), Upper Turlock Lake (FPA-2 and FPA-3), and the Laguna formations (FPA-4), indicate a vertical downward gradient (Figure 21). The downward vertical gradient is relatively weak between the Riverbank Formation (FPA-1) and the shallow portion of the Upper Turlock Lake Formation (FPA-2), but much greater between the shallow Upper Turlock Lake (FPA-2) and deeper Upper Turlock Lake (FPA-3) and Laguna (FPA-4) formations. The water levels in the two deeper wells (FPA-3 and FPA-4) illustrate more of a pumping response. Water levels in USGS nested well FPE, which has three screens (FPE-1, FPE-2, and FPE-3), indicate strong downward gradients from the Upper Turlock Lake Formation to the Lower Turlock Lake Formation. USGS nested well OFPB, with screens in the Riverbank (OFPB-1) and Upper Turlock Lake (OFPB-2) formations illustrate that downward vertical gradients also occur along the eastern edge of the Study Area.

Figure 30 illustrates hydrographs for many intermediate aquifer and deep aquifer wells along the eastern edge of the Study Area shown on cross section I-I'. Water levels in Well 293, screened in the Lower Turlock Lake and Laguna formations, are higher than in adjacent Well 294, screened in deeper sands of the Laguna Formation; this indicates a downward vertical gradient from the Lower Turlock Lake Formation into the Laguna Formation. Water levels in Well 45, screened in the Lower Turlock Lake and Laguna formations, are higher than in nearby Well 41, screened in the Upper and Lower Turlock Lake formations. This may be a result of the generally higher pumping rates in Well 41, creating a localized pumping-induced upwards vertical gradient. As illustrated by comparison of water levels at Well 54 (in the northeastern edge of the Study Area) to water levels at Well 312 (in the southeastern edge of the Study Area) water levels decrease towards the Tuolumne River.

2.3. GROUNDWATER QUALITY

Communications with the City indicate that their groundwater production well network has been impacted by high concentrations of arsenic, nitrate, tetracholorethylene (PCE), and uranium. Approximately 20 wells have been removed from service, either temporarily or permanently, because of high concentrations of one or more of these constituents. In addition to those listed above, dibromochloropropane (DBCP) has been identified as a constituent of concern. This study provides a city-wide, reconnaissance-level evaluation of groundwater quality that can be used to help locate future MAR projects.

Groundwater quality in the Study Area was evaluated using water quality data provided by the City and publically available water quality data from the State Water Resources Control Board (SWRCB) Geotracker GAMA (for Groundwater Ambient Monitoring Assessment) online database. Data collected for this study were analyzed to characterize groundwater quality both horizontally (i.e., in map view) and vertically, using the cross sections described in Section 2.1.2.

2.3.1. Groundwater Quality Data Sources, Collection, and Synthesis

This subsection describes data collection and the development of work products to interpret and visualize groundwater quality information.

2.3.1.1. Groundwater Quality Data for Maps

The SWRCB Geotracker GAMA online database aggregates groundwater elevation and quality information from several sources, including State and Regional Water Board regulated sites, Department of Pesticide Regulation, Department of Water Resources, Lawrence Livermore National Laboratory, SWRCB domestic and supply well data, and the USGS. Groundwater quality data are available for download by source on a county-by-county basis. Groundwater quality data for all sources in Stanislaus County were downloaded in September 2015 for use in this analysis. The data download included well names, locations, water quality sampling results, and data qualifiers. Specifically, it is important to note that wells associated with Water Board regulated sites (e.g., a leaking underground storage tank site) are generally located with higher levels of accuracy than data from other sources (e.g., water supply wells). Therefore, location information for City of Modesto supply wells in the Geotracker GAMA data download were replaced with more accurate locations provided by the City in the form of GIS shapefiles. The downloaded data were filtered to include only the latest sampling results for arsenic, DBCP, nitrate, PCE, and uranium. This filtered dataset was used to create maps for each contaminant, where the symbols for each well indicate the concentration relative to the maximum contaminant level (MCL). MCL's for each constituent of concern are provided in Table 1 below.

Table 1: Maximum Contaminant Levels for Constituents of Concern

Constituent of Concern	Maximum Contaminant Level
Arsenic	10 µg/L
Dibromochloropropane (DBCP)	0.2 µg/L
Nitrate (as NO_3)	45 mg/L
Tetrachloroethylene (PCE)	5.0 µg/L
Uranium	20 pCi/L

2.3.1.2. Groundwater Quality Data for Cross Sections

The City provided a Microsoft Excel workbook with water quality sampling results from 2000–2014 for their production well network, which is the same network of wells used to develop the geologic cross sections described in Section 2.1.2. The latest water quality sampling results for nitrate, arsenic, uranium, and DBCP at each well were extracted from the Excel dataset and added to the cross sections. The cross sections with water quality information are provided as Figures 31 through 39. Additionally, trends for each constituent were evaluated using the Mann-Kendall test, which is a statistical evaluation of upward or downward monotonic trends for the variable of interest. Results of the Mann-Kendall analyses (i.e., either increasing trend, decreasing trend, no trend, or insufficient number of samples) are indicated on the cross sections. Results above the MCL for each constituent are indicated on the cross sections by bolding and italicizing the result.

Data from the Excel spreadsheet were also used to develop Stiff diagrams for each cross-section well with sufficient sampling results. Stiff diagrams provide a graphic representation of the relative distributions of major cations and anions in a water sample. The Stiff plotting technique uses parallel horizontal axes extending on each side of a vertical zero axis. Concentrations of cations (sodium plus potassium, calcium, and magnesium), in milli-equivalents per liter (meq/L), are plotted sequentially on each axis to the left of zero. Similarly, anion (chloride, bicarbonate, and sulfate) concentrations are plotted sequentially on each axis to the right of zero. The resulting points are connected to give an irregular polygonal shape or pattern, which provides a distinctive method of showing water composition differences and similarities. The width of the pattern is an approximate indication of the total ionic content.

2.3.2. Results of Groundwater Quality Analysis

Maps of the latest sampling results available on the Geotracker GAMA database are shown on Figure 40 through Figure 44 for arsenic, DBCP, nitrate, PCE, and uranium, respectively. Cross sections with water quality information are shown on Figures 31 through 39 (refer to Figure 3 for the cross section location map).

2.3.2.1. Arsenic

Arsenic occurs naturally in groundwater as a result of the dissolution of arsenic-bearing rocks, but it can also be present due to the use of certain fertilizers and pesticides. Arsenic is generally detected at higher concentrations in the western and southern parts of the City (Figure 40). Most arsenic detections above the MCL occur in the western-central portion of the City, along Highway 99. No notable trends in arsenic are present based on the Mann-Kendall analysis or visual inspection of data on the cross sections.

2.3.2.2. Dibromochloropropane

DBCP was used as the active ingredient in the nematacide Nemagon, which was used as a soil fumigant in agricultural areas until the compound was banned in 1979. DBCP is sporadically detected in groundwater beneath the City (Figure 41). Two of the latest results in the Geotracker database were above five times the MCL, one occurring in 1986 and the other in 1990. Several wells in and near the southeastern portion of the City (near Yosemite Boulevard/ Route 132) had detections above the MCL.

2.3.2.3. Nitrate

Nitrate in groundwater comes from the use of fertilizers and from animal waste (e.g., manure from dairies, septic systems). Nitrate is widely detected throughout the City at concentrations above one-half the MCL, with numerous detections above the MCL (Figure 42). Increasing trends for nitrate are observed sporadically on the cross sections. In some cases, it appears that nitrate concentrations are higher in upper portions of the aquifer (e.g., shallow wells 29, 100, and 223 on Section D-D' have relatively high nitrate concentrations compared to nearby wells). However, there are also cases of higher concentrations from deeper wells with long screen intervals completed in the Lower Turlock Lake and Laguna formations. It is possible that these wells with long screen intervals act as conduits for the downward migration of nitrate, but the degree to which this occurs is difficult to discern due to the many unknown, long, or multi-level screened intervals.

2.3.2.4. Tetrachloroethylene

PCE is generally associated with isolated, point-source contaminant releases (e.g., from a dry cleaner or leaking sewer pipes). In Modesto, detections of PCE above the MCL are generally associated with one of two sites in the central portion of the City (Figure 43). PCE contamination at both the McHenry Village[1] and Modesto Groundwater Contamination[2] sites are attributed to former dry cleaning operations. The McHenry Village site is located on McHenry Avenue near the intersection with Briggsmore Avenue, and the Modesto Groundwater Contamination site is also located on McHenry Avenue, roughly one mile south of the McHenry Village site. It is documented that PCE from these sites has impacted nearby supply wells.

2.3.2.5. Uranium

Uranium is a naturally occurring contaminant commonly found in eastern San Joaquin Valley aquifers. Uranium in Modesto-area groundwater occurs as the result of dissolution from alluvial materials originating from the Sierra Nevada. Detections of uranium above the MCL occur throughout the central and western portions of the City (Figure 44). As with nitrate, it is difficult to discern any possible vertical trends in uranium concentrations from data presented on the cross sections.

2.3.2.6. Major Cations and Anions

Calcium and bicarbonate are generally the dominant cations and anions, respectively, in groundwater beneath Modesto. Groundwater from some wells nearer to and within the Corcoran Clay (see Section C-C' and D-D') has higher ionic strength relative to elsewhere in the area, and often shows a more pronounced sodium and chloride signature. This area of higher ionic strength is generally the area south of the Tuolumne River.

2.3.3. Water Quality Data Limitations

The maps included herein provide a reconnaissance-level assessment of the spatial distributions of the constituents of concern, but are limited in that they contain data

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[1] http://geotracker.waterboards.ca.gov/profile_report.asp?global_id=SLT5S1883227

[2] http://yosemite.epa.gov/r9/sfund/r9sfdocw.nsf/vwsoalphabetic/Modesto+Ground+Water+Contamination?OpenDocument

representing mixed groundwater depths and ages. The Geotracker GAMA water quality data do not include information on well depth, which precluded development of depth-dependent water quality maps at county- or city-wide scales. Well screen information is only available for a subset of the City supply wells used to develop cross sections and stiff diagrams. Where supply well screen information is available, there are often multiple screened intervals or a single, long screened interval that spans more than one hydrogeologic unit. Similarly, the database contains results from a wide range of times. As an example, the average sampling year of the arsenic results plotted on Figure 40 is 2004, but data range from 1966 through 2015. Given these limitations of the readily available datasets, site-specific groundwater quality evaluations will be required for local projects.

2.3.4. Overview of Groundwater Quality in Study Area

Groundwater quality is generally better in the eastern and southeastern (i.e., north of the Tuolumne River to Route 132) portions of the Study Area. These locations generally have fewer instances of arsenic, nitrate, and uranium detections near or above the respective MCLs, although DBCP has been detected above the MCL from several wells along Route 132. Vertical distribution of water quality was difficult to discern due to a lack of screen information for some wells, and the presence of long and/or multiple screened intervals within a single casing.

2.4. CONSIDERATIONS FOR MANAGED AQUIFER RECHARGE

The hydrogeologic characterization indicates that favorable areas for subsurface recharge strategies occur in the eastern and northeastern portions of the Modesto Service Area. These areas are associated with the following favorable criteria for MAR strategies:

- thicker sand units that appear to be more continuous across the Study Area
- relatively high percentage of sand in intermediate and lower aquifers to allow recharge to benefit those aquifers relied on for groundwater production
- deeper groundwater levels to maximize subsurface storage
- favorable groundwater quality with lower concentrations of constituents of concern
- upgradient locations that optimize recharge water recovery within the Study Area
- numerous production wells with relatively high production capability and favorable specific capacities in the intermediate and deeper aquifers.

For surface recharge, the conditions listed above are also considered favorable criteria. In addition, relatively permeable surficial and shallow sediments in the vadose zone above the water table are required. Previous analyses conducted for MID and DWR investigated the potential of using surface recharge methods throughout the Study Area (WRIME, 2007). Results of this analysis, as illustrated on Figure 45, show that the most promising locations for surface recharge facilities are generally from Highway 99 to about 10 miles to the northeast (WRIME, 2007). Within the Study Area, the areas with the highest potential for enhanced surface recharge are in the eastern and southeastern regions as well as along the northern border (WRIME, 2007) (Figure 45).

Enhancing recharge for the City of Modesto may be achieved by either surface or subsurface methods, or a combination of both. In general, favorable areas for surface recharge in the eastern Study Area overlap portions of the favorable areas for subsurface recharge.

In order to select possible sites for potential MAR strategies in the more favorable eastern and northeastern areas, existing land use was reviewed. In particular, the presence of open space, including parks that may provide sufficient land to accommodate either surface basins or recharge/ASR wells, were singled out. Based on park information provided by the City, there is a higher concentration of parks in the eastern part of the Study Area, particularly along the banks of Dry Creek and the Tuolumne River.

Based on the analysis of hydrogeologically-favorable areas for MAR strategies, a preliminary assessment of potential MAR strategies is provided in the following sections. Considerations for this assessment include availability of source water for recharge, land use, infrastructure, and institutional issues. In addition, the analysis selects various candidate locations for evaluation of MAR strategies using numerical modeling.

3. AQUIFER RECHARGE ANALYSIS

In order to develop reasonable MAR alternatives for further evaluation, information on target aquifers and recharge methods was evaluated with various criteria including the availability of source water, accessibility of existing infrastructure, land use, and permitting issues. Areas of maximum benefit (including vertical aquifer zones) were identified in this analysis, thus allowing future MAR investigations to be strategically focused.

3.1. MAR ALTERNATIVES

For the selection of MAR alternatives, specific criteria were developed from a previous surface recharge analysis (WRIME, 2007), the hydrogeologic characterization (Section 2), and data received from the City regarding existing infrastructure location and sizing, land use, and well locations. For each MAR alternative identified in the Study Area, the potential for surface percolation and/or direct injection (including ASR) was considered. The alternatives are described in Section 3.1.1 and summarized in Table 2.

3.1.1. Alternative Identification

To begin alternative development, two focus areas were identified based on findings from the hydrogeologic characterization and the 2007 surface recharge analysis. The findings of these two analyses corroborate and indicate that MAR alternatives could potentially be developed in eastern and southeastern portions of the Study Area. In addition, there is a higher concentrations of parks on the eastern Study Area, particularly along the banks of Dry Creek and the Tuolumne River, providing open space that could potentially accommodate surface recharge basins and/or recharge wells. Based on this information, two focus areas were identified as follows:

1. Southern Study Area, centered on the Tuolumne River
2. Eastern edge of Study Area.

Data received from the City were overlain on these focus areas and analyzed for potential opportunities for direct injection and/or surface percolation. The location of MID transmission facilities and City infrastructure was considered, as were land use types that might be favorable to MAR. Current knowledge of proposed future development was also considered. In summary, the following City data were considered during alternative development:

- Well location and current status
- Schools (note: not City-owned)
- City parks
- Golf courses
- Existing city water pipes
- MID transmission lines

- General Plan Land Use (current set used for the City's Water Master Plan and Wastewater Master Plan)
- Future Pipelines (Capital Improvement Program [CIP]) detailed in the City's 2010 Engineer's Report.

Potential sites for MAR were then identified and analyzed to determine the target aquifer and appropriate recharge method(s). Hydrogeologic cross sections described in Section 2 were instrumental in this process. This characterization concluded that the greatest production from City wells from July 2014 – June 2015 in the focus areas was from intermediate and deep aquifers. As groundwater recharge potential can be directly correlated to groundwater production capacity, this information was used to identify the location and depths of target recharge locations. Additionally, local groundwater flow directions are toward the west and southwest along the eastern and southeastern regions of the Study Area. Thus, water recharged in the focus areas could be recovered from existing downgradient production wells or, for vertical downward flow, collected from wells screened in deep aquifer zones.

3.1.2. Alternative Descriptions

Seven initial MAR alternatives were developed and evaluated. These are listed below and shown on Figure 46 relative to the overall Service Area. Each is described in the following section along with a summary of potential advantages and disadvantages of each location.

- Alternative 1 – Creekside Golf Course
- Alternative 2 – Sutton Park
- Alternative 3 – South of Mary Grogan Community Park
- Alternative 4 – Sanders Park
- Alternative 5 – Freedom Park
- Alternative 6 – Orchard Park
- Alternative 7 – Ustach Park

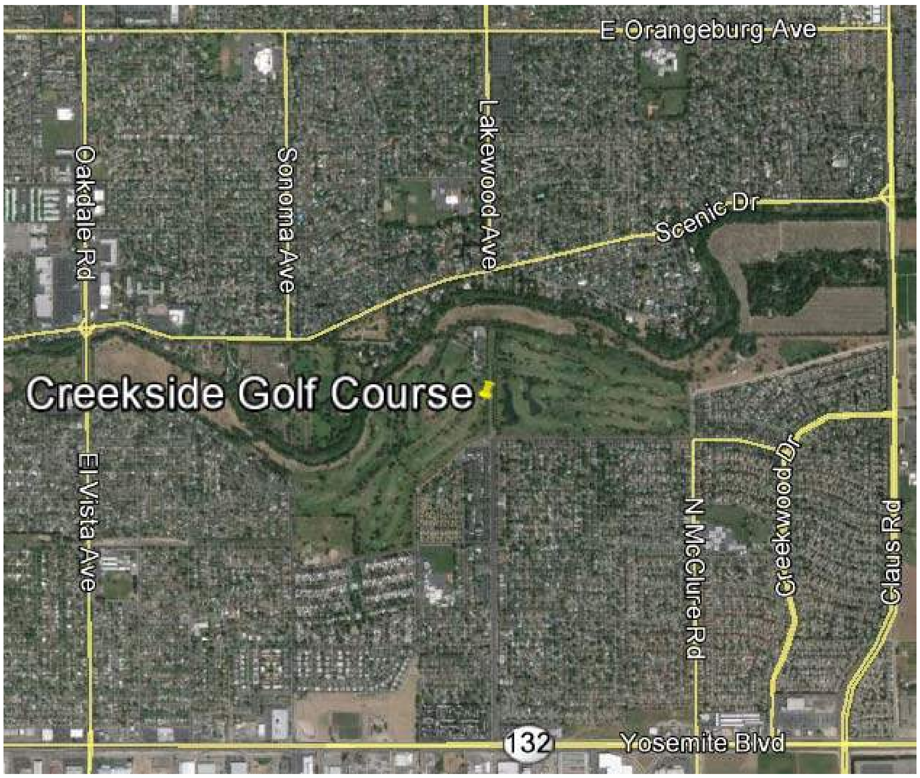
3.1.2.1. Alternative 1 – Creekside Golf Course

The Creekside Golf Course site is in the southeastern portion of the Study Area on the banks of Dry Creek. By converting the existing water hazards into percolation ponds, MAR could be achieved. As the recharge strategy at this site is surface percolation, the targeted aquifer would be the Riverbank Formation, the shallowest formation in the Study Area. With an approximate area of 1.4 acres available for percolation and assuming the site is hydrologic soil group B with an infiltration rate of 0.5 feet per day, the estimated percolation rate would be 0.7 acre-feet/day.

- Advantages
    - o Average to high MAR capacity for surface percolation

- o Potential ability to percolate storm water and MID water
- o No major change from existing land use

- Disadvantages
  - o Potential water loss to Dry Creek
  - o Unknown ability to expand size of water hazards



3.1.2.2. Alternative 2 – Sutton Park

Sutton Park is an undeveloped park located in the southeastern part of the Study Area. The specific MAR strategy for this location would add percolation ponds and multi-use trails to create a MAR project with recreational resources similar in concept to Veterans Oasis Park in Chandler, Arizona, a municipal park that combines recreation, education, and recharge. (See http://www.chandleraz.gov/content/PR_Veterans_Oasis_Park_Map.pdf). Sutton Park has potential for both percolation and injection, and is upgradient from existing production Well 59. The park has approximately 15 acres available for percolation, and assuming the site is hydrologic soil group B with an infiltration rate of 0.5 feet per day, the estimated percolation rate would be 7.5 acre-feet/day. For direct injection, assuming that the injection potential in this area is equivalent to half the extraction capacity of Well 59, or 700 gallons per minute (gpm), an injection well at this location has the potential to recharge approximately 3.1 acre-feet/day targeting the Upper and Lower Turlock Lake formations.

- Advantages
    - High MAR capacity for surface percolation
    - Potential site for both surface percolation and/or direct injection
    - Potential for multi-use benefits
    - Located next to high school which presents opportunities to further expand multi-use benefits
    - Immediately adjacent to a MID transmission line, easing water delivery
    - Upgradient from extraction Well 59 (for downgradient capture of recharged water) and adjacent to future CIP pipeline (per 2010 EIR)
    - No major change from existing land use
    - Opportunity to provide open space/park for future planned “Village Residential” land use

No specific disadvantages have been identified.

3.1.2.3. Alternative 3 – South of Mary Grogan Community Park

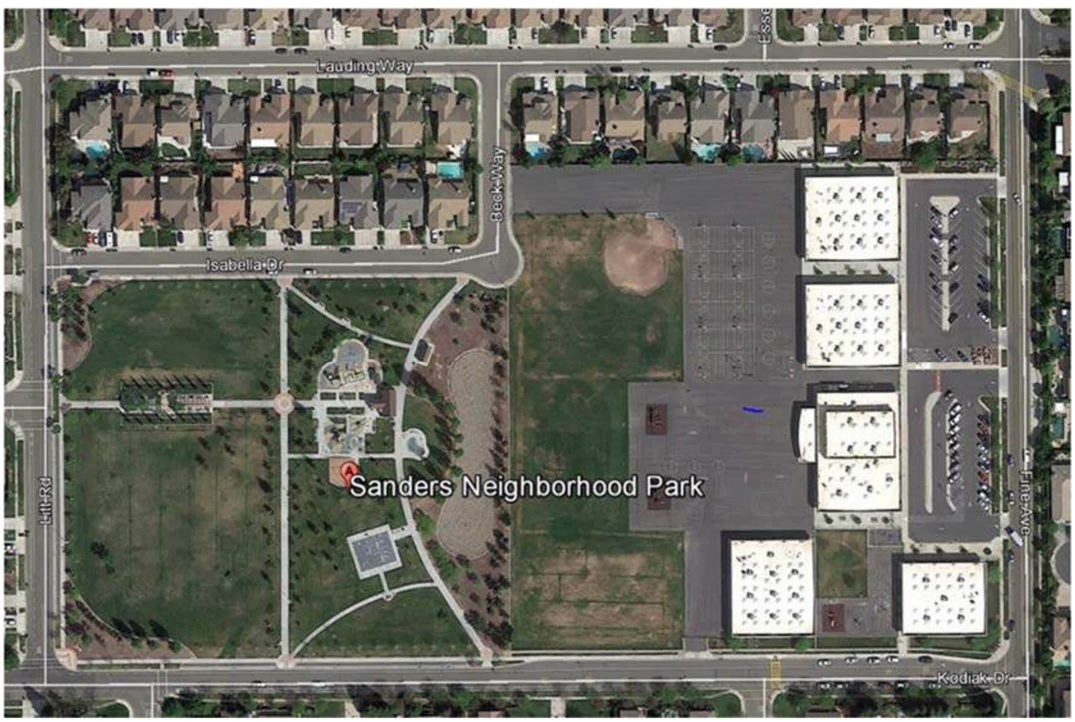
The parcel of land identified for this MAR alternative is an undeveloped piece of land immediate adjacent to Mary Grogan Community Park, east of James Enoch High School. Located in the northeastern part of the Study Area, the proposed MAR strategy for this location would be to add percolation ponds and multi-use trails to create a MAR project with recreational resources similar in concept to Veterans Oasis Park in Chandler, Arizona (http://www.chandleraz.gov/content/PR_Veterans_Oasis_Park_Map.pdf). This site is appropriate for both percolation and injection and is upgradient from existing production Well 54. The park has approximately 11 acres available for percolation, and assuming the site is hydrologic soil group B with an infiltration rate of 0.5 feet per day, the estimated percolation rate would be 5.5 acre-feet/day. For direct injection, assuming that the injection potential in this area is equivalent to half the extraction capacity of Well 54, or 1,200 gpm, an injection well at this location has the potential to recharge approximately 5.3 acre-feet/day targeting the Upper and Lower Turlock Lake formations.

- Advantages
    - High to average MAR capacity for surface percolation, providing for expanded recreational facilities
    - Potential site for both surface percolation and/or direct injection
    - Location may provide recreational and outdoor space for future “Residential” planned land use
    - Future CIP pipeline planned adjacent to parcel
- Disadvantages
    - Relatively far from MID transmission pipeline

3.1.2.4. Alternative 4 – Sanders Park

Sanders Park is a developed park located immediately to the west of Mary Sanders Elementary at the intersection of Kodiak Drive and Litt Street. Located in the northeastern part of the Study Area, the proposed MAR strategy for this location would be direct injection. This site is not ideal for percolation but is appropriate for injection and is near existing production Wells 52 and 62. For direct injection, assuming that the injection potential in this area is equivalent to half the average extraction capacity of Wells 52 and 52, or 950 gpm, an injection well at this location has the potential to recharge approximately 4.2 acre-feet/day targeting the Lower Turlock Lake Formation.

- Advantages
    - Space available for wells
    - Upgradient of existing production wells
    - Near elementary school, possible multi-benefit or educational project
- Disadvantages
    - Not ideal for percolation



3.1.2.5. Alternative 5 – Freedom Park

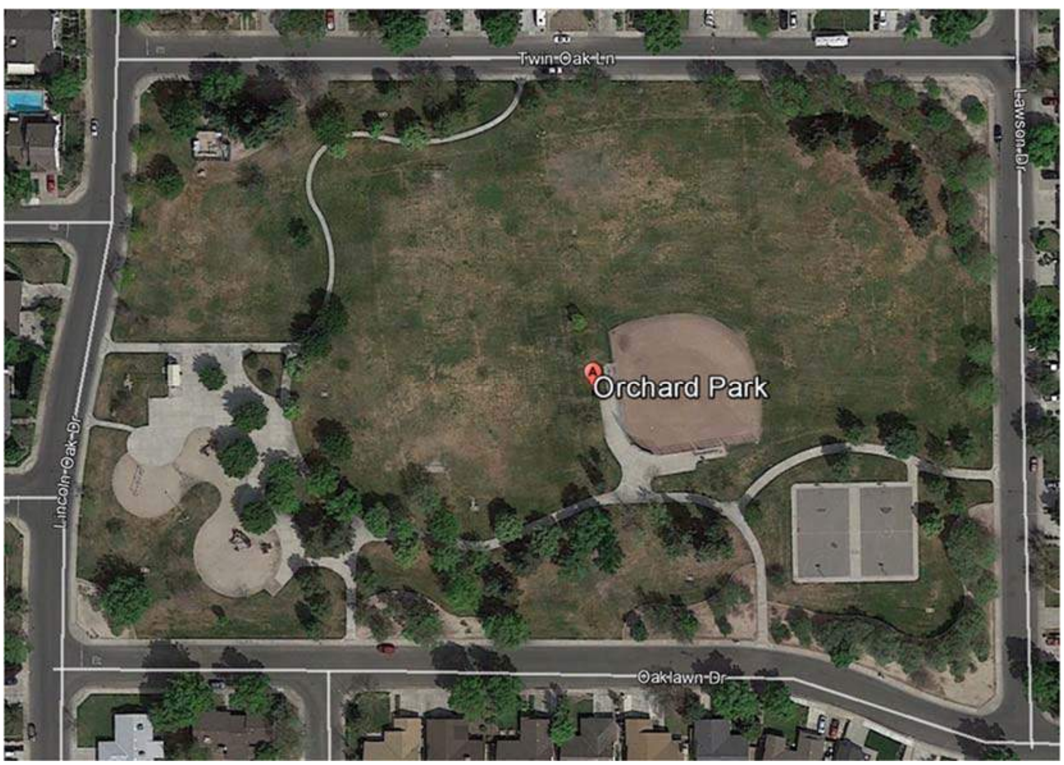
Freedom Park is a developed park located immediately to the west of Freedom Elementary and to the north of Daniel J Savage Middle School at the intersection of Maid Marianne Lane and Sharon Avenue. Located in the eastern part of the Study Area, the proposed MAR strategy for this location would be direct injection. There are no obvious opportunities for percolation, but the park is appropriate for injection and is the site of existing production Well 62. For direct injection, assuming that the injection potential in this area is equivalent to half the extraction capacity of Well 62, or 1,100 gpm, an injection well at this location has the potential to recharge approximately 4.9 acre-feet/day targeting the Lower Turlock Lake Formation.

- Advantages
    - Potential to pair with extraction Well 62 in existing large enclosure
    - Relatively near to MID transmission line
    - Near elementary and middle school, possible multi-benefit or educational project
- Disadvantages
    - No obvious opportunities for percolation

3.1.2.6. Alternative 6 – Orchard Park

Orchard Park is a developed park located at the intersection of Twin Oak Lane and Lawson Drive. Located in the eastern part of the Study Area, the proposed MAR strategy for this location would be direct injection. There are no obvious opportunities for percolation but the park is appropriate for injection and is the site of existing production Well 46. For direct injection, assuming that the injection potential in this area is equivalent to half the extraction capacity of Well 46, or 575 gpm, an injection well at this location has the potential to recharge approximately 2.5 acre-feet/day targeting the Lower Turlock Lake Formation.

- Advantages
  - Potential to pair with extraction Well 46, though enclosure would need to be enlarged
  - Relatively near to MID transmission line
- Disadvantages
  - No nearby schools for possible multi-benefit or educational project
  - No obvious opportunities for percolation



3.1.2.7. Alternative 7 – Ustach Park

Ustach Park is a developed park located adjacent to Elizabeth Ustach Middle School along Bear Cub Lane. This site is appropriate for both percolation and injection and is upgradient from existing production Well 52. Existing production Well 52 is located in the southeast corner of the park and a storm drain basin, "West Basin", is across Bear Cub Lane. Located in the northeastern part of the Study Area, the proposed MAR strategy for this location would be to percolate treated water in West Basin and provide direct injection in the vicinity of Well 52. West Basin has approximately 2.5 acres available for percolation, and assuming the site is hydrologic soil group B with an infiltration rate of 0.5 feet per day, the estimated percolation rate would be 1.3 acre-feet/day. For direct injection, assuming that the injection potential in this area is equivalent to half the extraction capacity of Well 52, or 800 gpm, an injection well at this location has the potential to recharge approximately 3.5 acre-feet/day targeting the Upper and Lower Turlock Lake formations.

- Advantages
    - High MAR capacity for percolation
    - Potential to pair injection well with existing extraction well, although the existing enclosure would need to be enlarged
    - Existing West Basin storm drain basin is adjacent and available for flushing to waste
    - Existing West Basin may be converted to percolation facility providing for storm water runoff management in the winter and percolation of MID water in summer
    - Relatively near MID transmission line
    - Near two schools, possible multi-benefit or educational project

No specific disadvantages have been identified.

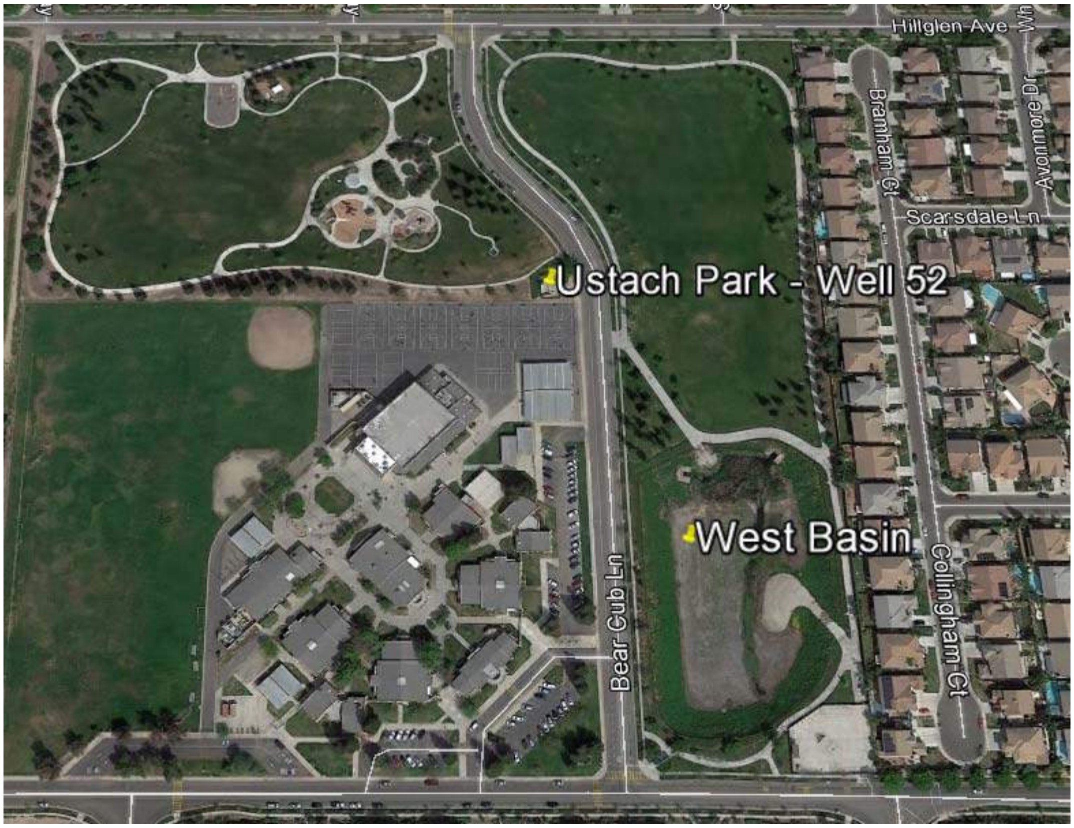

Hillglen Ave
Bramham Ct
Avonmore Dr
Scarsdale Ln
Ustach Park - Well 52
West Basin
Bear Cub Ln
Collingham Ct

Table 2: MAR Alternatives Summary

Alt. No.	Location	Nearest Extraction Well	Perc (P)/ Inject (I)	Target Injection Formation	Pros/Cons	Approximate Acreage Available for Percolation	Estimated Percolation Rate (acre-feet/day)	Estimated Injection Rate (acre-feet/day)
1	Creekside Golf Course	--	P	Riverbank	Pros - Ave.-High MAR capacity - Storm and MID water - No land use change Cons - Water loss to Dry Creek - Set water hazard size	1.4	0.7	--
2	Sutton Park	59	P/I	Riverbank	Pros - High MAR capacity - Multi-use benefits, by HS - Adjacent to MID line - Up-gradient from extraction well and adjacent to future CIP pipeline (per 2010 ER) - Open space/park for future planned "VR" use Cons -	15	7.5	3.1
3	South of Mary Grogan Park	54	P/I	Riverbank	Pros - Ave.-High MAR capacity - Multi-use benefits, by school/recreation facilities - Adjacent future CIP pipe - Future planned "Res" use Cons - Farther from MID line	11	5.5	5.3

Alt. No.	Location	Nearest Extraction Well	Perc (P)/ Inject (I)	Target Injection Formation	Pros/Cons	Approximate Acreage Available for Percolation	Estimated Percolation Rate (acre-feet/day)	Estimated Injection Rate (acre-feet/day)
4	Sanders Park	52 & 62	I	Lower Turlock	Pros - Space available for wells - Upgradient of existing production wells - Near elementary school Cons - Not ideal for percolation	--	--	4.2
5	Freedom Park	62	I	Lower Turlock	Pros - Pair w/existing extraction well in large enclosure - Relatively near MID line - Near two schools Cons - No obvious percolation opportunities	--	--	4.9
6	Orchard Park	46	I	Lower Turlock	Pros - Pair w/existing extraction well, enlarged enclosure -Relatively near MID line Cons - No nearby schools - No obvious percolation opportunities	--	--	2.5

Alt. No.	Location	Nearest Extraction Well	Perc (P)/ Inject (I)	Target Injection Formation	Pros/Cons	Approximate Acreage Available for Percolation	Estimated Percolation Rate (acre-feet/day)	Estimated Injection Rate (acre-feet/day)
7	Ustach Park	52	P/I	Riverbank & Lower Turlock	<u>Pros</u> - Existing West Basin storm drain basin adjacent for "flush to waste", potentially dual purpose in diff seasons - High MAR capacity - Pair w/existing extraction well, enlarged enclosure - Relatively near MID line - Near two schools <u>Cons</u> -	2.5	1.3	3.5

3.2. Source Water Availability

3.2.1. Water Delivery

As part of the MRWTP Phase 2 Expansion project, the City will be receiving up to an additional 30 million gallons per day (mgd) of treated surface water from MID, bringing total potential treated water deliveries to 60 mgd. Under the original agreement, the City's contract with MID requires the City to pay for the first 30 mgd of water, regardless of whether it takes delivery or not. Currently, the City's water delivery schedule with MID is being renegotiated and thus different scenarios for source water availability for MAR need to be considered.

While the schedule for such deliveries is not finalized, future water availability would vary depending on hydrologic conditions. Two scenarios were considered based on the proposed deliveries estimated by the City: full delivery of 60 mgd and a below normal year delivery of 30 mgd (selected assuming a reduction in 'normal' precipitation in the future as a result of climate change). Table 3 and Table 4 show the calculated volume potentially available for MAR. Demand and supply amounts were developed from the City's 2010 Urban Water Management Plan (UWMP).

As shown on Table 3, under a below normal year scenario, water would not be available for MAR. The variability in availability based on the proposed schedule would require analysis using assumptions regarding year type; such analysis is beyond the scope of this project. However, as shown on Table 4, a full delivery (60 mgd) provides an average of approximately 13,850 AFY or 12 mgd for recharge. For the purposes of this analysis, it is assumed that water would be available for MAR between November and February.

Table 3: Water Available for Recharge – with 30 mgd Surface Water Delivery

Year	Demand (mgd)	MID Water (mgd)	Groundwater (mgd)	Total Supply (mgd)	Available for MAR (mgd)
2020	61	30	12	42	0
2025	67	30	18	48	0
2030	73	30	26	56	0
2035	80	30	34	64	0
				Average Volume Available for MAR (MGD)	0
				Average Volume Available for MAR (AFY)	0

Note: Demand and groundwater volumes taken from City's 2010 UWMP (West Yost Associates, 2011).

Table 4: Water Available for Recharge – with 60 mgd Surface Water Delivery

Year	Demand (mgd)	MID Water (mgd)	Groundwater (mgd)	Total Supply (mgd)	Available for MAR (mgd)
2020	61	60	12	72	11
2025	67	60	18	78	12
2030	73	60	26	86	13
2035	80	60	34	94	14
Average Volume Available for MAR (MGD)					12.4
Average Volume Available for MAR (AFY)					13,850

Note: Demand and groundwater volumes taken from City's 2010 UWMP (West Yost Associates, 2011).

3.2.2. Injection Potential

To estimate injection amounts for each potential MAR site, it was assumed that, per a general rule of thumb, it is possible to inject half of what can be extracted at any existing well. The extraction rates provided by the City (Well Evaluation Table) for the existing production well nearest each potential MAR site were used to estimate injection potential where direct injection was proposed (see Table 2). For sites with more than one nearby well, well flow rates were averaged. Table 5 below lists the assumed well production rates for each of the City's production well located near a proposed MAR site.

Table 5: Well Flows

Extraction Well	Flow per Well (gpm)
46	1,150
52	1,600
54	2,400
59	1,400
62	2,200

Based on these extraction rates, injection rates are estimated for each site on Table 6.

Table 6: Potential Injection Rates by Site

Injection Site	Correlated Extraction Well	Target Formation	Estimated Injection Rate (gpm)	Estimated Injection Rate (AF/ month of operation)
Sutton Park	59	Riverbank/Upper Turlock/Lower Turlock	700	94
Mary Grogan Park	54	Riverbank/Upper Turlock/Lower Turlock	1,200	161
Sanders Park	52 & 62	Lower Turlock	950	128
Freedom Park	62	Lower Turlock	1,100	149
Orchard Park	46	Lower Turlock	575	76
Ustach Park	52	Riverbank/Upper Turlock/Lower Turlock	800	106

3.3. Engineering Considerations

Key parameters considered in the selection of MAR sites included proximity to water production and distribution infrastructure, including both MID transmission lines and City distribution lines and extraction wells. Proposed future pipelines, as identified in the City's CIP, were also included in the analysis. Locations where previously-unidentified pipelines would be required are also noted by site.

One additional consideration to be addressed is the quality of water to be injected, specifically with regard to residual chlorine, given that potable water would be injected into the groundwater basin. Residual chlorination in injection water has both positive and negative effects. The presence of residual chlorine in the injectate will help to reduce biofouling, thereby minimizing well backflushing and maintenance and extending the operating life of the well. However, chlorine residual, when present with organic carbon, may result in the formation of residual byproducts, including trihalomethanes (THMs) and halo acetic acids (HAAs).

Recently, multiple studies have been conducted to evaluate the fate and transport of disinfection by products (DBPs) in the subsurface. Studies (Pavelic et al., 2006, 2007; Quanrud et al., 2003; Pyne, 2006; City of Roseville, 2011) have indicated that in anoxic (oxygen-depleted) aquifers, in-situ biological and geochemical processes reduce DBP concentrations and/or inhibit the formation of DBPs. Based on data collected to date, groundwater in the Study Area is under both oxic and anoxic conditions (Jurgens, et al., 2008). Therefore significant groundwater quality impacts from DBPs are not expected to occur when groundwater is anoxic (as may be the case for water directly injected into deeper aquifer zones). The potential for DBP formation should be analyzed during a field pilot program at selected MAR locations to assess the potential for geochemical interactions resulting from the mixing of surface water and groundwater.

3.4. Permitting and Institutional Considerations

3.4.1. Permitting Considerations

Percolation of potable water into the subsurface is permitted by the State Water Resources Control Board under its General Permit for the discharge of low-threat groundwater to land (Water Quality Order No. 2003-0003-DWQ, *Statewide General Waste Discharge Requirements (WDRs) for Discharges to Land with a Low Threat to Water Quality*). Requirements for coverage under this permit are listed below.

- Percolated water must comply with all applicable Basin Plan provisions, including meeting water quality objectives governing the discharge.
- A Notice of Intent (NOI) or a Report of Waste Discharge (ROWD) must be filed to comply with the terms and conditions of the General Permit to obtain coverage. Included in this package are:
  - A project map
  - Evidence of California Environmental Quality Act (CEQA) compliance
  - A discharge monitoring plan
- Regular reporting relating to the volume of water 'discharged' and monitoring results are required.

Groundwater injection can be conducted under a statewide general permit for injection with potable water (SWRCB Water Quality Order 2012-0010, *General WDR for ASR Projects that Injection Drinking Water into Groundwater*). Requirements for coverage under this permit include the following:

- Water injected into the aquifers must be treated to meet all drinking water standards consistent with the requirements of a California Department of Public Health (CDPH) domestic water supply permit.
- All injection wells must be constructed in compliance with the requirements of the California Well Standards by a licensed well driller under the supervision of a California licensed engineer or geologist.
- For all injection wells, the well construction details and lithologic log must be documented and the well construction (well screen, filter pack, annular seal) must limit the injected water to the specified aquifer target zones.
- The project must not be prohibited by local agency ordinance, prohibition, or other applicable law or regulation.
- The project must be consistent with the CEQA project description provided in this Order and any project level CEQA environmental impact evaluation that has been completed. This may entail an anti-degradation assessment to address concerns about potential groundwater quality impacts from injection of potable water with a chlorine residual and the potential for DBP formation in the subsurface.

To obtain coverage under this General Permit, the following must be submitted to the SWRCB Division of Drinking Water:

- An application fee for a threat and complexity of "3-C" as described in California Code of Regulations, Title 23, Section 2200.
- Completed Form 200.
- A technical report that addresses the items listed in Attachment C of the General Permit as follows:
    - If a pilot test is planned, at a minimum, the technical report shall address the pilot test information requirements listed in Attachment C of the permit. The water quality characterization shall include all the analytes listed in the Monitoring and Reporting Plan (MRP), Order WQ 2012-0010.
    - If a pilot test has been completed, a technical addendum is submitted that describes the pilot test, presents the data collected, and completes or revises the technical report and anti-degradation analysis as appropriate.
    - If a pilot test is not planned, adequate information must be included to answer all the items listed on Attachment C of the General Permit and a complete technical report must be submitted.

Pilot injection testing can be conducted under this same Order, but in all cases, operation of an injection project cannot not cause groundwater quality to exceed any of the following:

- Primary or Secondary MCLs. Injected water shall comply with any new MCL on the date that the new MCL applies to the drinking water system.
- Numeric water quality objectives in the Basin Plan for beneficial uses within the project's area of hydrologic influence.
- Any Basin Plan water quality objective for the beneficial uses of groundwater.

Other permitting considerations include the requirement for well construction permits for any new well (obtained from the County), and the registration of all injection wells with the U.S. Environmental Protection Agency's (USEPA's) Underground Injection Control Program. Finally, modification to City drinking water system permits may be required to address new source(s) of water.

3.4.2. Institutional Considerations

There are several related institutional issues to be considered relative to an MAR project in the Study Area, including agreements for water deliveries, the Sustainable Groundwater Management Act (SGMA) of 2014, and compliance with the California Environmental Quality Act (CEQA).

The City is currently receiving treated surface water from MID under its water delivery agreement. One significant aspect of this water is that it can only be distributed within the MID service area, north of the Tuolumne River. Legal clarification may be required regarding when this 'banked surface water' is considered groundwater to be used through the City's water delivery service system. Additional considerations relative to the City's proposed agreement with MID for Phase 2 water include year declaration (i.e., parameters that will be used to identify the water year type), volume delivered, and timing. Depending on the definitions utilized in that agreement, seasonal groundwater banking could be precluded. This would limit the City's MAR projects to long-term groundwater banking.

While long-term groundwater banking is considered a beneficial use of water, the longer groundwater remains in the basin, the more time it has to migrate beyond the City's production wells and beyond the ability of the City to retrieve and use the banked water. The fate of the recharged water is analyzed further in Section 4.

Additionally, the recent passage of SGMA will provide a layer of groundwater basin management that has not yet been conceived. It is unknown exactly which Groundwater Sustainability Agency will be responsible for the sustainable use of the Modesto Subbasin, and how that may impact the City's ability to recharge, bank and extract water.

Finally, any project to be implemented in the groundwater basin must comply with CEQA. Given the nature and extent of the proposed MAR project(s), a full CEQA analysis (i.e., environmental impact report) will likely be required prior to any MAR project construction and operation.

4. GROUNDWATER MODELING EVALUATION OF RECHARGE ALTERNATIVES

A regional steady-state model constructed by the USGS was refined in the region of the City of Modesto in order to simulate recharge alternatives. Recharge alternatives were based on the potential recharge sites identified and described in Section 3.

4.1. MODEL DESCRIPTION

The regional steady-state model was originally constructed by the USGS using standard MODFLOW 2000 input file structure and executable code. The original MODFLOW model input files were imported into the Aquaveo Groundwater Modeling System (GMS) by others for the City in support of another project; the GMS files were provided to Todd Groundwater for review and use. Todd Groundwater checked the imported files, ran a simulation, and post-processed results to ensure model performance. Additional details of the steady-state model are provided below.

4.1.1. Regional Steady State Model

Construction and application of the regional steady-state MODFLOW model was originally documented in the 2007 USGS Scientific Investigation Report (SIR) 2007-5009 (Phillips et al., 2007). The model simulates regional groundwater and surface-water flow over a 2,700 square kilometer (km^2) area. The model comprises 16 layers, 153 rows, and 137 columns, with a uniform grid spacing of 400 meters. The westernmost 21 columns of the regional model (west of the San Joaquin River) are inactive. The model grid is rotated 37 degrees counterclockwise of true north, and is geo-referenced in the Albers 120 meters coordinate system. The model units are meters and days. All model input and output data use these units (e.g., aquifer hydraulic conductivities are in units of meters/day (m/day), pumping rates are in cubic meters per day (m^3/day), and model layer elevations, thicknesses, simulated groundwater elevations, and simulated drawdown are in meters or meters above mean sea level).

The total thickness of the wedge-shaped model ranges from about 220 m (722 feet) near the Sierra foothills to 430 m (1,411 feet) along the western portion of the Central Valley near the San Joaquin River. The model layer thicknesses were built around the Corcoran Clay (Layer 8) as described in the 2007 SIR. Hydraulic conductivity was distributed using sediment texture by layer, except for the Corcoran Clay, which was assumed to be homogeneous. Model layers 1 through 7 are simulated as unconfined/convertible using hydraulic conductivities, while model layers 8 through 16 are simulated as fully-confined using transmissivities.

For the steady-state model, the USGS developed boundary conditions, recharge, and well pumping rates that are representative of water year 2000 hydrologic conditions. Model boundary conditions include specified heads along the lengths of the northern (northwestern), southern (southeastern), and western (southwestern) boundaries in all 16 model layers. The southwestern boundary corresponds to the San Joaquin River. The western segments of the Stanislaus, Tuolumne, and Merced Rivers are also represented using constant heads in Layer 1 only. The eastern (northeastern) boundary is specified as no-flow in all 16 layers.

There are 4,422 active pumping wells in the model, including municipal wells, other known private wells, and hypothetical agricultural wells spaced every 1,200 meters (Phillips, 2015). Many of the wells (including City wells) are represented in multiple model layers and are counted as multiple wells in the model. For example, there are 105 City wells in the model, but they are simulated as 314 model wells because most of the City wells pump from more than one model layer. Most (94 percent) of the simulated City wells pump from Model Layers 6 through 11.

Total recharge to the water table is simulated based on estimated agricultural water use and return flow rates, infiltration of precipitation, and leakage from surface water.

The model calibration and overall results are described in the 2007 SIR. The model is generally well-calibrated in the City area. Groundwater flow in the different model layers is generally from east to west toward the San Joaquin River. Vertical gradients are generally downward from the unconfined upper aquifer system to the deeper water-bearing aquifer zones, where most of the municipal and agricultural pumping occurs.

4.1.2. Local Refined-Grid Steady State Model

In order to better simulate complex flow hydraulics and conduct accurate flowpath analyses around City wells, a refined local model was created from the regional steady-state USGS model. This local refined-grid steady state model was used to simulate recharge alternatives.

The local-scale steady-state model occupies a sub-area within the regional model domain. Regional-to-local model conversion is sometimes referred to as "telescopic grid refinement." Using this approach, all of the input data and simulation results are extracted from the regional model and re-interpolated to a local model grid. The regional model aquifer top and bottom elevations, hydraulic conductivities and transmissivities, and areal recharge values from the regional model grid are converted into discrete points, then interpolated into the refined model grid, such that the local model input parameters are essentially identical to those in the regional model. The groundwater elevations computed from the regional model are applied as initial conditions (starting heads) and specified head boundary conditions for the local-scale model. Application of regional model heads to local model specified head boundaries provides a flow simulation that is consistent with the regional model. The finely-spaced local model grid provides a more detailed representation of the local flow conditions, including drawdown and flow paths around City wells, while maintaining the aquifer characteristics and calibration quality of the regional model.

Figure 47 shows the local steady-state model area. The active local model area extends from the Stanislaus River on the north, to a southern boundary arc approximately 3 to 4 miles south of the Tuolumne River, and from the western boundary near the San Joaquin River to the regional model eastern boundary. This area was selected in order to incorporate City production wells in the Modesto Service Area and wells in the Cities of Riverbank, Oakdale, and Waterford in addition to other regional wells in the model.

A new local model grid was constructed using a uniform 100 meter grid spacing. A 37-degree grid rotation was applied, identical to the regional model. There are 326 rows and 398 columns in the local model.

The top and bottom elevations and hydraulic conductivity values for each of the 16 model layers are identical to those in the regional model. Model Layers 8 through 16 were converted from "fully confined" to "unconfined/confined" in order to compare effective hydraulic conductivities in each layer.

For each of the 16 layers, active/inactive zones were defined based on the locations of dry cells in the regional model. The northern, southern, and western boundaries for each of the 16 model layers are identical; however the eastern boundary for each of Layers 1 through 7 are different than the eastern boundary for Layers 8 through 16 (Figure 47). The eastern boundary of each model layer in the regional model extends to the eastern foothills. But, because cells west of the eastern boundary in Layers 1 through 7 are dry, they are not used in the local model. Therefore, the eastern boundaries of Layers 1 through 7 in the local model were moved westward, west of the dry zones in each layer. Layer 1 has the smallest active model area, reflecting the dry cells in Layer 1 of the regional model. All boundary arcs in each of the 16 model layers were assigned specified heads, extracted from the calibrated regional model solution.

As mentioned previously, there are 4,422 wells in the regional steady-state model. Roughly one third of these are in the local model. Rather than extracting the simulated wells from the regional model (and introducing location errors from the block-centered 400-meter regional model grid), individual municipal, agricultural, and other pumping wells were re-imported to the local model as discrete point objects at known coordinate locations. The original well location, depth, and pumping rate information used to construct the regional model was provided by the USGS. Well coordinates, well screen intervals and depths, and associated model layer assignments and pumping rates were imported and assigned in GMS. The pumping rates used in the initial local model are average 2000 rates, as determined by USGS; as described in the next section, these were revised to reflect more recent pumping and the City's installation and operation of new wells since 2000.

Local Refined-Grid Steady-State Model Results

The local model was run and the results post-processed. Consistent with the regional model, the simulated local model heads indicate overall flow from the foothills on the east toward the San Joaquin River on the west. Numerous cones of depression are simulated around the pumping wells in the various model layers. Vertical gradients are present between the shallow, intermediate, and deep aquifer zones. Comparison of the local model groundwater elevation contours with the regional model illustrate that the local model flow solution is almost identical to the regional model.

Importantly, groundwater elevations for 2000 from the local model were also well-calibrated to the 2000 groundwater elevations measured in City wells. The reliability of the City's water level data could not be confirmed previously because levels are measured in production wells and may not reflect static conditions. However, because City measurements matched simulated water levels for 2000, data may be sufficiently accurate to represent groundwater levels for the purposes of the recharge analysis.

4.2. RECHARGE ALTERNATIVE SIMULATIONS

The local refined-grid steady state model, herein referred to as "the model," was used to simulate three recharge project alternatives and a no-project scenario in which no recharge projects were assumed. MODPATH was used to simulate flow paths from the injection wells. The no-project scenario is referred to as the Baseline simulation. A summary of the Baseline simulation and each of the three Alternative simulations (Alternatives A, B, and C) is presented below. A summary of the Alternative recharge scenarios is presented in Table 7 at the end of Section 4.2. The recharge facilities simulated in each Alternative and the April 2015 measured depth to water contours are illustrated on Figure 48.

Baseline Simulation

The model was modified to incorporate revised pumping rates for the City of Modesto wells. First, total production for each City well was updated in the model using the most recent pumping data (from July 2014 to June 2015). Total pumping during this time for City wells was 37,810 AF. Simulated water levels from this time period were compared to water level measurements in City wells. Unlike the 2000 simulation, these data sets did not compare well and groundwater levels in the model simulations were significantly higher than measured water levels in the eastern Study Area. This could be due to the fact that only City production data were updated and other inflows and outflows associated with 2015 conditions were not modified from conditions in 2000.

The discrepancy between simulated and measured 2015 water levels indicates that simulated groundwater elevations for the baseline and recharge alternative may not be accurate. However, the *changes* associated with recharge alternatives would remain applicable. Therefore, the model is being applied to analyze the change to water levels associated with the recharge alternatives. The resultant change is then compared to the actual recent groundwater levels for further assessment of each alternative.

To create a baseline for the analysis, Modesto pumping rates in the model were reduced to reflect future groundwater estimates provided in the City of Modesto 2010 Urban Water Management Plan (UWMP). As described in Section 3, the City of Modesto 2010 UWMP (West Yost Associates, 2011) estimates that average groundwater use from 2020 to 2035 is projected to be 25,100 AFY. Model pumping at City of Modesto wells was reduced by 33.6

percent, from 37,810 AFY to 25,100 AFY, to reflect this future projected average groundwater use. This reduced pumping was used for the Baseline simulation and the Alternative simulations. Simulated groundwater elevations for the Baseline are shown on Figure 49. The amounts of change in water level elevations are shown on Figure 50. The contours are represented as negative values of drawdown from the model, indicating that the reduced pumping causes water levels to rise about 1 meter over the Study Area.

No enhanced recharge associated with the alternatives was simulated in the Baseline simulation. Therefore, this represents the "No Project" model scenario.

Alternative A

Alternative A simulates recharge at each of the injection and percolation locations identified in Section 3 and illustrated on Figures 46 and 48. Injection wells are simulated at six locations: Sutton Park, South of Mary Grogan Community Park (Grogan Park), Sanders Park, Freedom Park, Orchard Park, and Ustach Park. Recharge ponds are simulated at four locations: Creekside Golf Course, Sutton Park, Grogan Park, and Ustach Park. The injection rates and the percolation rates are based on the estimates provided in Section 3. Data are summarized in Table 7 (presented at the end of Section 4.2).

The injection wells are screened across multiple sand intervals identified on the cross sections. In general, injection well screens span the Upper Turlock Lake, Lower Turlock Lake, and Laguna formations.

As described in Section 3, water deliveries may result in surplus water up to 13,850 AFY available for MAR. The City anticipates that this water will be available during a four month period from November through February. If each injection well site has only one injection well, then the total recharge volume for the injection wells and recharge ponds at the estimated injection and percolation rates would be 4,619 AF during the four month period (Table 7). This is only approximately 33 percent of the water available for MAR in a full delivery of 60 mgd.

To increase the injection capacity beyond the 4,619 AF, Alternative A simulates the maximum number of injection wells at each park, assuming at least a 900 to 1,000 foot spacing between injection wells to minimize well interference. Two or three injection wells are simulated at five of the six parks, while Freedom Park has one injection well because it is too small to accommodate anther injection well (Figure 48).

Alternative A simulates 8,294 AF of recharge over the four month period at 14 injection wells and 4 ponds. This is approximately 60 percent of the water available for recharge during a full delivery year. Injection well rates range from 2.5 to 5.3 AF/day (305 to 638 AF/4 months) and percolation rates range from 0.7 to 7.5 AF/day (85 to 900 AF/4 months). Recharge rates and recharge volumes are summarized in Table 7.

A MODPATH simulation was run to illustrate the flow paths from the injection wells and recharge ponds.

Alternative B

Alternative B simulates 13,850 AF of recharge over the four month period by adding 10 injection wells to an alignment along the eastern edge of the Service Area. The 10 aligned injection wells are illustrated on Figure 48. Alternative B also simulates recharge at the same 14 injection wells and 4 recharge ponds simulated in Alternative A. Accordingly, Alternative B simulates recharge at 24 wells and 4 ponds. Data for Alternative B are summarized in Table 7 (presented at the end of Section 4.2).

The 10 aligned injection wells are spaced 1,000 feet apart and more than 2,000 feet east of the Alternative A injection wells (Figure 48). The aligned injection wells are screened across the Upper Turlock Lake, Lower Turlock Lake, and Laguna formations. Injection rates at the new injection wells are 4.63 AF/day (555.6 AF/4 months), which is close to the average injection rate for the injection wells along the eastern boundary of the Service Area. Unlike the recharge methods for the previous analysis, these wells are not located on particular land use or City property. Rather they are simulated to evaluate the overall impact of the maximum amount of recharge rather than to evaluate recharge at any specific parcel or location.

A MODPATH simulation was to simulate flow paths from the injection wells and recharge ponds.

Alternative C

Alternative C also simulates 13,850 AF of recharge, but does so with injection wells only; recharge ponds are not simulated in Alternative C. To compensate for the loss of recharge volume from the ponds, five additional injection wells were added to the model. Four of the additional injection wells are located in parks in the eastern region of the Service Area: Brewer Rose Park, Sonoma Park, Lakewood Park, and Sipherd Park. The fifth new injection well is located roughly between Freedom Park, Sipherd Park, and the line of 10 injection wells along the eastern edge of the Service Area. The new injection wells are more than 1,000 feet from each other and from other injection wells. Alternative C simulates recharge at 29 injection wells. Wells are shown on Figure 48. Data for Alternative B are summarized in Table 7 (presented at the end of Section 4.2).

The injection well rates for the four new wells located in parks were determined based on the flow rates for the nearest City extraction well. It was assumed that the injection rate could be half of the extraction rate provided by the City in their well evaluation spreadsheet. This is consistent with the methodology used to estimate the injection rates at the injection well sites identified in Section 3 and simulated in each of the Alternatives. Injection rates for the four new wells in the parks range from 1.1 to 4.4 AF/day (133 to 530 AF/4 months). The fifth new injection well has an injection rate of 4.0 AF/day (482 AF/4 months) so that total recharge is 13,850 AF. The injection wells are screened in the Upper Turlock Lake, Lower Turlock Lake, and Laguna formations. Recharge rates and recharge volumes are summarized in Table 7.

Table 7 - Model Recharge Scenarios

Recharge Locations		Potential Recharge Rates					Alternative A				Alternative B				Alternative C			
		Percolation		Injection		Total	Percolation	Number of	Injection	Total	Percolation	Number of	Injection	Total	Percolation	Number of	Injection	Total
		AF/day	AF/4 months	AF/day	AF/4 months	AF/4 months	AF/4 months	Wells	AF/4 months	AF/4 months	AF/4 months	Wells	AF/4 months	AF/4 months	AF/4 months	Wells	AF/4 months	AF/4 months
1	Creekside Golf Course	0.7	85	-	-	85	85	-	-	85	85	-	-	85	-	-	-	-
2	Sutton Park	7.5	900	3.1	372	1,272	900	3	1,115	2,015	900	3	1,115	2,015	-	3	1,115	1,115
3	South of Mary Grogan Park	5.5	657	5.3	638	1,295	657	3	1,913	2,571	657	3	1,913	2,571	-	3	1,913	1,913
4	Sanders Park	-	-	4.2	503	503	-	2	1,006	1,006	-	2	1,006	1,006	-	2	1,006	1,006
5	Freedom Park	-	-	4.9	584	584	-	1	584	584	-	1	584	584	-	1	584	584
6	Orchard Park	-	-	2.5	305	305	-	2	610	610	-	2	610	610	-	2	610	610
7	Ustach Park	1.3	151	3.5	424	575	151	3	1,272	1,423	151	3	1,272	1,423	-	3	1,272	1,272
Alternative B Injection Wells		--	--	--	--	--	--	--	--	--	-	10	5,556	5,556	-	10	5,556	5,556
Alternative C Injection Wells																		
	Brewer Rose Park	--	--	--	--	--	--	--	--	--	--	--	--	--	-	1	331	331
	Sonoma Park	--	--	--	--	--	--	--	--	--	--	--	--	--	-	1	530	530
	Lakewood Park	--	--	--	--	--	--	--	--	--	--	--	--	--	-	1	133	133
	Sipherd Park	--	--	--	--	--	--	--	--	--	--	--	--	--	-	1	318	318
	Eastern Service Area	--	--	--	--	--	--	--	--	--	--	--	--	--	-	1	482	482
	Total	**15**	**1,794**	**24**	**2,825**	**4,619**	**1,794**	**14**	**6,500**	**8,294**	**1,794**	**24**	**12,056**	**13,850**	**-**	**29**	**13,850**	**13,850**

4.3. Simulation Results

Simulation results are shown as groundwater mounding contours and particle tracking. Simulated mounding contours for recharge Alternatives A, B, and C are shown on Figures 51, 54, and 58, respectively. These maps show the change in groundwater elevations associated with groundwater mounding due to recharge. The mounding analysis is shown relative to the Baseline simulation and indicate how much water levels rise and where with each alternative. The mounding contours are shown for model layers 1 and 7: model layer 1 illustrates groundwater mounding from the recharge ponds and model layer 7 illustrates groundwater mounding from the injection wells.

MODPATH particle tracks are shown on multiple figures for each Alternative: Alternative A particle tracks are shown on Figures 52 and 53, Alternative B particle tracks are shown on Figures 55, 56, and 57, and Alternative C particle tracks are shown on Figures 59, 60, and 61. The results are discussed below.

Alternative A

Results of the simulation of Alternative A are shown on Figure 51. Contours represent groundwater mounding as a result of increased recharge and are shown for both Model Layer 1 and 7. Model layer 1 elevations illustrate groundwater mounding around the four recharge ponds at Grogan Park, Ustach Park, Sutton Community Park, and Creekside Golf Course. Mounding is higher at Sutton Park and Grogan Park than at either Ustach Park or Creekside Golf Course because percolation rates are higher (Table 7). The most significant mounding in model layer 1 occurs beneath the recharge pond at Sutton Community Park (approximately 9.5 meters, or 31 feet) and Grogan Park (approximately 9.2 meters, or 30 feet). Maximum mounding in layer 7 is approximately 11.5 meters (38 feet) at the Grogan Park injection wells (Figure 51).

Groundwater mounding is simulated in model layer 7 around the injection wells in Grogan Park, Sanders Park, Ustach Park, Freedom Park, Orchard Park, and Sutton Community Park. Mounding is greatest at Grogan Park because it has three injection wells and the highest injection rates of any location. Vertical gradients are downward from model layer 1 to 7.

As shown on Figure 48, depth to water measured in April 2015 in the vicinity of Sutton Community Park is between 70 and 75 feet and at Grogan Park is between 50 and 55 feet. Based on this comparison, it appears that the aquifer system has sufficient storage for the recharge simulated in Alternative A. It is noted that this analysis is conservative given the continuous nature of the recharge as simulated in the steady-state model and increased pumping is not occurring at the location of injection as would occur if the well were an ASR well.

Particle tracks from the recharge ponds and injection wells for Alternative A are illustrated on Figures 52 and 53. The particle tracks are grouped and color-coded based on their travel time. The red dots represent particle tracks that have traveled between 0 and 5 years from the recharge ponds and injection wells and the colors change every five years up to 20 to 25 years.

Particle tracks from the recharge ponds (Figure 52) show that the recharge water from Ustach Park is extracted by Well 52, located in the same park. Most of the particles from the Grogan Park recharge pond stop at the edge of the model domain in layer 1. Some of the particles from Grogan Park travel towards a MID well and others remain in the aquifer system after 25 years. The particle tracks show that the water from the recharge pond at the Creekside Golf Course is extracted primarily by adjacent City Well 204 after approximately 15 years. Recharge from the Sutton Community Park pond travels to the west and remains in the aquifer after 25 years.

Particles tracks from the injection wells show that most of the injected water is extracted by either City or MID wells. Some of the water remains in the aquifer for more than 25 years. The injected water at Sutton Community Park generally travels towards the Tuolumne River and is mostly extracted by City wells, although some water remains in the aquifer after 25 years.

Alternative B

Mounding contours on Figure 54 illustrate groundwater mounding at the recharge ponds in model layer 1 and at the injection wells in model layer 7. The most significant mounding in model layer 1 occurs beneath the recharge ponds at Sutton Community Park (approximately 10.8 meters, or 35 feet) and Grogan Park (approximately 10.6 meters, or 35 feet). Model layer 7 shows the mounding created by the 10 aligned injection wells simulated in Alternative B. Maximum mounding in model layer 7 is approximately 15 meters (49 feet) at Grogan Park and Sanders Park.

As shown on Figure 48, depth to water measured in April 2015 in the vicinity of Sutton Community Park is between 70 and 75 feet and at Grogan Park and Sanders Park is between 50 and 55 feet. With local mounding indicated at 35 feet to 49 feet, simulations indicate that water levels rise close to the surface in local areas for this alternative. Drawup is expected to be even higher in the injection well; further, this drawup would be exacerbated by well inefficiency. As noted in Alternative A, the analysis for Alternative B is conservative given the continuous nature of the recharge as simulated in the steady-state model, Further, increased pumping is not occurring at the location of injection as would occur if the well were an ASR well. Nonetheless, this simulation indicates that vadose zone and aquifer storage represent limitations for large recharge volumes.

Particle tracks are illustrated on separate figures for the recharge ponds (Figure 55), ten aligned injection wells (Figure 56), plus the 14 injection wells at the parks (Figure 57). Figure 55 shows that recharge water from the pond at Grogan Park reaches the edge of the model domain or remains in the aquifer after 25 years. Most of the water from the recharge pond at Ustach Park is extracted by Well 39 after approximately 20 years. Water from the recharge pond at the Creekside Golf Course is extracted by either Well 204 after approximately 15 years, or remains in the aquifer after 25 years. Most of the recharge from the pond at Sutton Community Park is extracted by City wells, while some of the water remains in the aquifer after 25 years.

As illustrated on Figure 56, mounding along the eastern edge of the Service Area results in radial flow to the east toward MID wells and to the west toward City wells. Most of the water is extracted after approximately 15 years. Some of the water remains in the aquifer after 25 years.

Figure 57 shows that the water injected at the Alternative A injection wells (as part of Alternative B) follow a similar pattern to Alternative A (Figure 53). However, the particles in Alternative B migrate further to the west of the injection wells as a result of mounding and increased gradients caused by the injection wells on the eastern edge of the Service Area. Most of the water is extracted by City wells (or a few MID wells) to the west and northwest of the injection wells. Some of the injected water remains in the aquifer after 25 years.

Alternative C

Mounding contours in model layers 1 and 7 are illustrated on Figure 58. Groundwater mounding caused by the injection wells occurs throughout the eastern Service Area in model layer 1 and 7. The maximum mounding in Layer 1 is approximately 8.4 meters (27.5 feet) in the vicinity of Freedom Park. Localized groundwater mounds are evident around the four of the five new injection wells. Overall, groundwater mounding in model layer 7 is similar to Alternative B. The most significant mounding in model layer 7 is approximately 15 meters (49 feet) at Grogan Park and Sanders Park.

Similar to Alternative B, mounding in the northeastern Service Area indicates that recharge volumes may be too large to be accommodated by the aquifer system. Again, the conservative nature of the analysis adds uncertainty to this conclusion because recharge is continuous and injection wells are not being pumped for recovery. Nonetheless, mounding appears relatively close to the ground surface indicating the potential for insufficient subsurface storage.

Alternative C particle tracks are presented on separate figures for the five new injection wells (Figure 59), the 10 aligned injection wells (Figure 60), and the 14 injection wells at the parks (Figure 61). As shown on Figure 59, most of the water injected into the five new injection wells travels to the west and southwest and remains in the aquifer for more than 25 years. Some of the water is extracted by City wells, such as Well 41 at Sipherd Park.

The particle tracks from the ten wells along the eastern edge of the Service Area (Figure 60) are similar to those simulated in Alternative B (Figure 56). Water injected along the eastern edge of the Service Area either travels east toward MID wells or west toward City wells. Most of the water is extracted after approximately 15 years, but some of the water remains in the aquifer after 25 years.

Particle tracks from the Alternative A injection wells are shown on Figure 61. These particle tracks follow a similar pattern to the particles simulated in Alternatives A and B (Figures 53 and 56). Some of the water is extracted by City or MID wells to the west of the injection wells and some of the water remains in the aquifer after 25 years. The injected water at Sutton Community Park migrates towards the Tuolumne River and is extracted primarily by City wells, although some water remains in the aquifer after 25 years.

4.4. MODEL SUMMARY AND CONCLUSIONS

The USGS regional steady-state model (Phillips et al., 2007) was refined within the City's Service Area and used to simulate recharge scenarios using both recharge ponds and injection wells. Groundwater pumping at City wells was updated to reflect the average amount of future groundwater use projected in the City's 2010 UWMP (25,100 AFY). The revised pumping rates were used for the Baseline "No Project" scenario and three Alternative scenarios which simulated various recharge configurations. Alternative A simulates recharge at the injection wells and recharge ponds identified and described in Section 3 and amounts to approximately 8,294 AF. Alternative B simulates recharge of 13,850 AF with the addition of 10 injection wells along the eastern edge of the Service Area. Alternative C also simulates recharge of 13,850 AF with only injection wells, including those used in Alternatives A and B plus five additional injection wells.

Results show that more groundwater mounding occurs from the injection wells, illustrated in model layer 7, than from the recharge ponds, illustrated in model layer 1. Maximum mounding simulated in Alternative A is approximately 11.5 meters (37.7 feet) in the vicinity of the Grogan Park injection wells. The maximum mounding simulated in Alternatives B and C is similar and approximately 15 meters (49 feet) in the vicinity of Grogan Park and Sanders Park. Based on April 2015 measurements, the depth to water in the vicinity of Grogan Park and Sanders Park is between 50 and 55 feet.

The close proximity of groundwater mounding and the ground surface indicates that recharge volumes may represent a limitation to MAR scenarios. In particular, the storage capacity of the vadose zone is not well known, given the lack of monitoring wells screened at the water table. Historical water levels measured in shallow ports of the USGS monitoring wells suggest higher water levels than deeper aquifers (Figure 21). If water levels are higher in the shallow aquifer than indicated from water level contour maps, then surface recharge may be more limited than suggested in the analysis. However, ASR wells may create additional storage capacity because the injection wells would be used for both recharge and recovery.

The MODPATH particle tracks show that most of the recharge water is extracted by City or MID wells within 25 years of percolation or injection. Some of the recharged water remains in the aquifer for more than 25 years and adds to long-term storage.

5. CONCLUSIONS AND RECOMMENDATIONS FOR A MAR PROGRAM

Potential opportunities for MAR were identified based on a groundwater characterization and recharge study. The study included a hydrogeologic characterization, identification of potential recharge sites, and simulation of recharge alternatives using a numerical model.

Nine geologic cross sections were developed throughout the Study Area to delineate the geologic formations and aquifer units. The cross sections included hydrofacies textures at more than 80 percent of the City wells in production over the last year (i.e., July 2014 to June 2015). Contacts between the geologic formations underlying the Study Area, which include the Modesto, Riverbank, Upper Turlock Lake, Corcoran Clay, Lower Turlock Lake, and Laguna formations, were estimated to provide a hydrogeologic framework. Sand bodies were correlated within each formation based on elevation and thickness.

The hydrogeologic conceptual model shows that the eastern and southeastern regions of the Study Area may be the most promising areas for subsurface recharge methods. Sand beds are thicker in the eastern Study Area. The greatest production from the City's wells from July 2014 to June 2015 was from intermediate and deep aquifer wells along the eastern edge of the Study Area and from the southern edge of the Study Area, immediately north of the Tuolumne River. The area of greatest groundwater production is also the area with the best overall groundwater quality, with relatively fewer detections of arsenic, nitrate, and uranium above their respective MCLs. Depth to water is greater in the eastern and southeastern area of the Service Area. Groundwater flow direction is to the west and southwest along the eastern and southeastern regions of the Study Area. Therefore, recharged water could be recovered from existing downgradient production wells.

Potential recharge locations were identified based on the hydrogeologic conceptual model, a previous surface recharge analysis, and existing infrastructure, land use, and well locations. Both the surface recharge analysis and hydrogeologic characterization agree that the eastern and southeastern regions of the Study Area should be the focus of MAR alternatives. Seven potential MAR locations were identified and evaluated: Creekside Golf Course, Sutton Park, South of Mary Grogan Community Park, Sanders Park, Freedom Park, Orchard Park, and Ustach Park. The potential recharge method (i.e., surface and/or subsurface) and recharge rates were estimated at each location. Surface percolation from recharge ponds was identified as a potential means of recharge at four of these locations while injection was identified as a potential means of recharge at six of these locations. Three of the locations were identified as having the potential for both surface and subsurface recharge. The City estimates that there will be up to 13,850 AFY of treated potable water available for MAR.

A refined local model was created from a regional steady-state USGS model and used to simulate recharge alternatives with both recharge ponds and injection wells. Groundwater production at City wells was updated to reflect the average amount of future groundwater use projected in the City's 2010 UWMP (25,100 AFY). A "No Project" scenario simulated no recharge in the Baseline simulation. Three alternative scenarios simulated various recharge configurations. Alternative A simulated recharge from recharge ponds and injection wells at the locations identified as part of this Study. Alternative B simulated recharge from the same locations as Alternative A along with an additional 10 injection wells aligned along the eastern edge of the Study Area. Alternative C simulated recharge from the injection wells simulated in Alternative B plus five additional injection wells.   Alternative A simulated 8,294 AFY of recharge, while Alternatives B and C simulated 13,850 AFY or recharge.

Simulation results show groundwater mounding from recharge at the ponds and injection wells. More mounding occurs from the injection well recharge than from surface recharge. However, surface recharge may have more limitations due to higher water levels in shallow aquifers. Additionally, more mounding occurs in Alternatives B and C than in Alternative A because of the higher volume of recharge being simulated. The maximum mounding simulated is approximately 15 meters (49 feet) in the vicinity of Grogan Park and Sanders Park in Alternatives B and C. Based on April 2015 measurements, the depth to water in this region is between 50 and 55 feet. The close proximity of groundwater mounding to the ground surface, especially for the larger recharge volumes simulated, indicates that subsurface available storage may be a limiting factor. It should be noted that these simulations are conservative in that the modeling assumes recharge is continuous and that injection wells are not being pumped for recovery.

The MODPATH particle tracks show that most of the recharge water is extracted by City or MID wells within 25 years, while some of the water remains in the aquifer for more than 25 years and adds to long-term storage. Particle pathlines and travel times are conservative because simulated injected water travels farther than would occur if the injection well were operating as an ASR well. More aquifer storage would be available if the injection wells also extracted the recharge water.

For this study, recharge analyses were limited primarily by the constraints of the steady-state modeling tool and the uncertainty associated with water level measurements in local wells. In addition, it would be helpful to better understand vertical gradients, the nature of confinement for the deep aquifer systems, and the current groundwater quality changes with depth. Steps to resolve these data gaps should be organized in a systematic and cost-effective workplan, focused on targeted locations in the eastern portions of the Service Area. Specific hydrogeologic recommendations include the following:

1. Implement a City-wide water level monitoring program that incorporates wells from each aquifer category and includes only inactive wells that are capable of static water level measurements. Active pumping wells that are not allowed to recover are not good candidates for the water level monitoring program.
2. Reinstate water level monitoring in all ports of the USGS monitoring wells in the City's northeastern Service Area.
3. Plan for a future field program for additional monitoring well installation.
4. Conduct a more focused analysis of eastern Service Area including vertical gradients, extent of aquifer confinement, and water quality with depth (vertical profiling).
5. Consider alternative recharge locations with greater depths to water.

These can be implemented while planning progresses with regard to availability of source water for MAR, permitting, and other institutional considerations.

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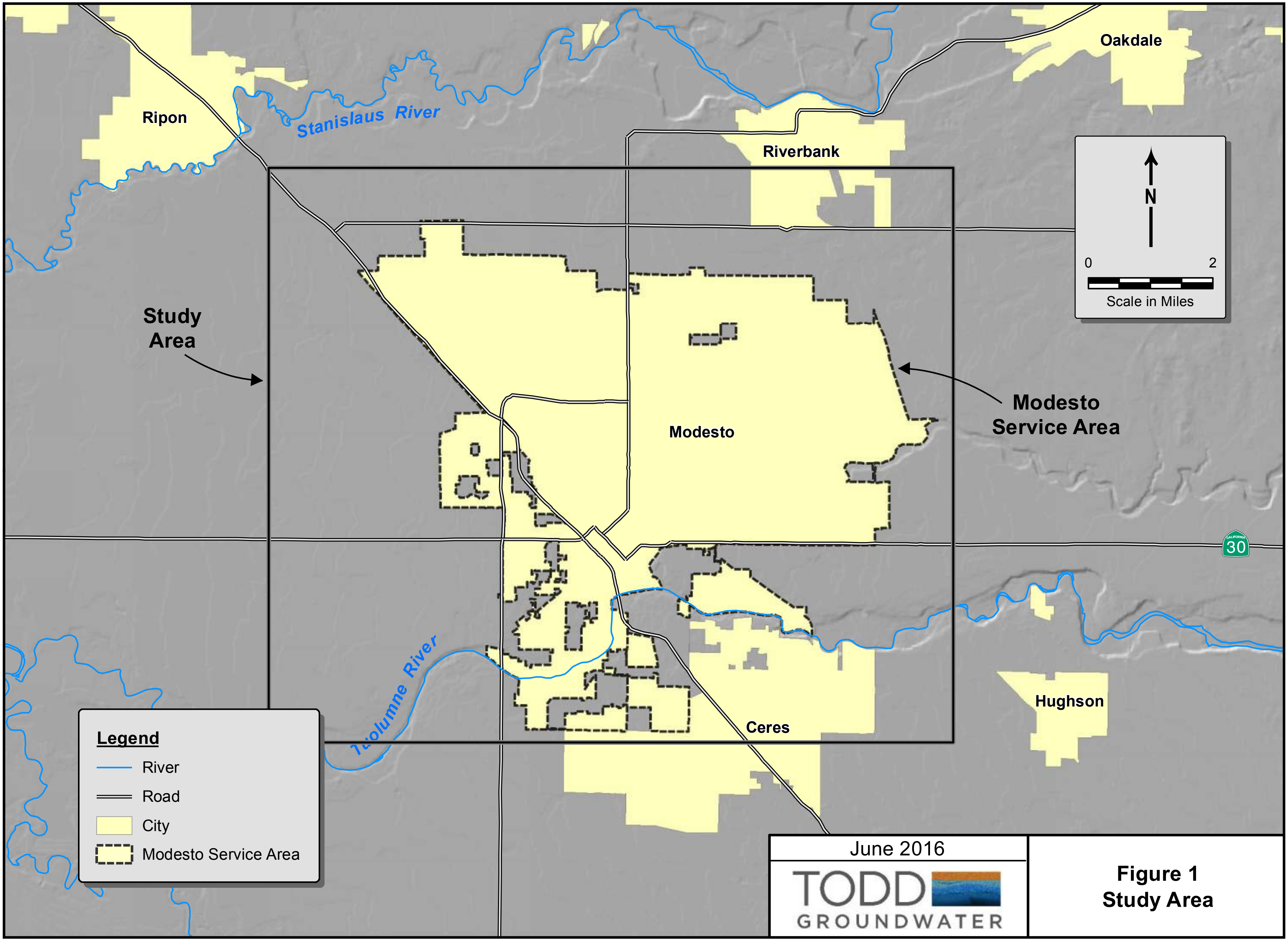


June 2016

TODD GROUNDWATER

Figure 1
Study Area

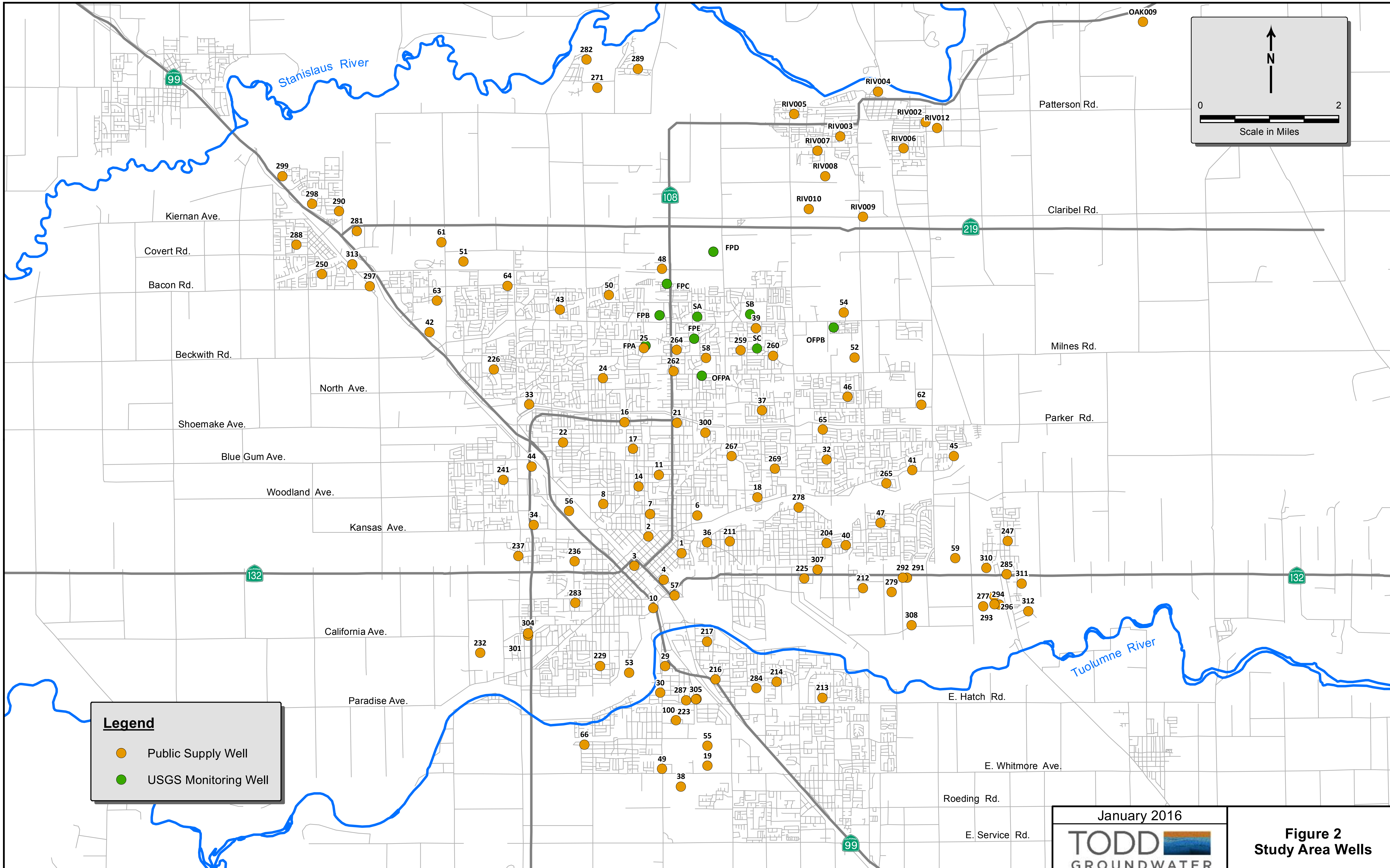
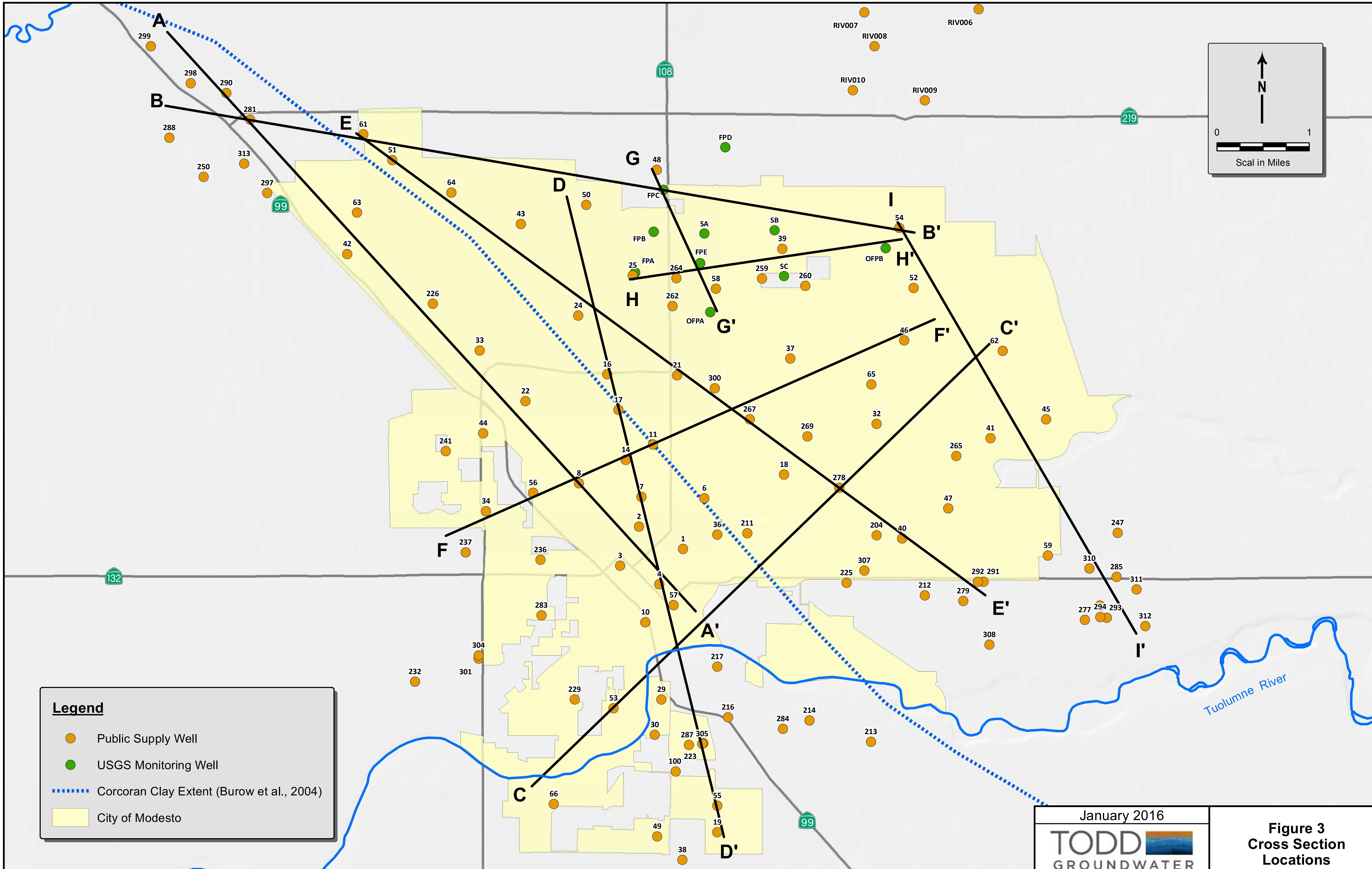
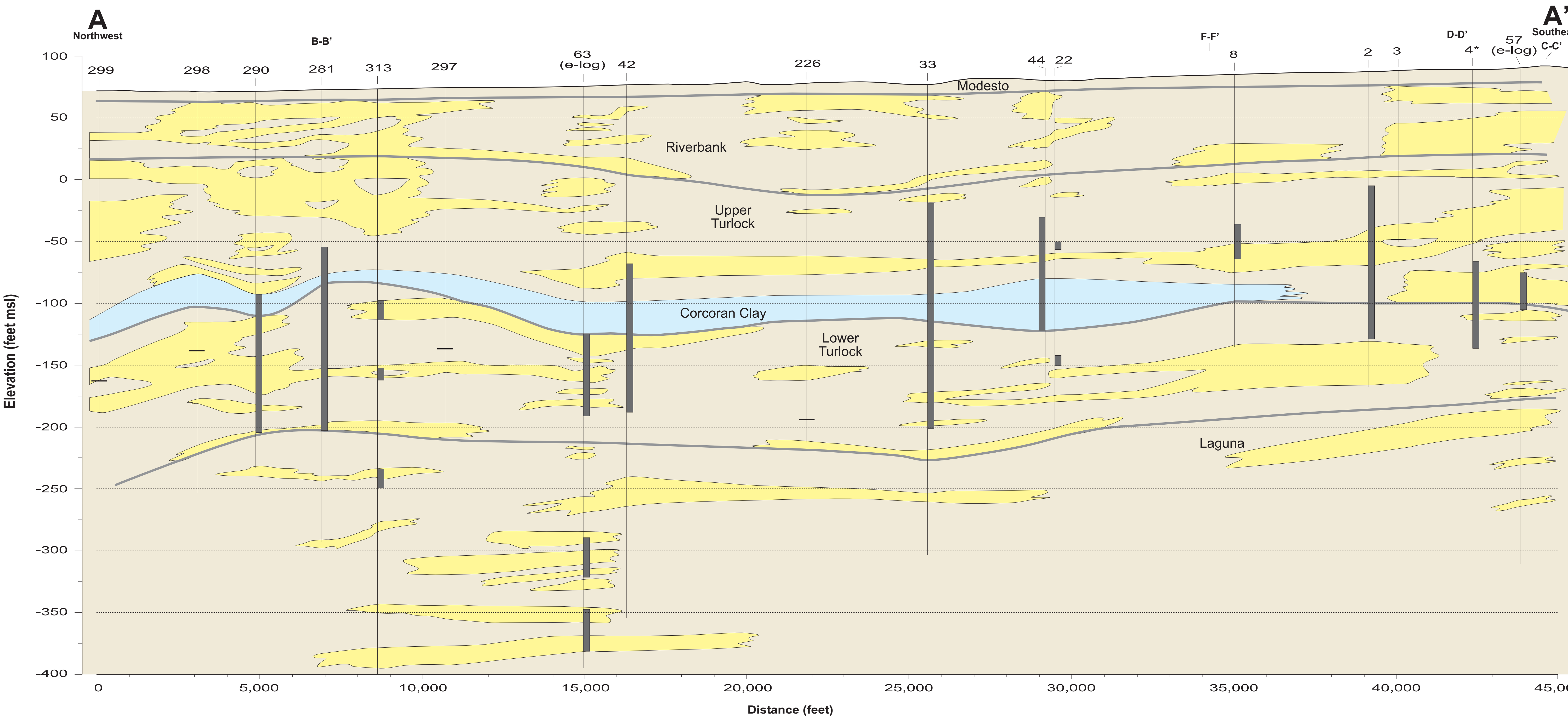


Figure 2
Study Area Wells



January 2016

Figure 3
Cross Section Locations



Notes: 1) Base of casing indicated by "—" for some wells without screened intervals.
2) * Well 4: Driller's Report does not contain lithology. Lithology inferred from adjacent wells.

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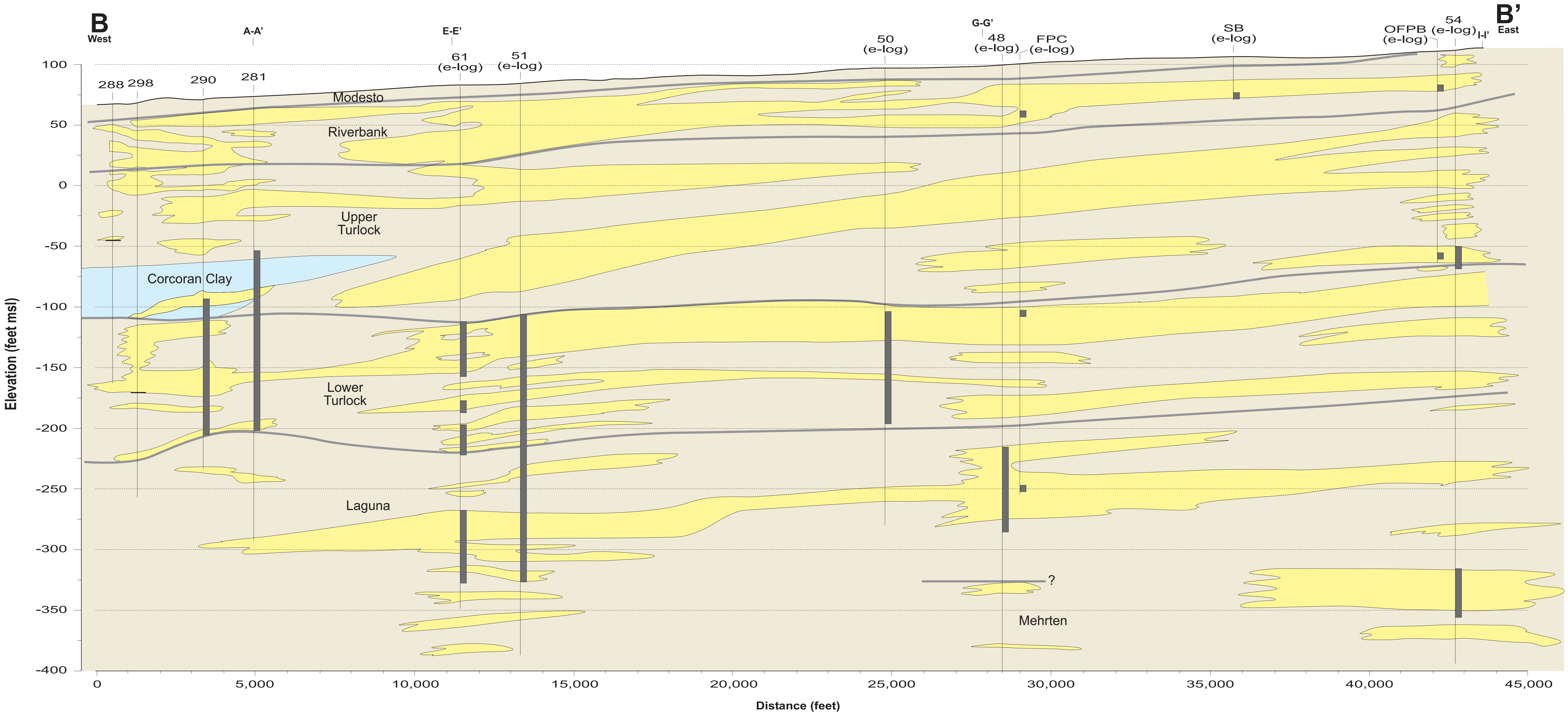
Figure 4
Cross Section A - A'



Note: Base of casing indicated by "—" for some wells without screened intervals.

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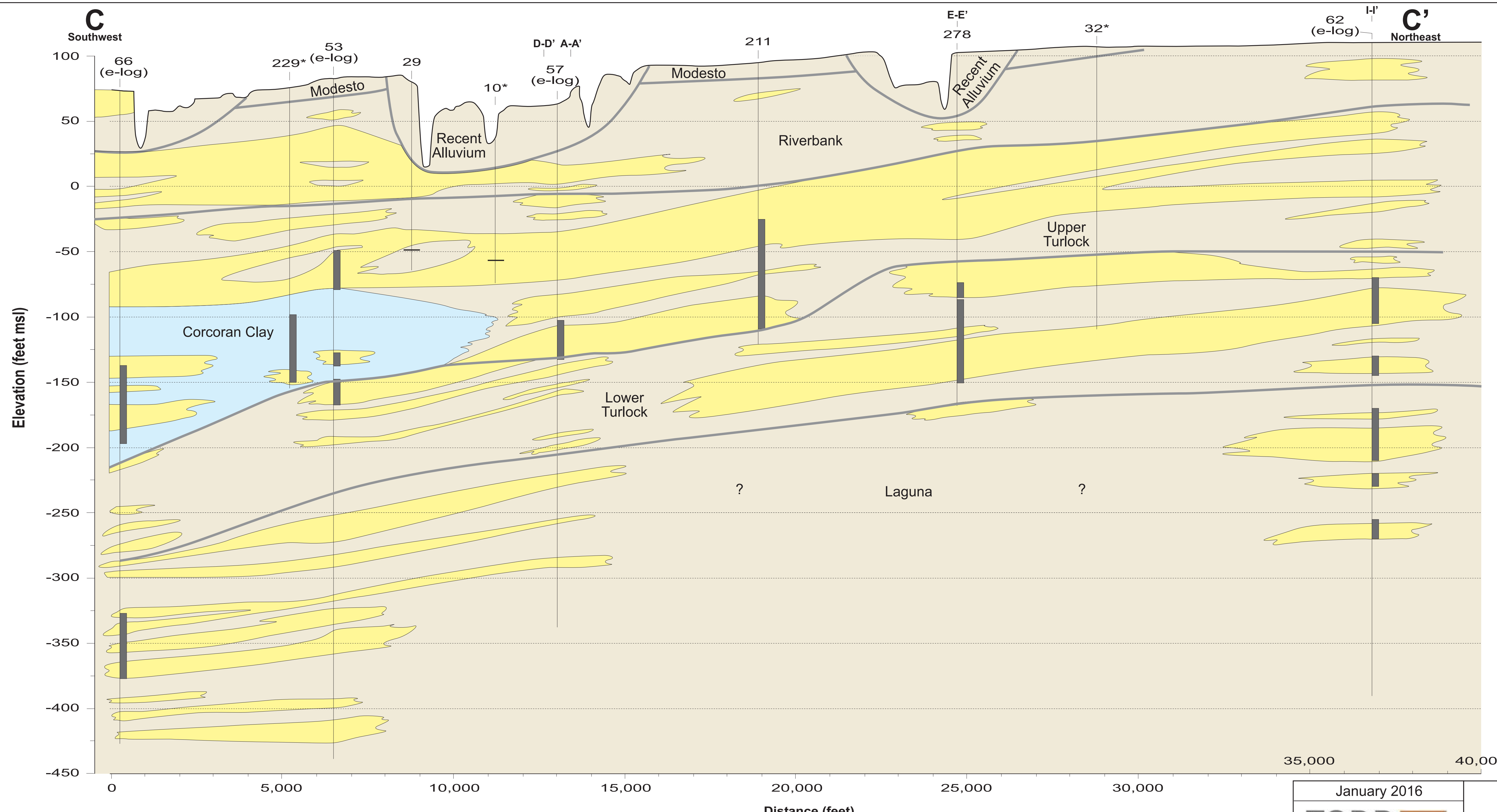
Figure 5
Cross Section B - B'



Notes: 1) Base of casing indicated by "—" for some wells without screened intervals.
2) * Wells 10 and 32: Driller's Report not available. Lithology inferred from adjacent wells.
Well 229: Lithology on Driller's Report only below depth of 128 feet.

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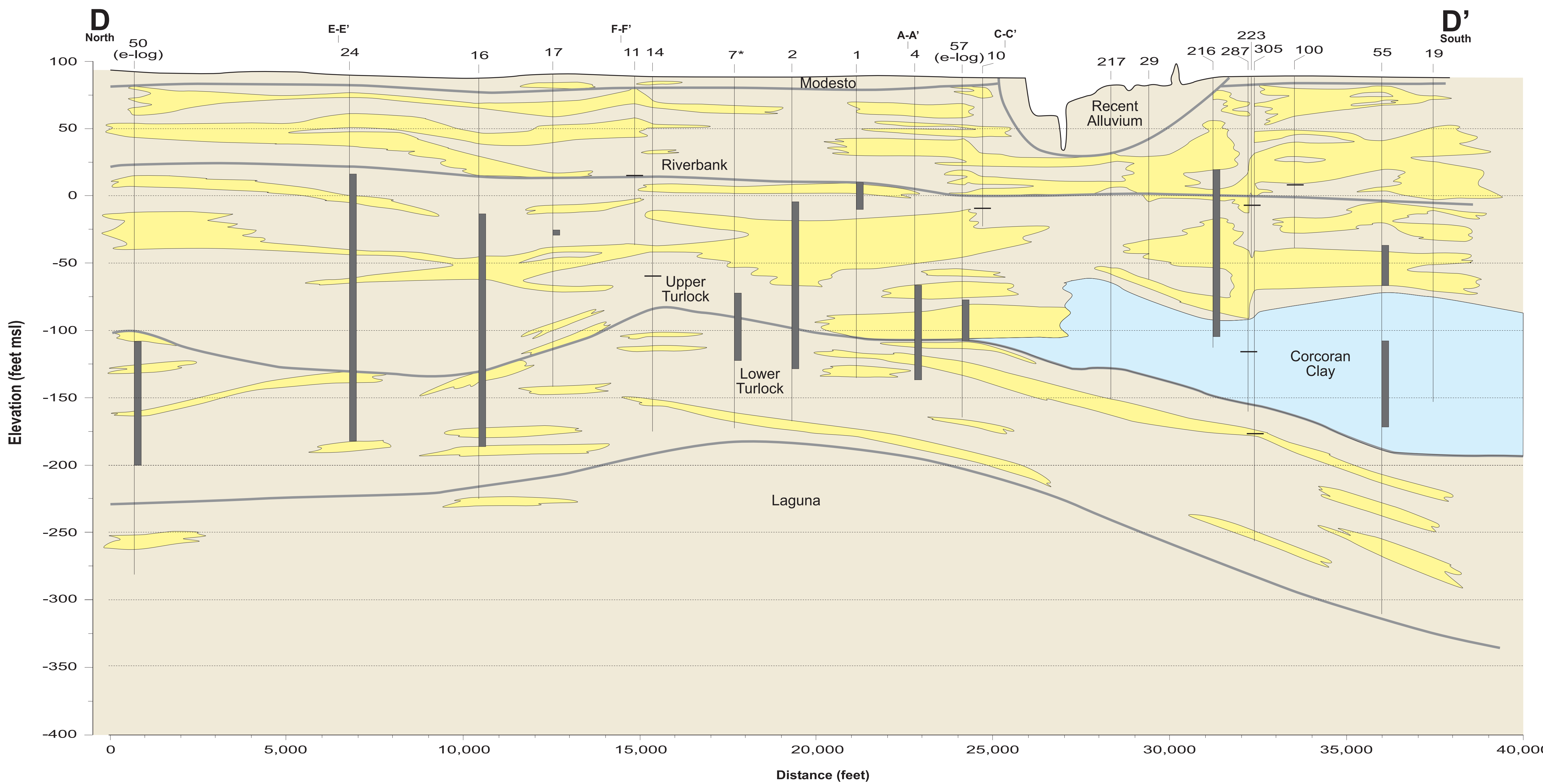
Figure 6
Cross Section C - C'



Notes: 1) Base of casing indicated by "___" for some wells without screened intervals.
2) * Well 7: Driller's Report not available. Lithology inferred from adjacent wells.

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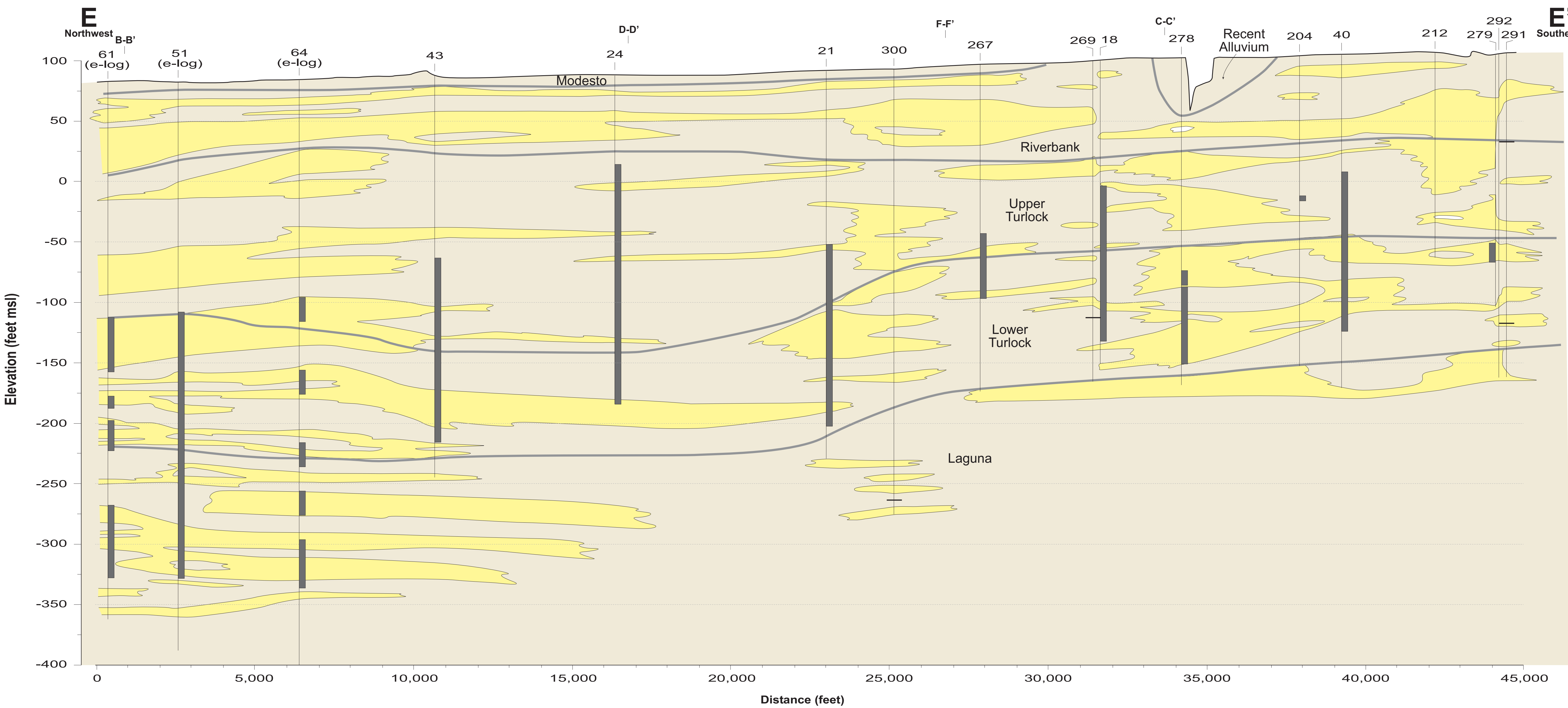
Figure 7
Cross Section D - D'



Note: Base of casing indicated by "—" for some wells without screened intervals.

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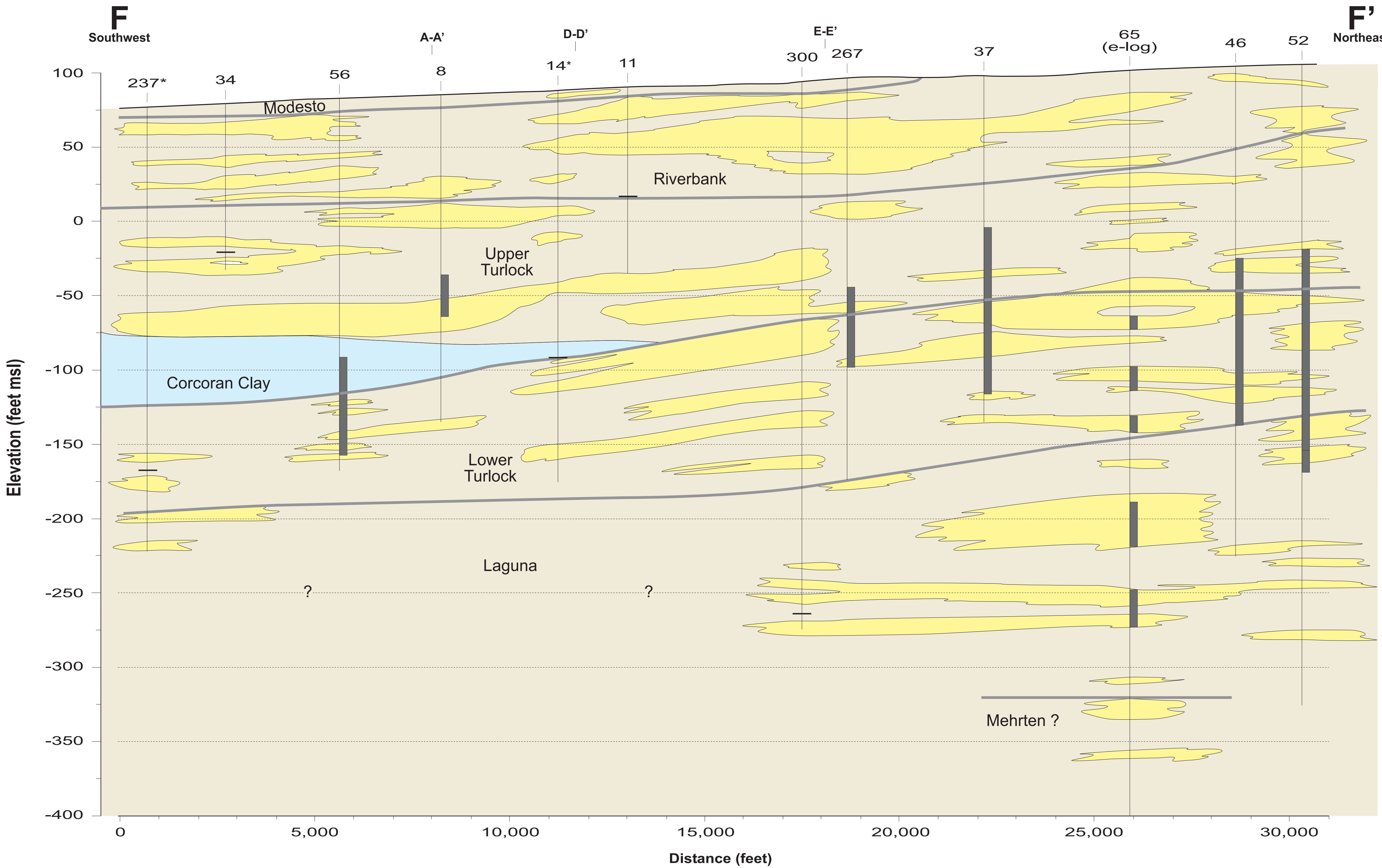
Figure 8
Cross Section E - E'



Notes: 1) Base of casing indicated by "——" for some wells without screened intervals.
2) * Well 14: Driller's Report not available. Lithology inferred from adjacent wells.
Well 237: Lithology on Driller's Report only below depth of 233 feet.
3) Horizontal scale has been revised from previous sections to allow closer inspection of the geologic units.

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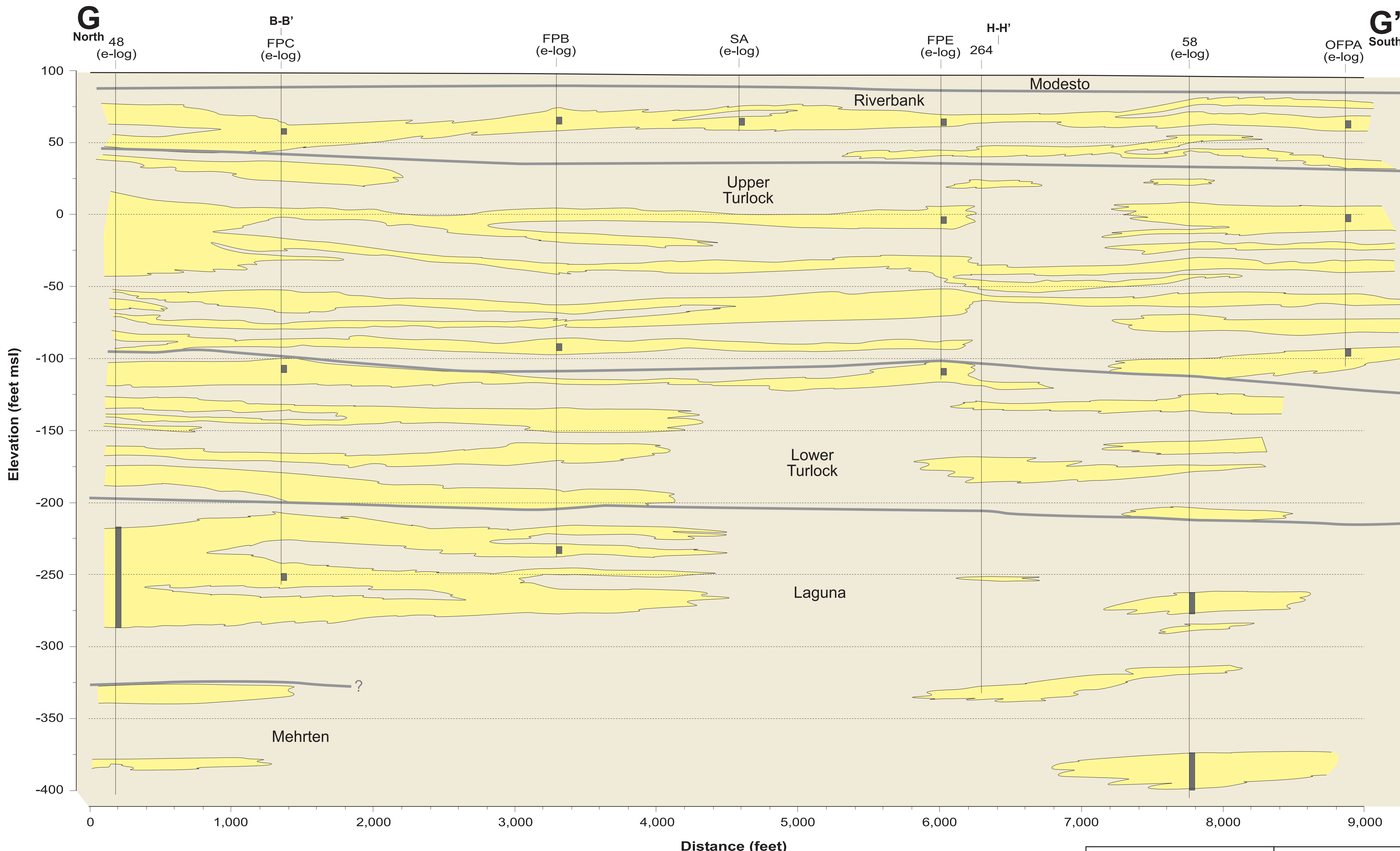
Figure 9
Cross Section F - F'



Notes: 1) Base of casing indicated by "—" for some wells without screened intervals.
2) Horizontal scale has been revised from previous sections to allow closer inspection of the geologic units.

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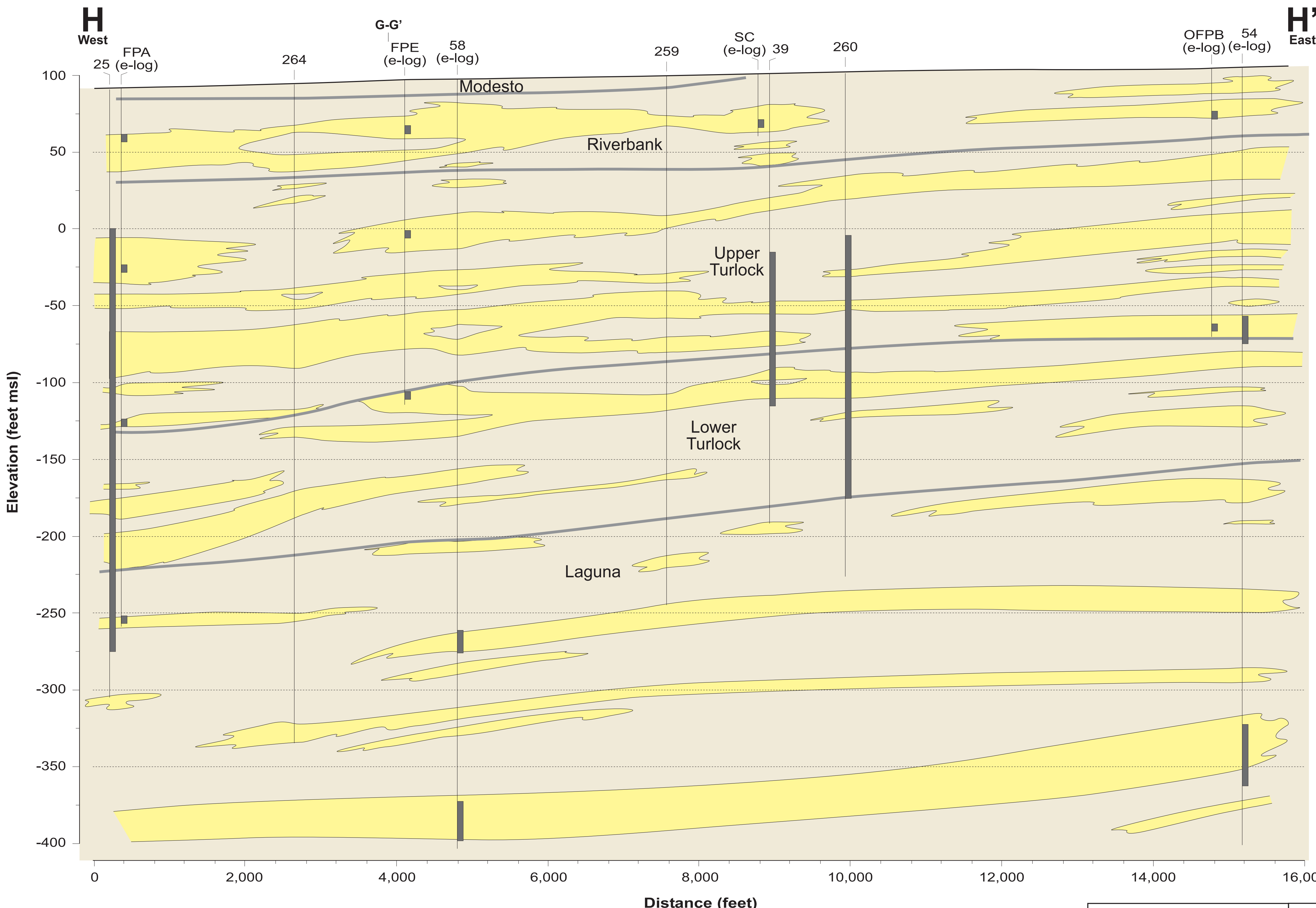
Figure 10
Cross Section G - G'



Notes: 1) Base of casing indicated by "—" for some wells without screened intervals.
2) Horizontal scale has been revised from previous sections to allow closer inspection of the geologic units.

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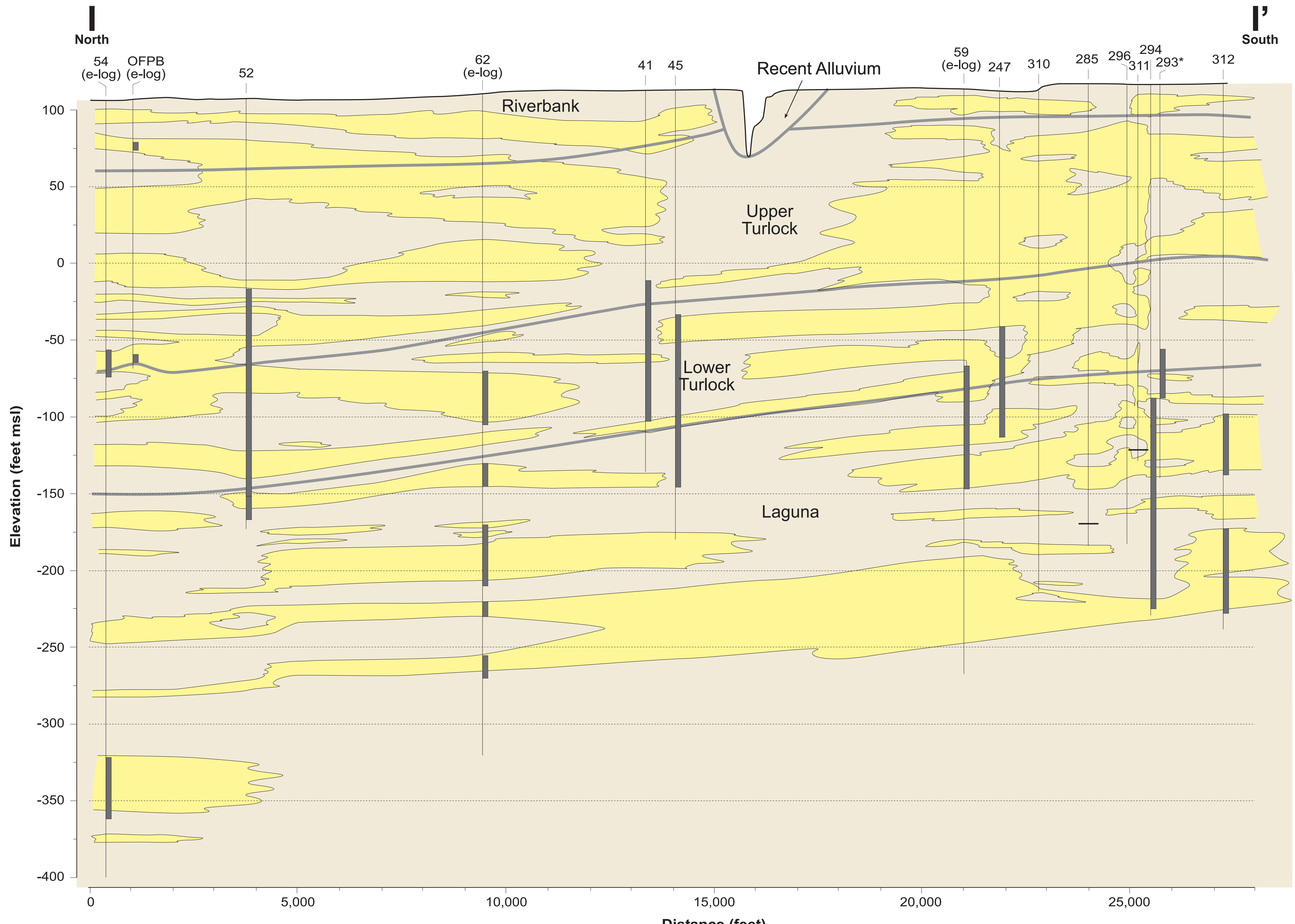
Figure 11
Cross Section H - H'



Notes: 1) Base of casing indicated by "——" for some wells without screened intervals.
2) * Well 293: Driller's Report not available. Lithology inferred from adjacent wells.

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Figure 12
Cross Section I - I'

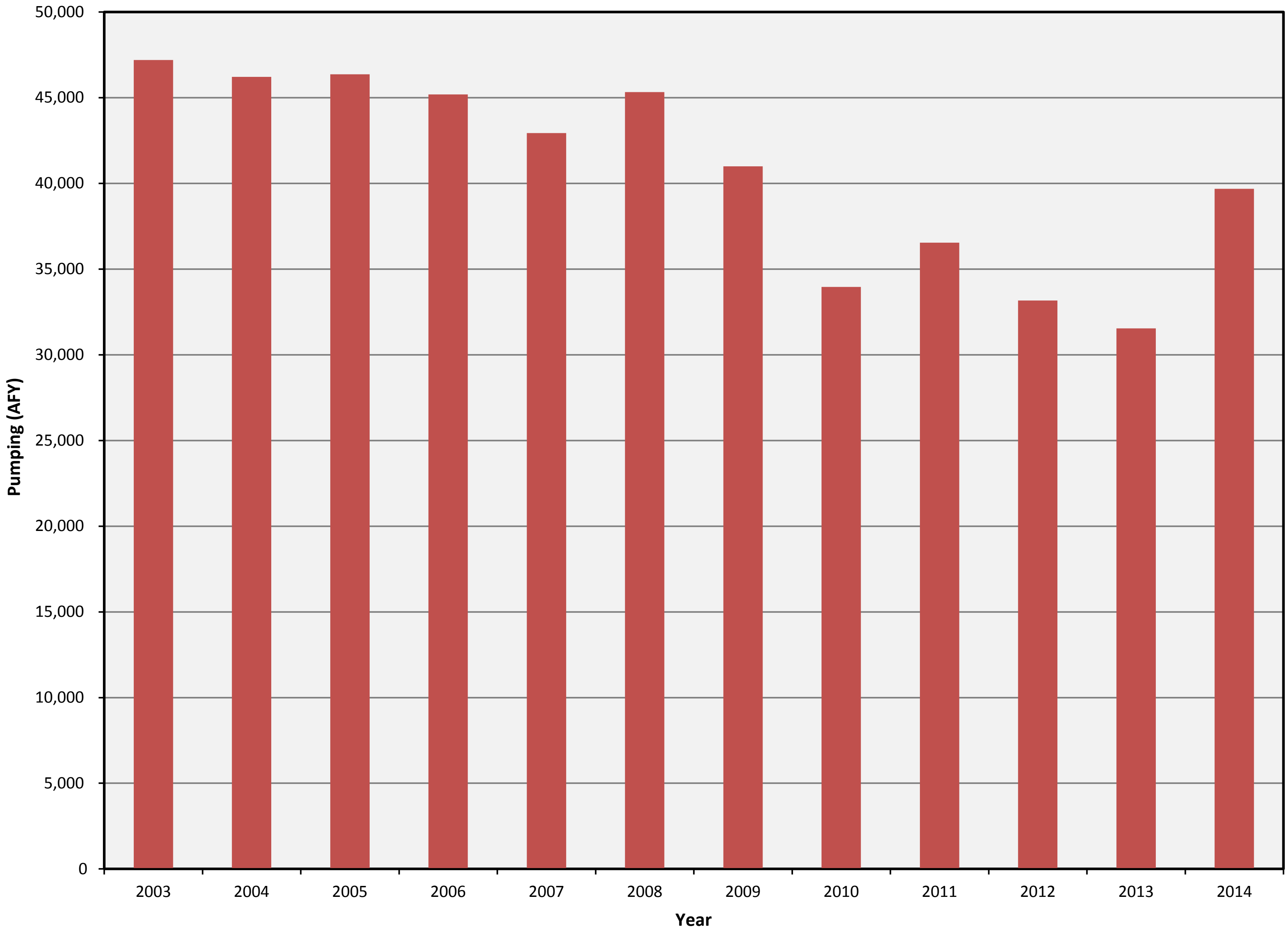

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Figure 13
City of Modesto Annual Production

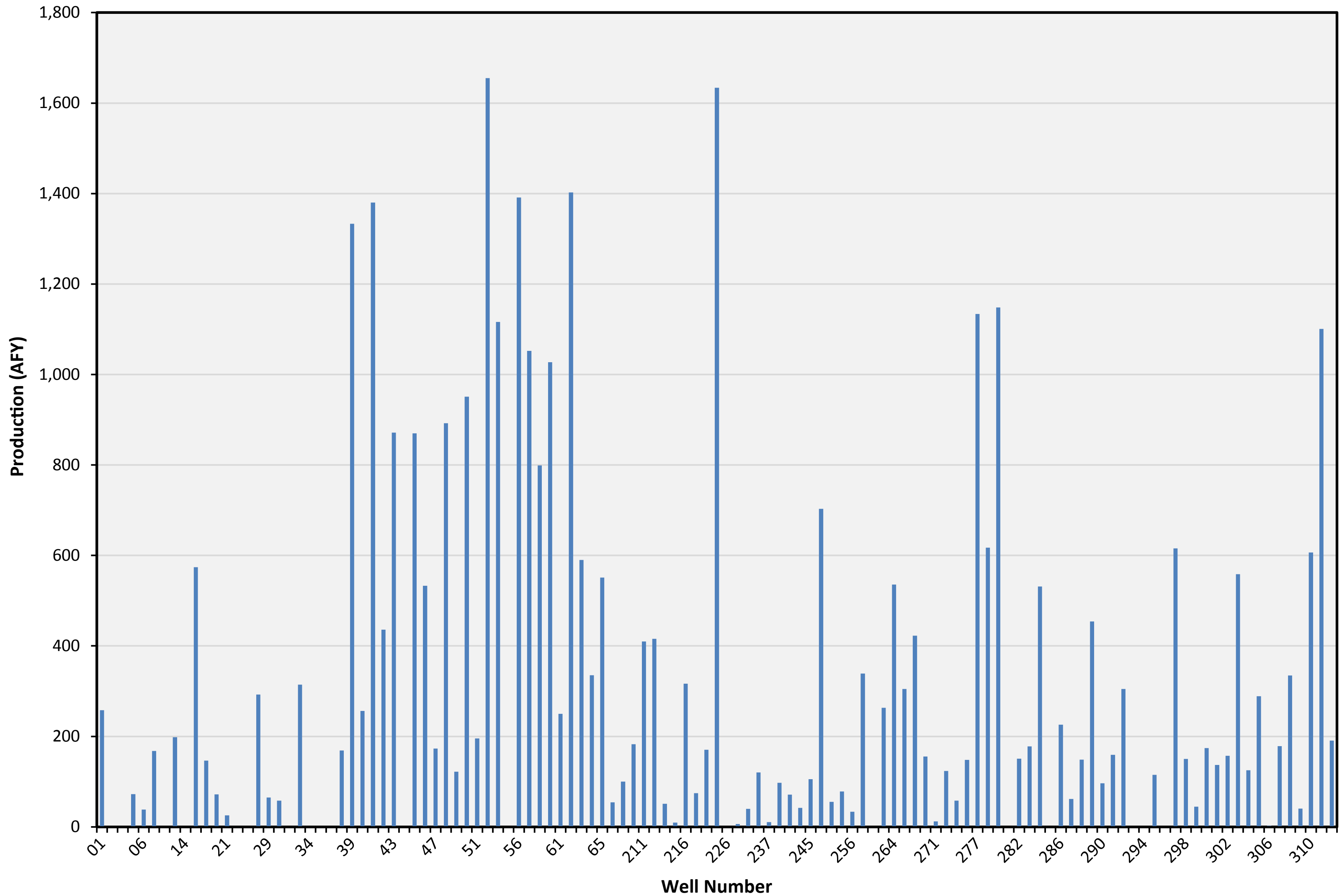

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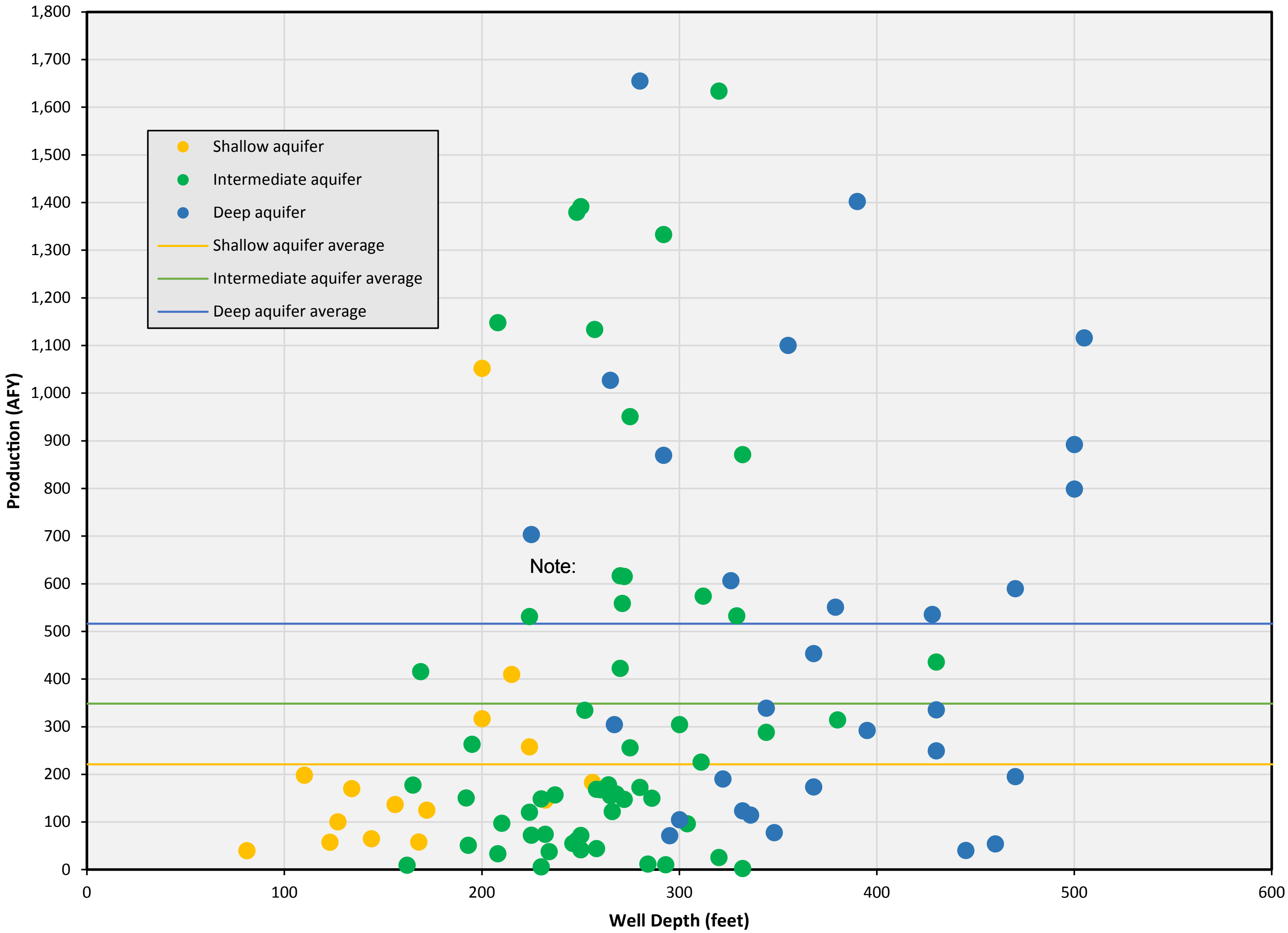
Figure 14
Average Annual Production by Well
July 2014 - June 2015



Note: Well Production July 2014 - June 2015.

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Figure 15
Recent Well Production and Aquifer Designation

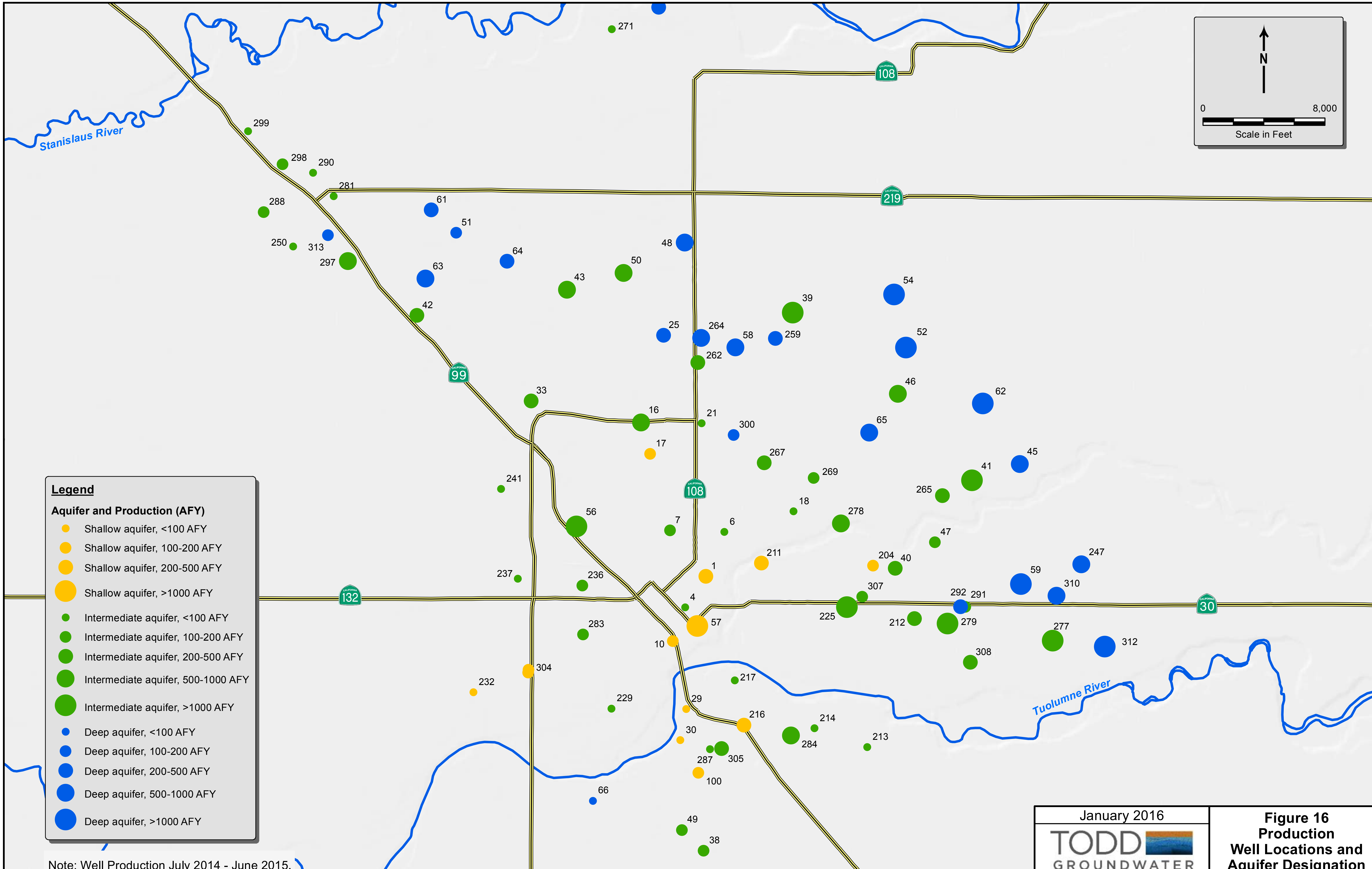

Figure 16
Production
Well Locations and
Aquifer Designation

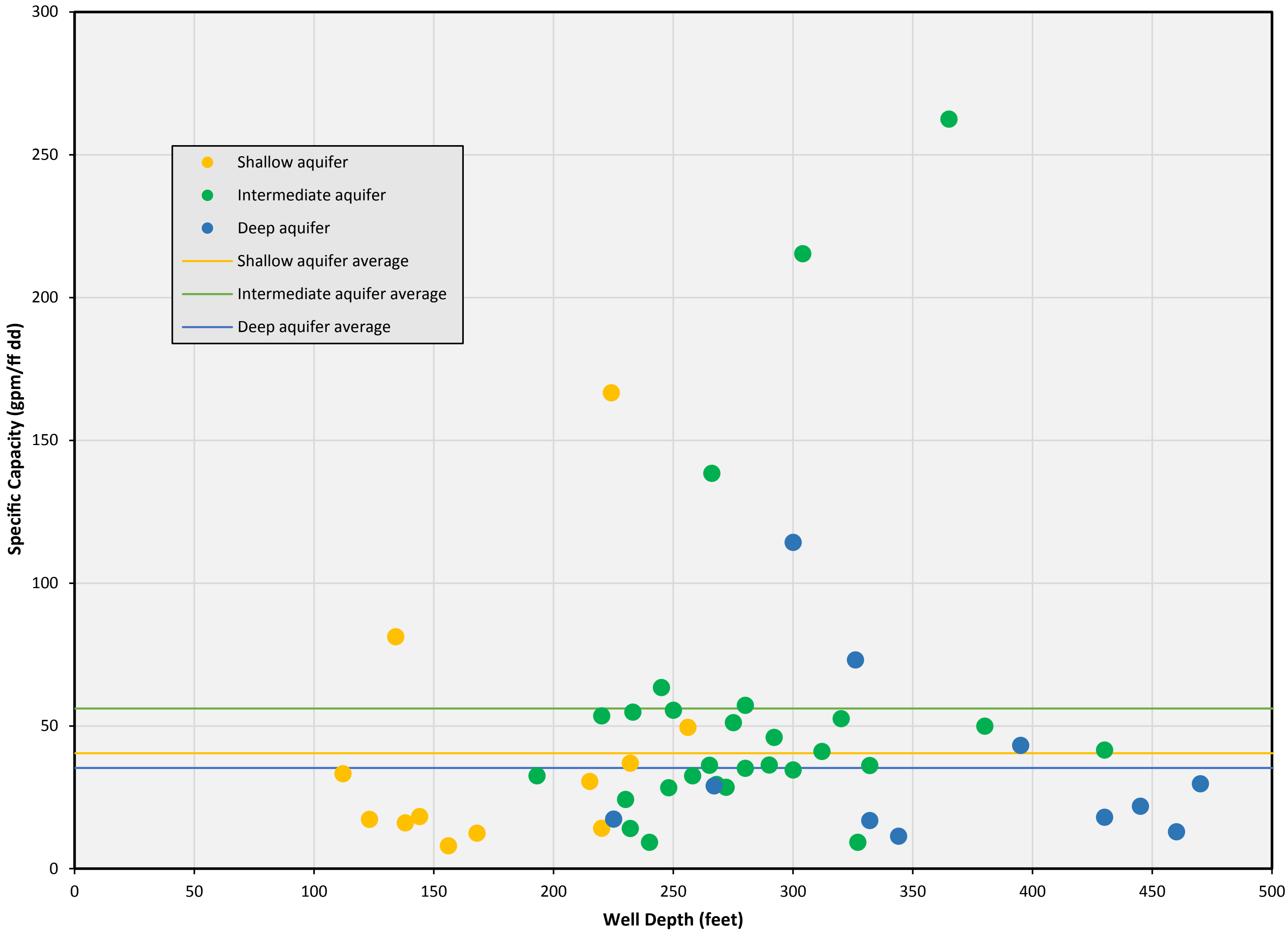

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Figure 17
Wells with Specific Capacity and Aquifer Designation

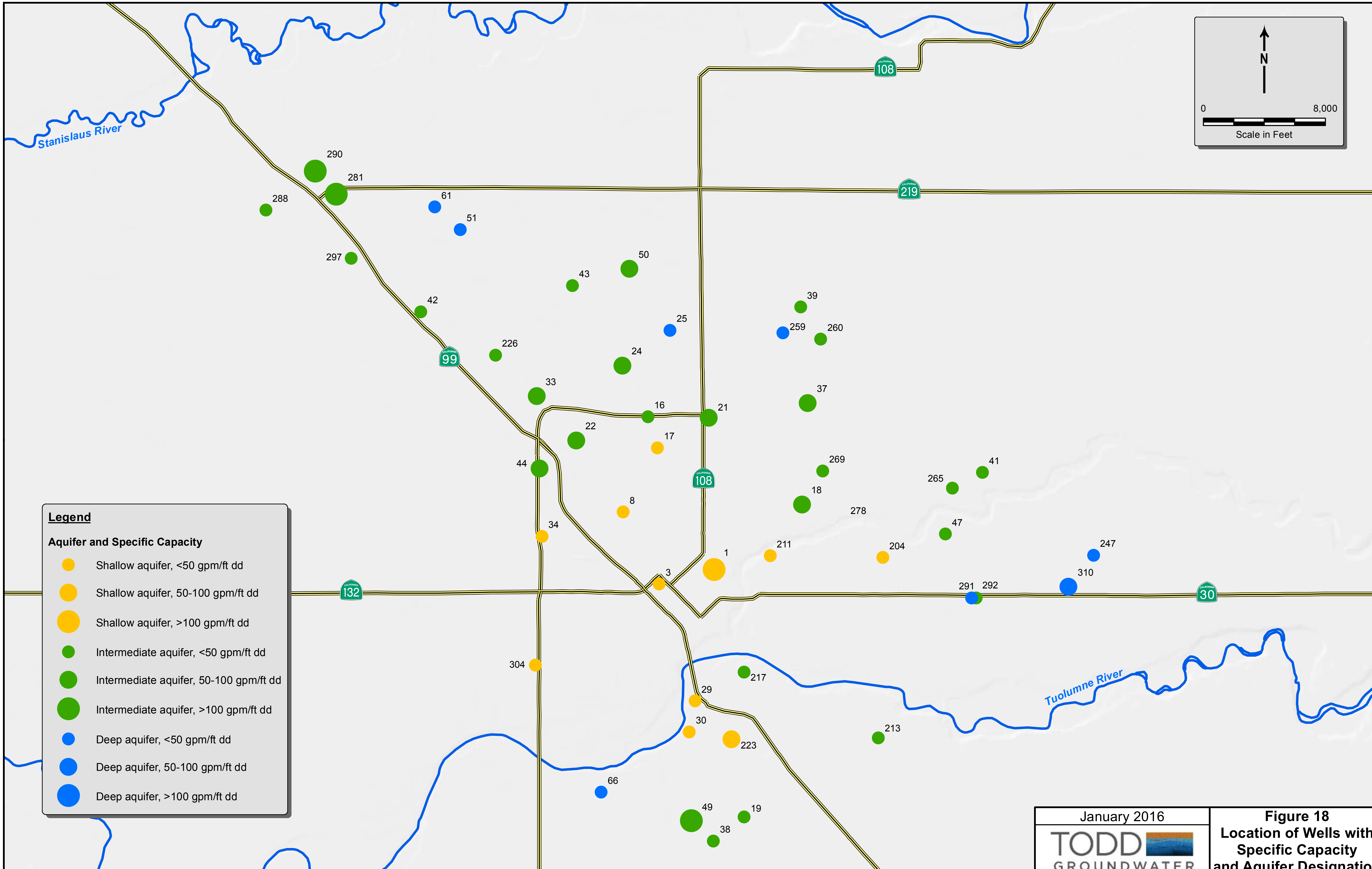

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Figure 18
Location of Wells with Specific Capacity and Aquifer Designation

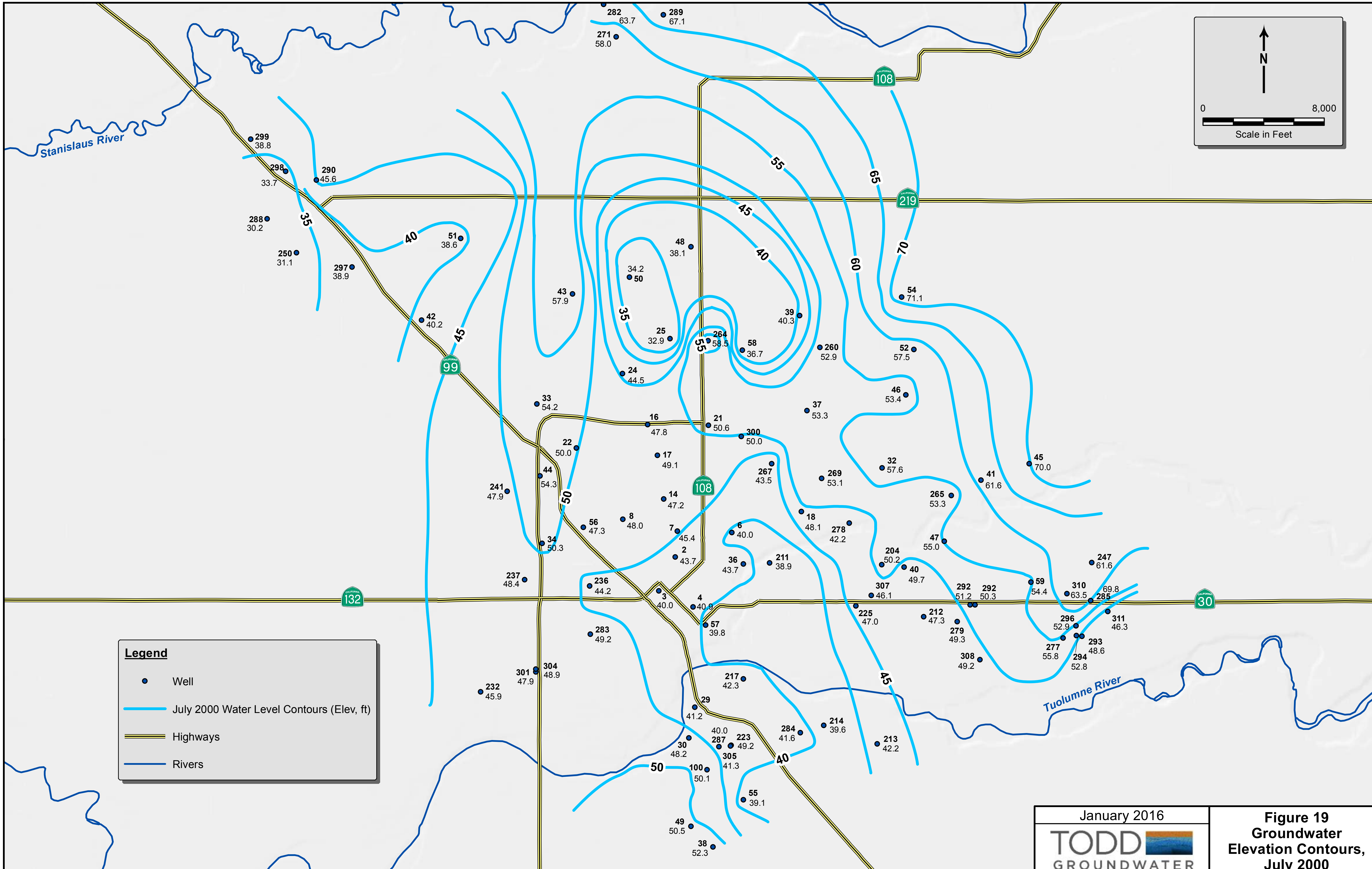

Figure 19
Groundwater Elevation Contours, July 2000

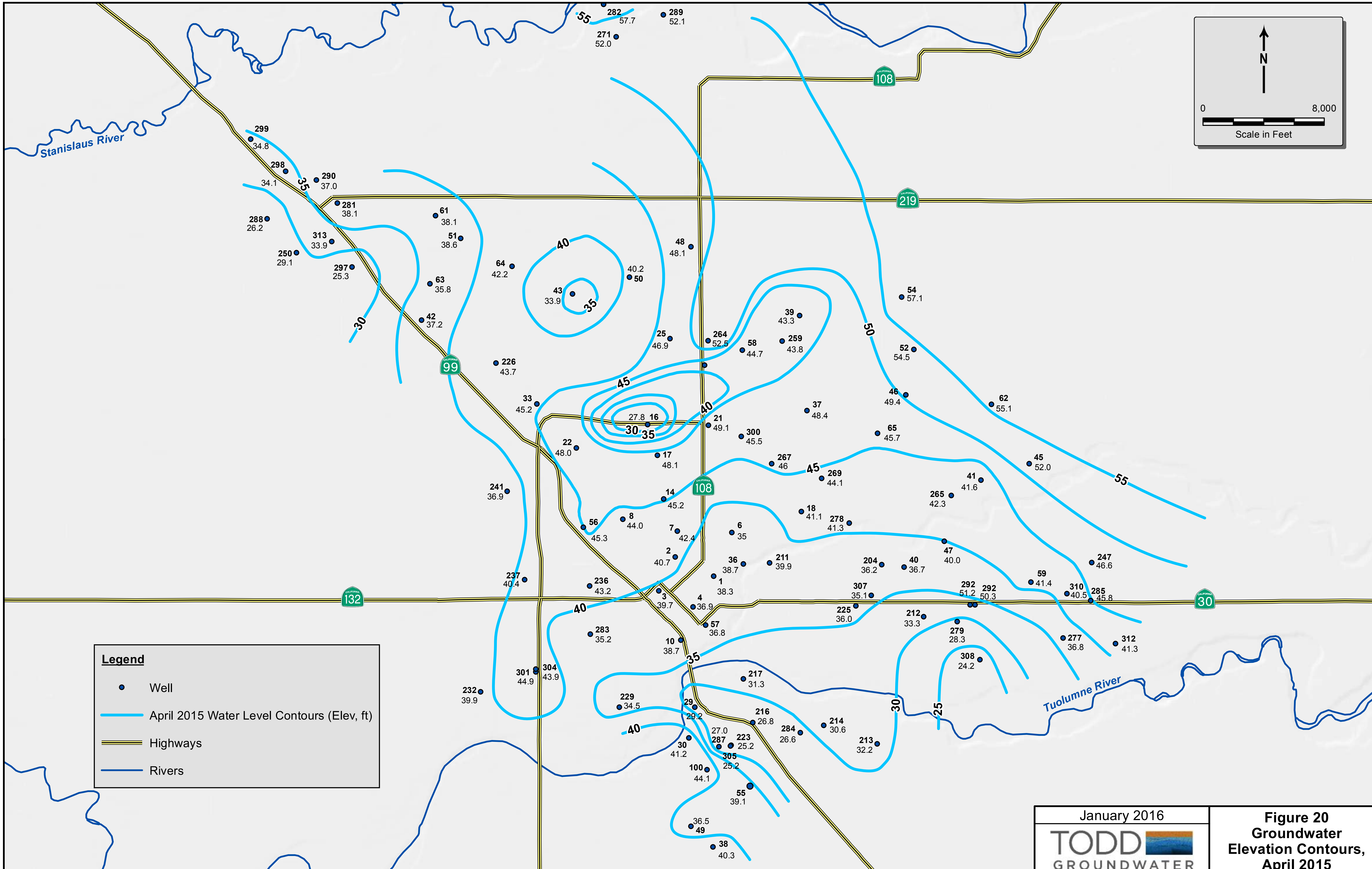

Figure 20
Groundwater Elevation Contours, April 2015

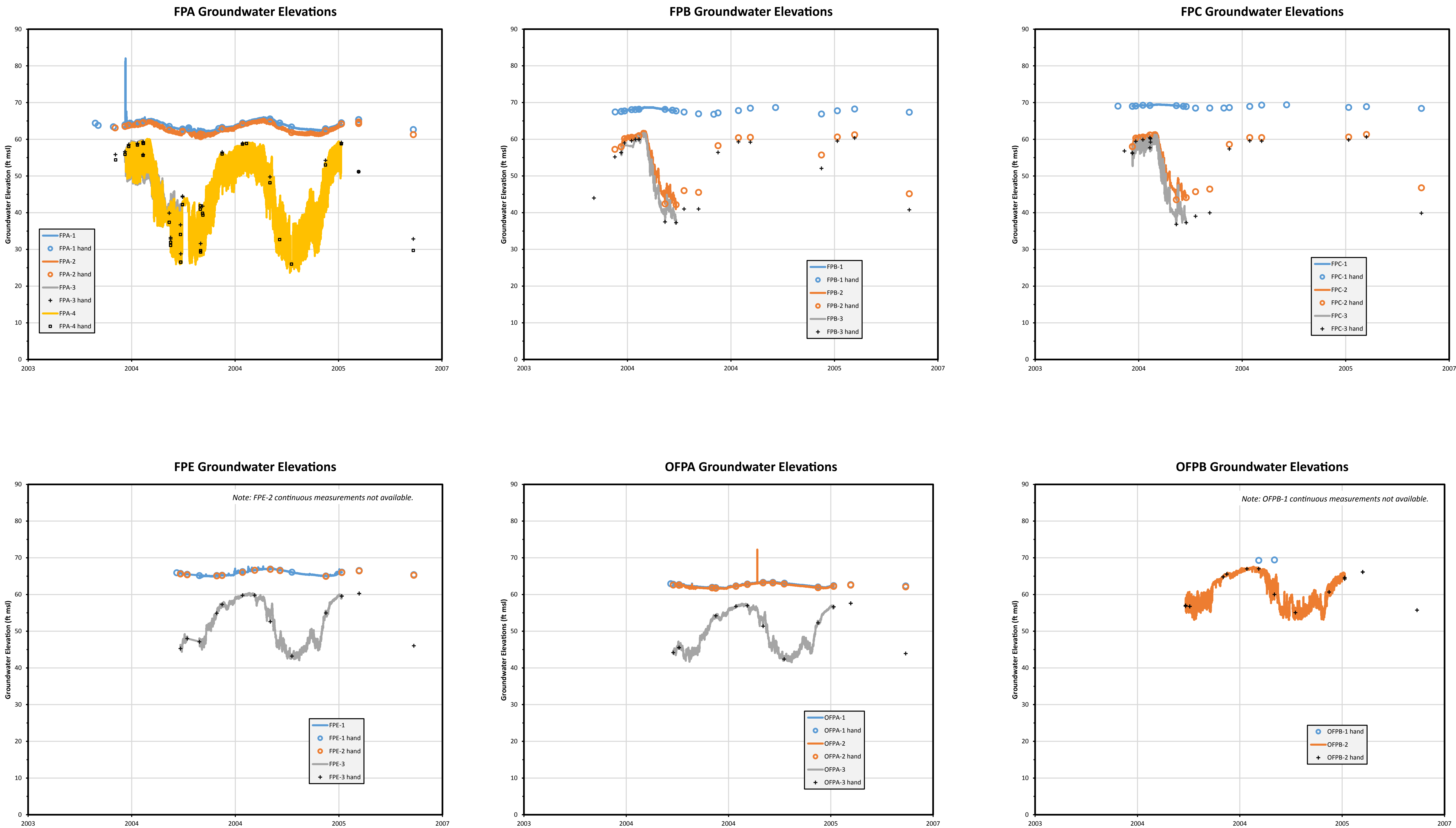

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Figure 21
Hydrographs for USGS Monitoring Wells

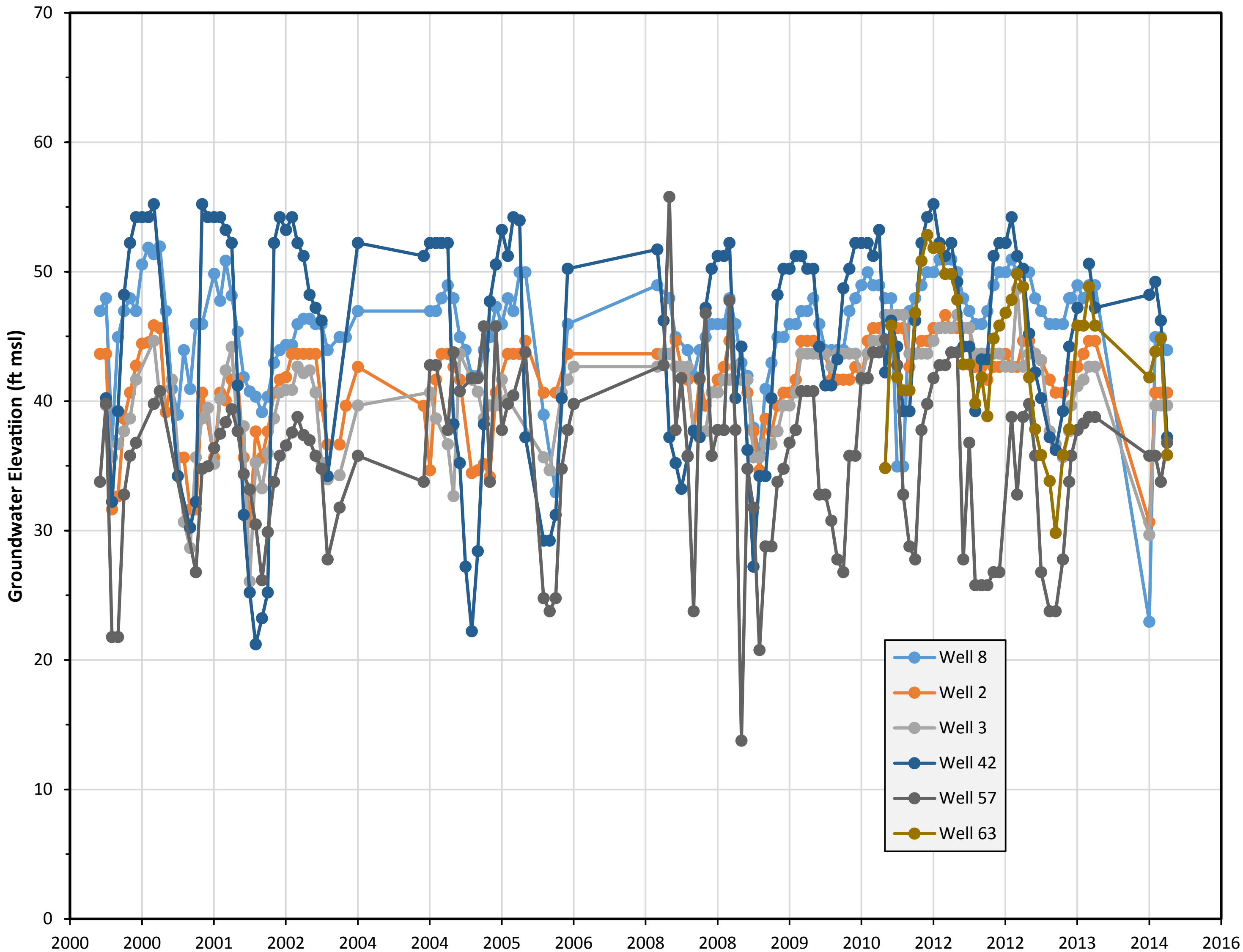

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Figure 22
Hydrographs for Select Wells on Cross Section A - A'

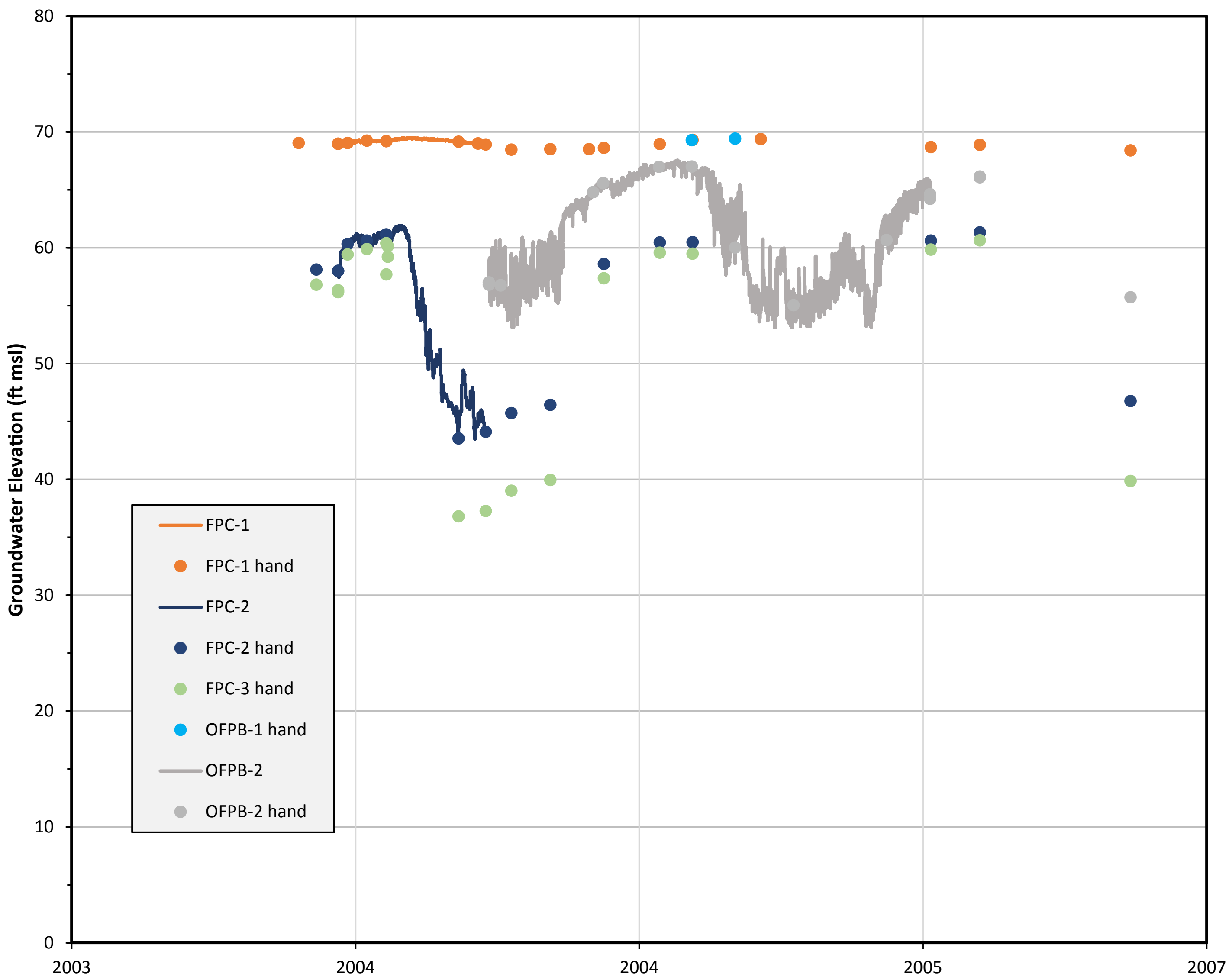

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Figure 23
Hydrographs for Select Wells on Cross Section B - B'

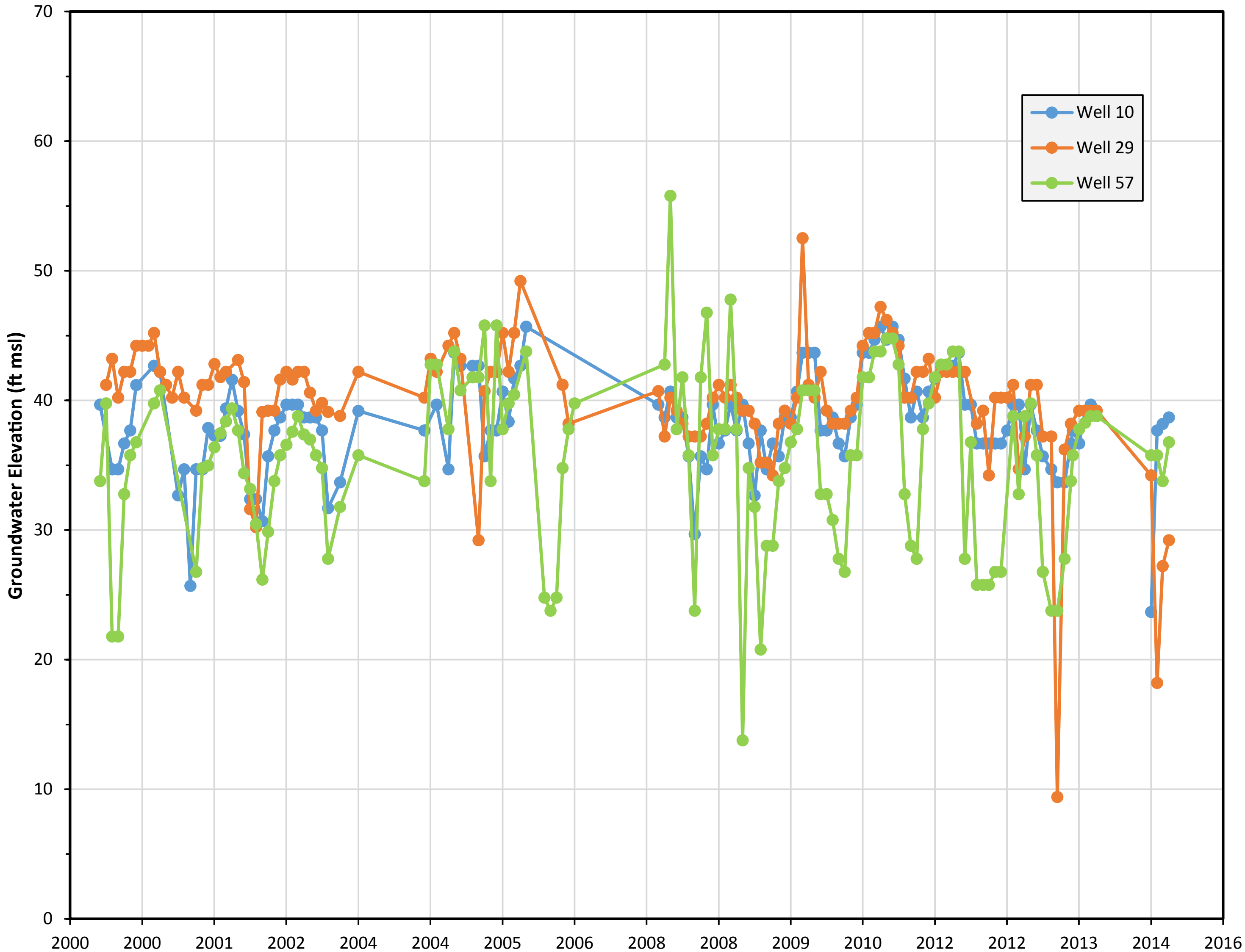

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Figure 24
Hydrographs for Select Wells on Cross Section C - C'

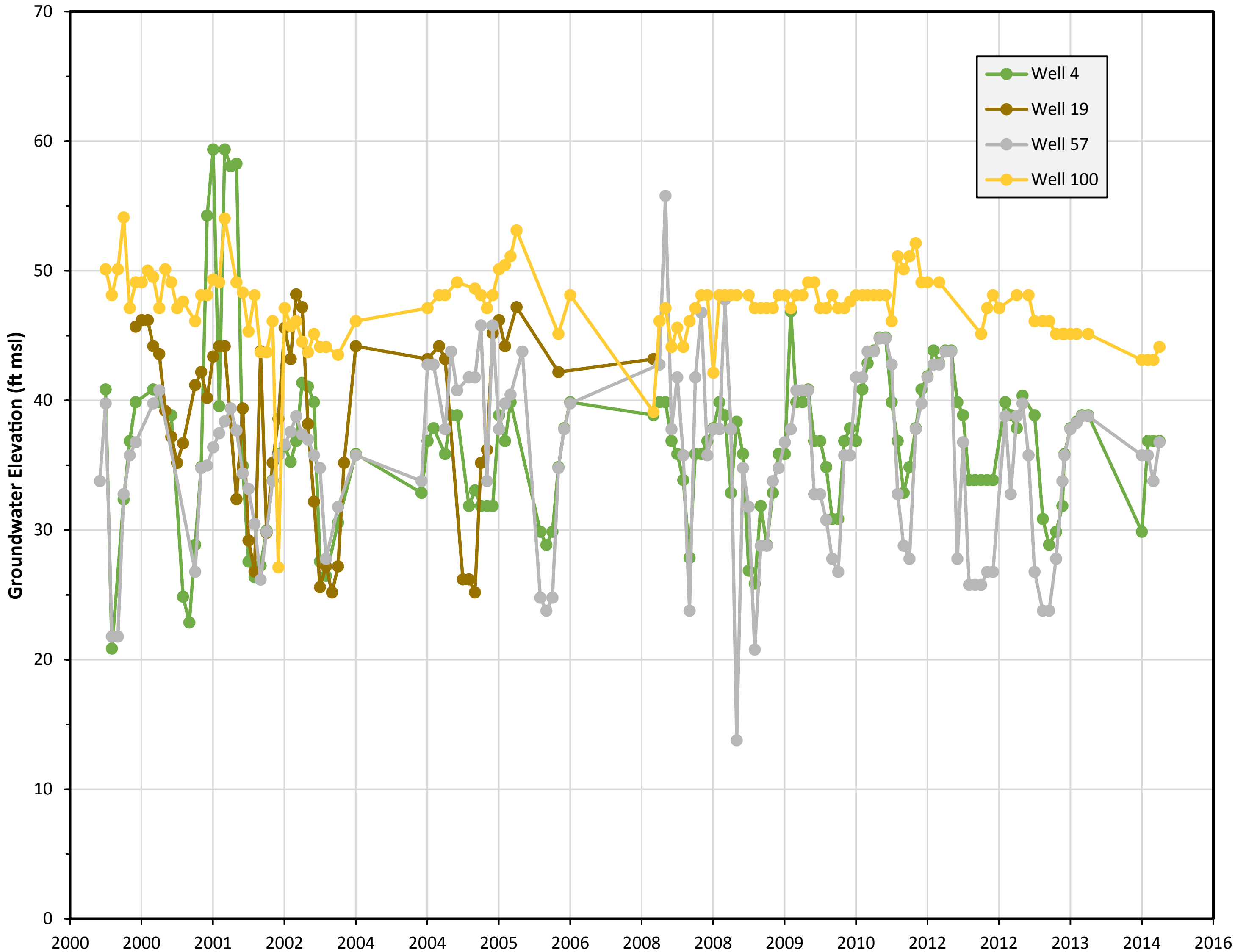

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Figure 25
Hydrographs for Select Wells on Cross Section D - D'

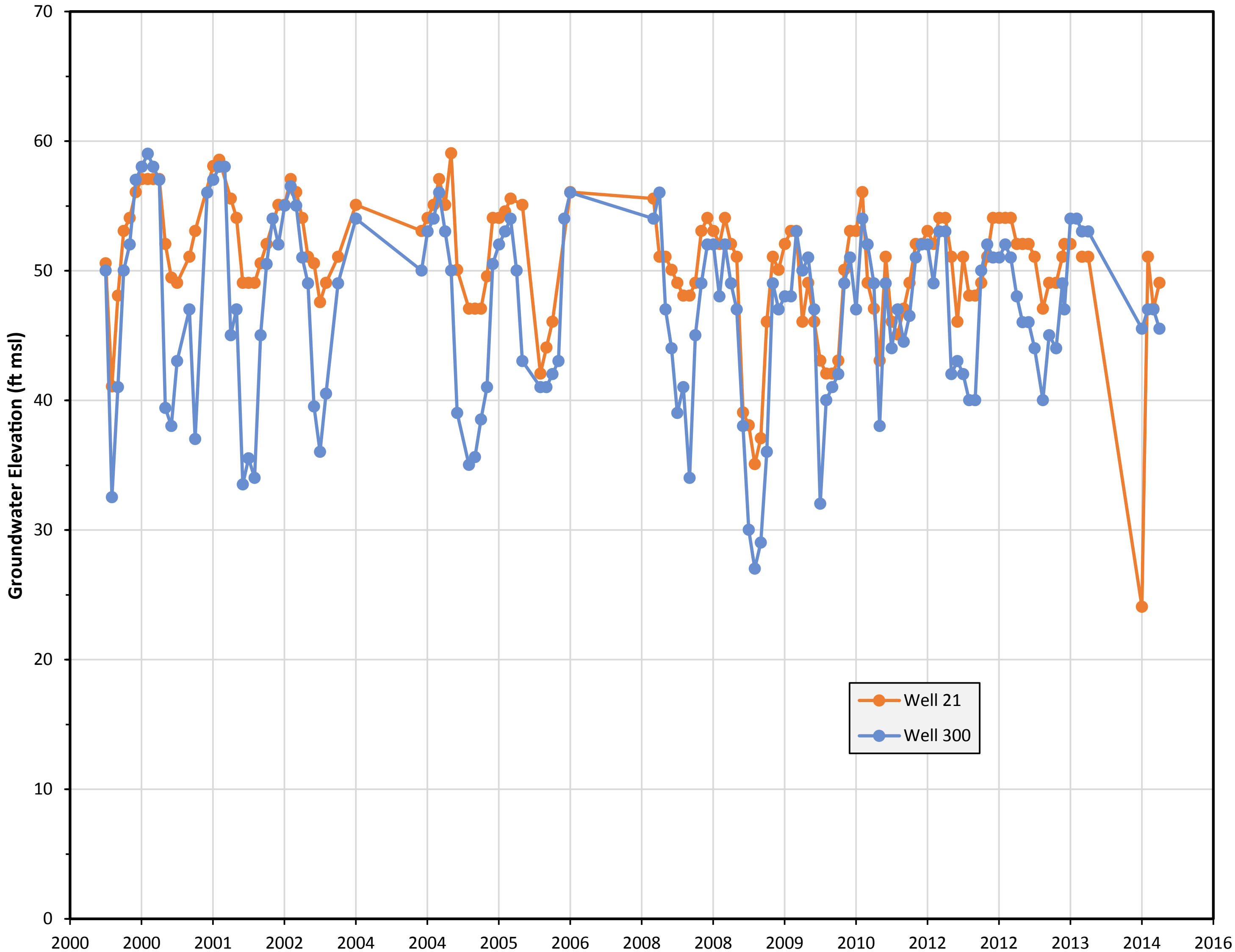

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Figure 26
Hydrographs for Select Wells on Cross Section E - E’

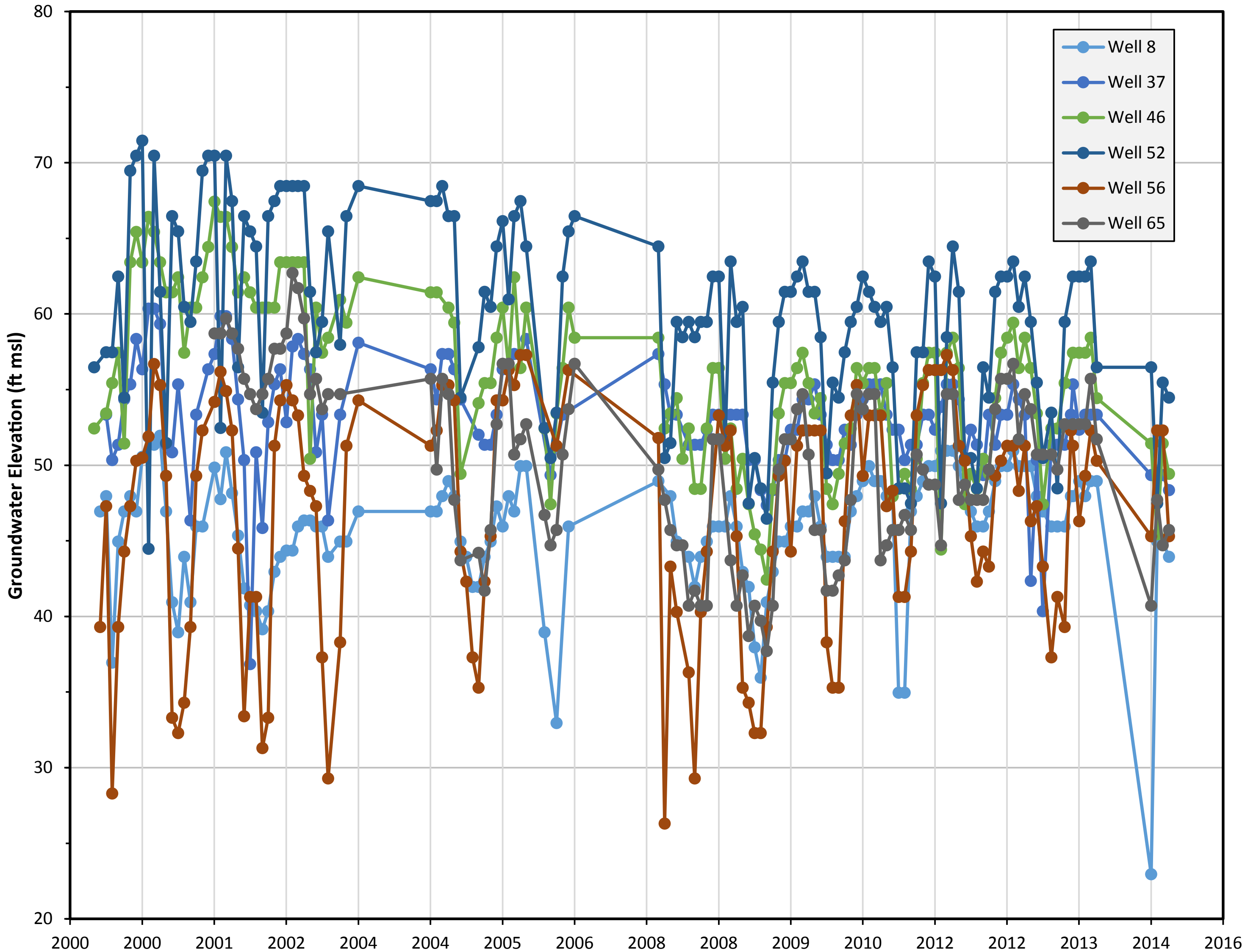

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Figure 27
Hydrographs for Select Wells on Cross Section F - F'

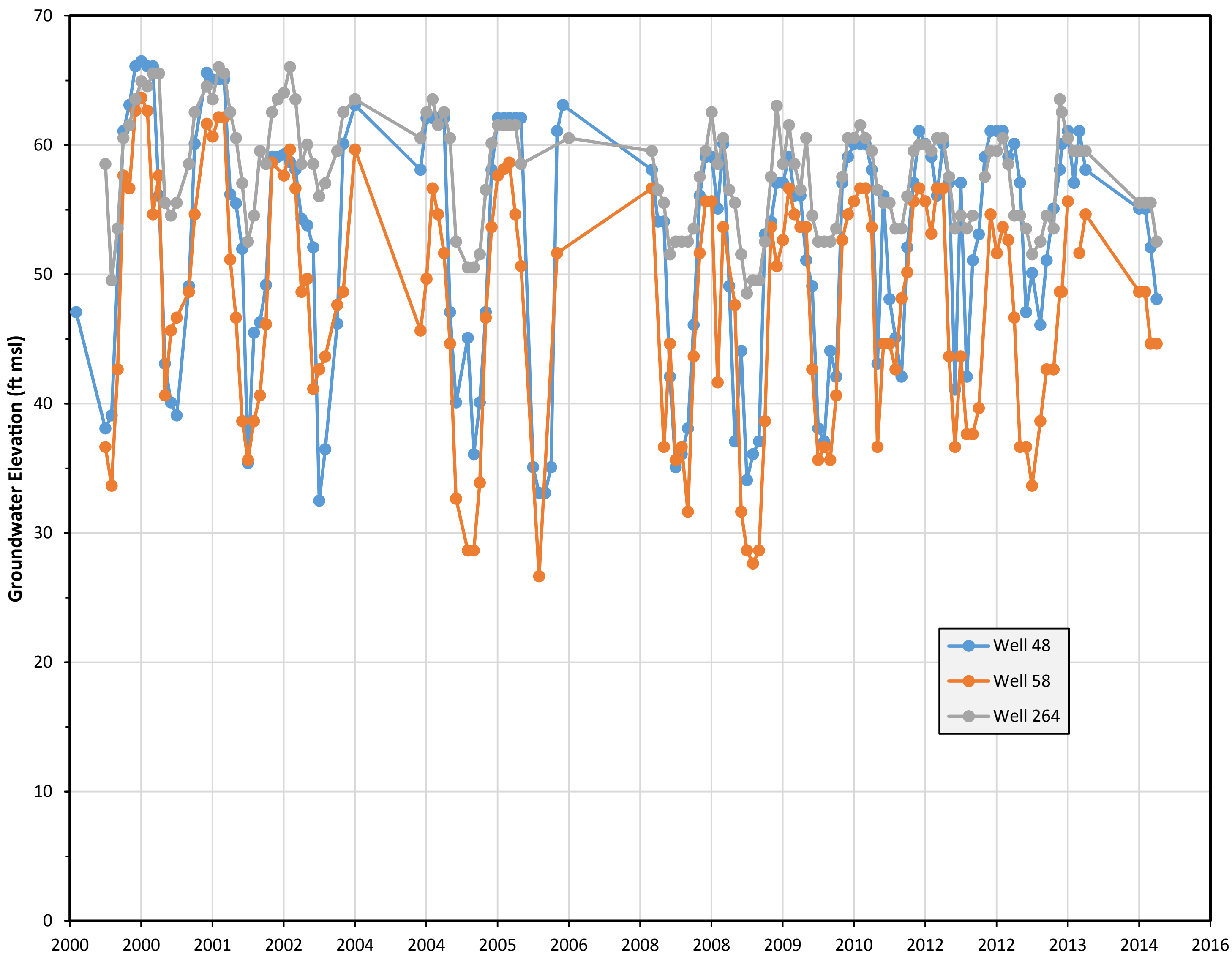

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Figure 28
Hydrographs for Select Wells on Cross Section G - G'

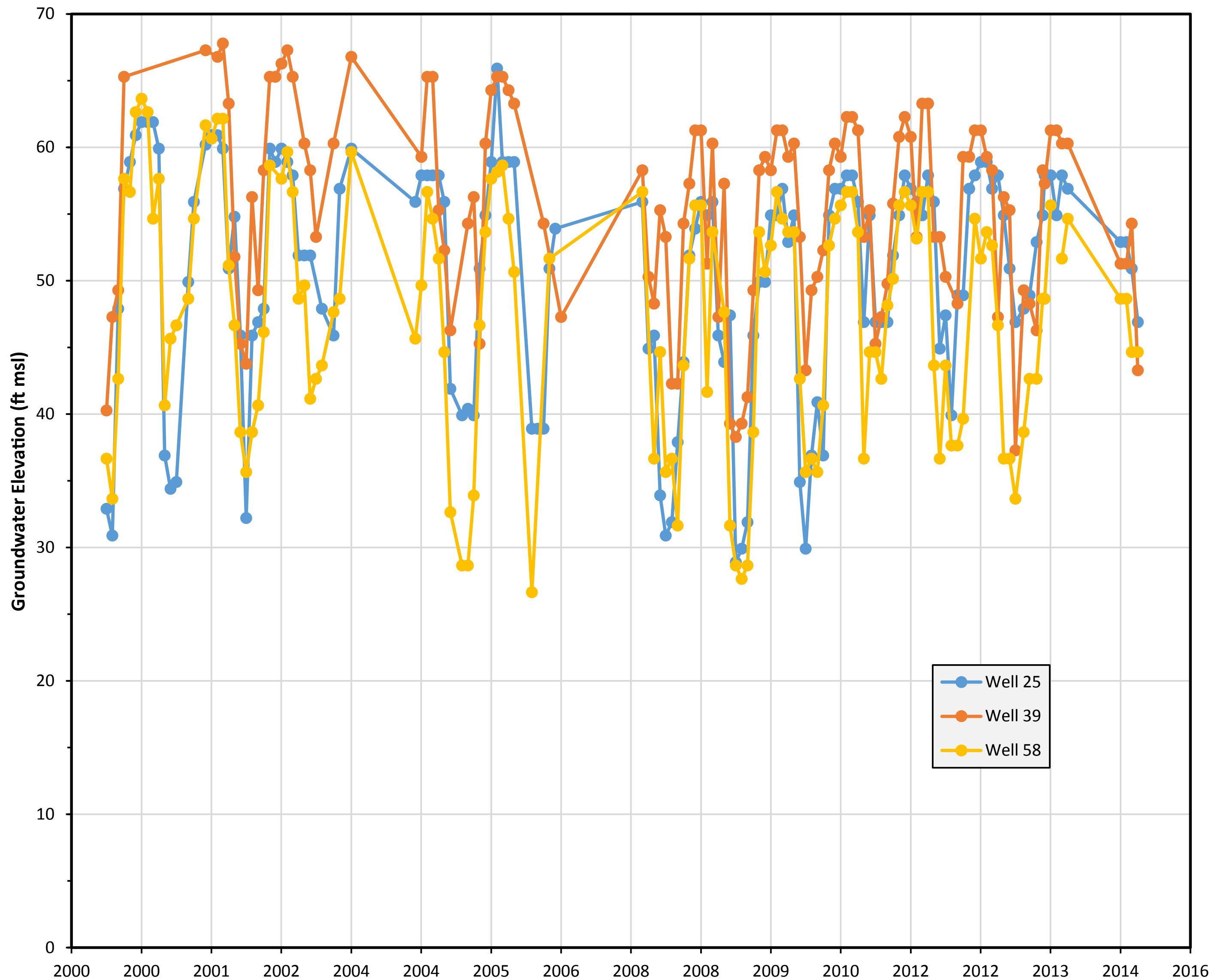

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Figure 29
Hydrographs for Select Wells on Cross Section H - H'

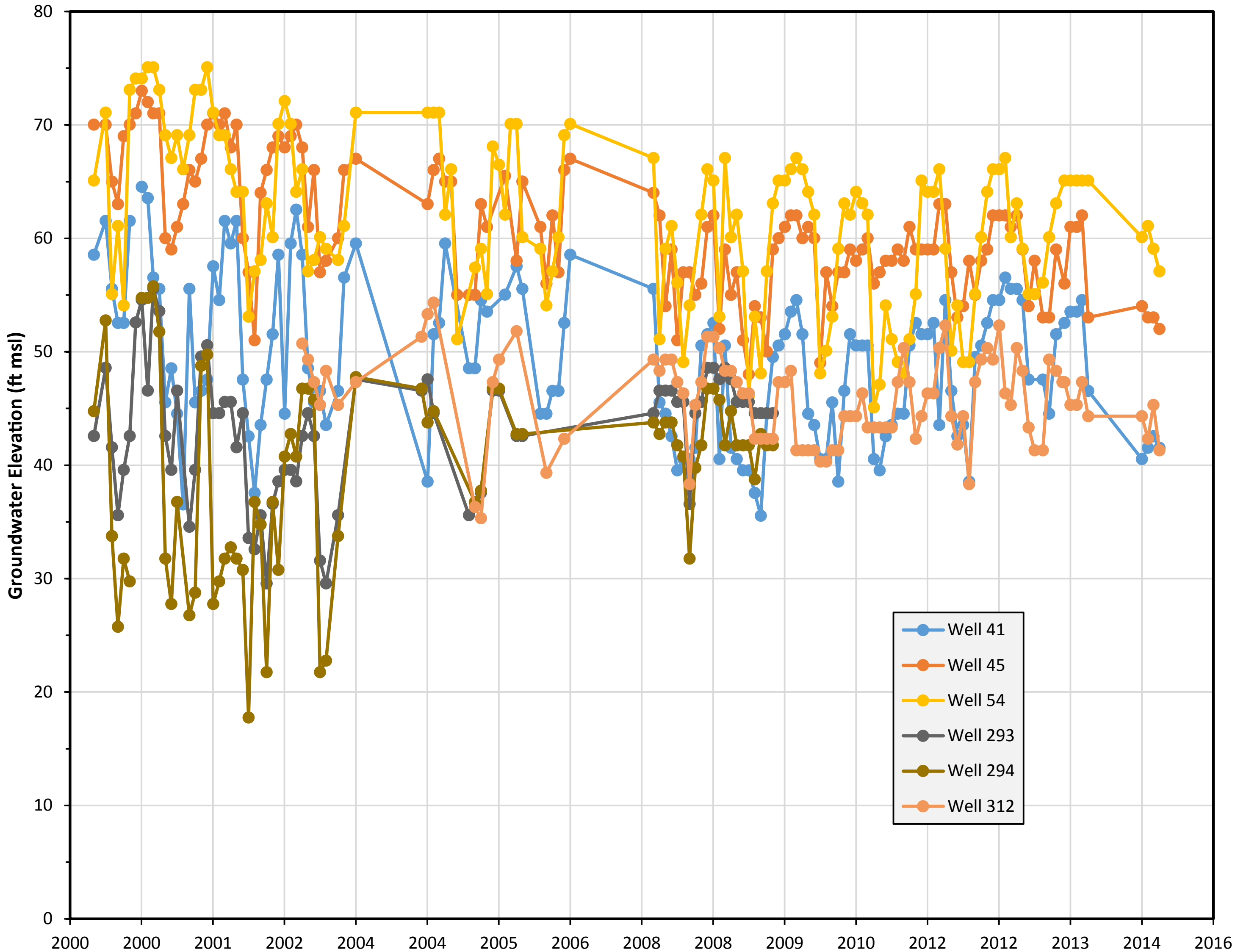

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Figure 30
Hydrographs for Select Wells on Cross Section I - I'

A
Northwest
A'
Southeast
B-B'
F-F'
D-D'
C-C'
299
298
290
281
313
297
63 (e-log)
42
226
33
44
22
8
2
3
4*
57 (e-log)
Modesto
Riverbank
Upper Turlock
Corcoran Clay
Lower Turlock
Laguna
Elevation (feet msl)
100
50
0
-50
-100
-150
-200
-250
-300
-350
-400
Distance (feet)
0
5,000
10,000
15,000
20,000
25,000
30,000
35,000
40,000
45,000
7.3 2014-05
8 2014-05
1.7 2012-02
ND 2012-02
32 2014-04
5.2 2014-12
4.4 2010-06
0 2014-05
39 2006-09
12 2006-06
3.3 2006-06
ND 2004-12
27 2014-02
7.3 2012-02
11 2014-11
ND 2012-02
27 2001-05
6 2001-03
32 2001-07
N/A N/A
23 2007-09
5 2005-09
15 2007-09
ND 2007-09
14 2005-09
5 2005-03
15 2005-06
ND 2005-09
37 2006-08
3 2002-03
0.7 2006-08
ND 2006-08
24 2014-03
2.9 2013-04
30 2014-11
ND 2014-02
22 2014-02
2.7 2014-03
9.5 2014-02
ND 2014-05
RMC water and environment
Notes: 1) Base of casing indicated by "—" for some wells without screened intervals.
2) * Well 4: Driller's Report does not contain lithology. Lithology inferred from adjacent wells.
Analytes (bold and italicized when above respective MCL)
Date of Latest Reported Sample
Mann-Kendall Trend Result
Nitrate (mg/L)
Arsenic (µg/L)
Uranium (pCi/L)
Dibromochloropropane (µg/L)
increasing
no trend
less than 4 samples
decreasing
(meq/L)
-10 -6 -2 2 6 10
Na+K
Ca
Mg
Cl
HCO3
SO4
January 2016
TODD GROUNDWATER
Figure 31
Cross Section A - A'
Water Quality

Note: Base of casing indicated by " ___ " for some wells without screened intervals.

Analytes (bold and italicized when above respective MCL)	Date of Latest Reported Sample	Mann-Kendall Trend Result
Nitrate (mg/L)		⇧ increasing
Arsenic (µg/L)		● no trend
Uranium (pCi/L)		○ less than 4 samples
Dibromochloropropane (µg/L)		⇩ decreasing

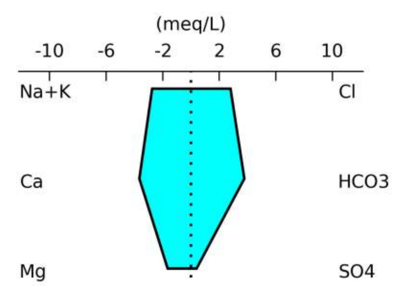

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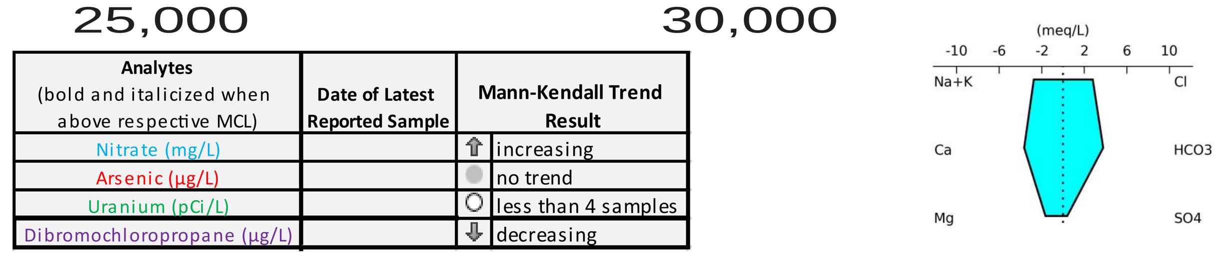
Figure 32
Cross Section B - B'
Water Quality



RMC water and environment

Notes: 1) Base of casing indicated by "___" for some wells without screened intervals.
2) * Wells 10 and 32: Driller's Report not available. Lithology inferred from adjacent wells.
Well 229: Lithology on Driller's Report only below depth of 128 feet.

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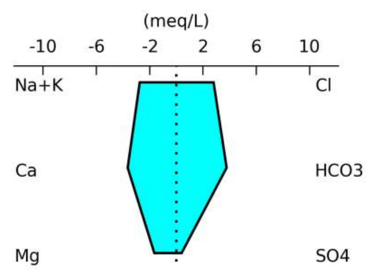
Figure 33
Cross Section C - C'
Water Quality

Notes: 1) Base of casing indicated by “___” for some wells without screened intervals.
2) * Well 7: Driller’s Report not available. Lithology inferred from adjacent wells.

Analytes (bold and italicized when above respective MCL)	Date of Latest Reported Sample	Mann-Kendall Trend Result
Nitrate (mg/L)		⇧ increasing
Arsenic (µg/L)		● no trend
Uranium (pCi/L)		○ less than 4 samples
Dibromochloropropane (µg/L)		⇩ decreasing



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RMC water and environment

Figure 34
Cross Section D - D’
Water Quality

Note: Base of casing indicated by "___ " for some wells without screened intervals.

Analytes (bold and italicized when above respective MCL)	Date of Latest Reported Sample	Mann-Kendall Trend Result
Nitrate (mg/L)		⇧ increasing
Arsenic (µg/L)		● no trend
Uranium (pCi/L)		○ less than 4 samples
Dibromochloropropane (µg/L)		⇩ decreasing

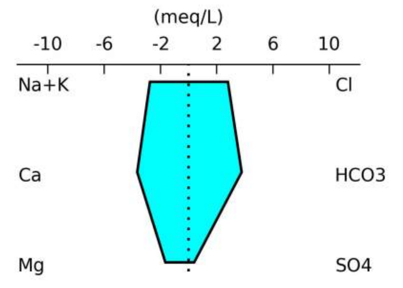

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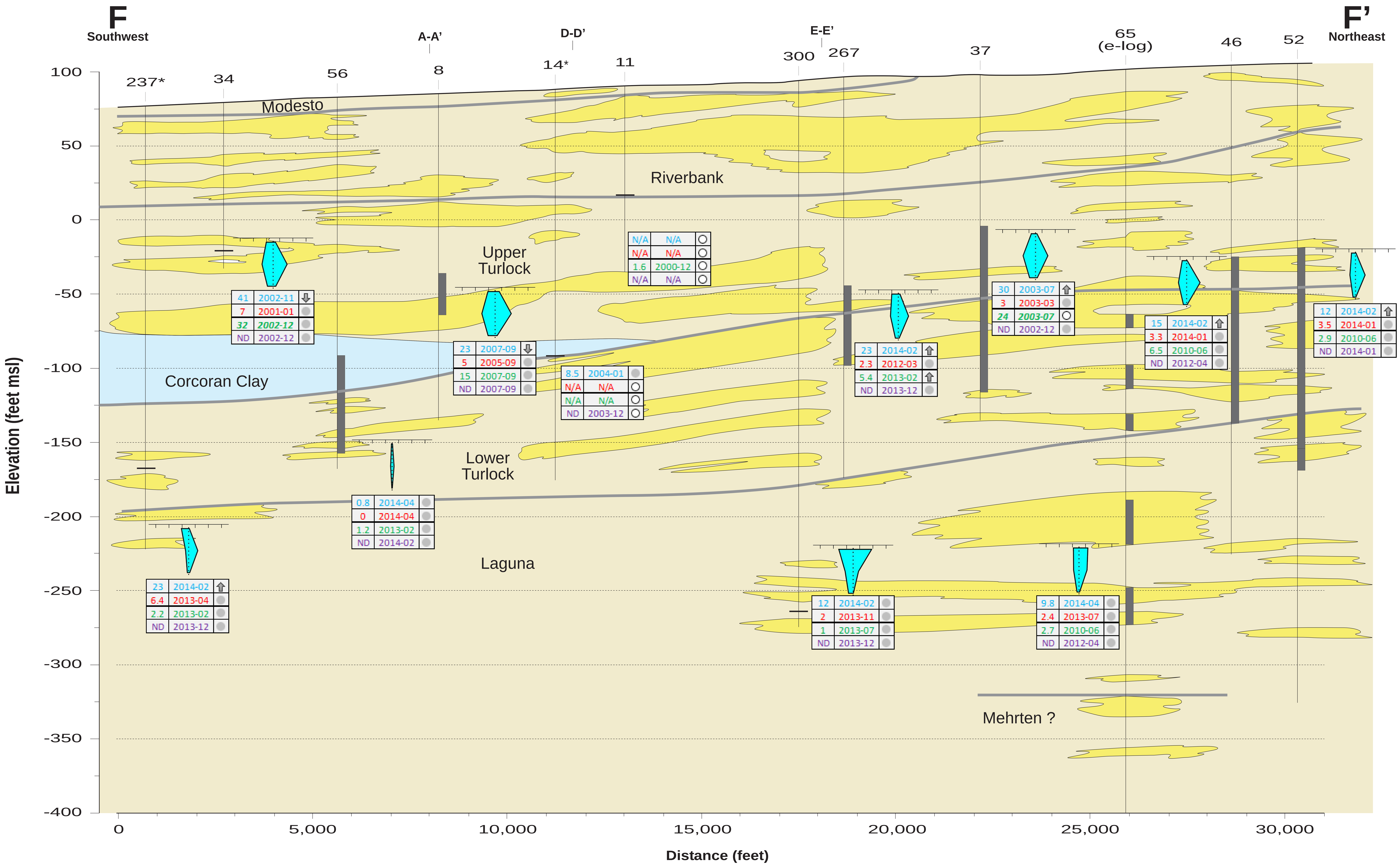
Figure 35
Cross Section E - E'
Water Quality



RMC water and environment

Notes: 1) Base of casing indicated by "—" for some wells without screened intervals.
2) * Well 14: Driller's Report not available. Lithology inferred from adjacent wells.
Well 237: Lithology on Driller's Report only below depth of 233 feet.

Analytes (bold and italicized when above respective MCL)	Date of Latest Reported Sample	Mann-Kendall Trend Result
Nitrate (mg/L)		⇧ increasing
Arsenic (µg/L)		● no trend
Uranium (pCi/L)		○ less than 4 samples
Dibromochloropropane (µg/L)		⇩ decreasing

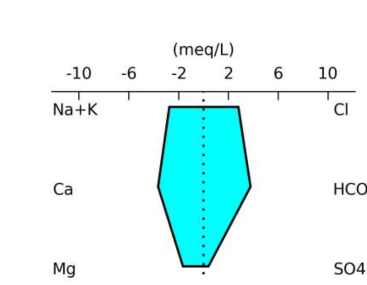


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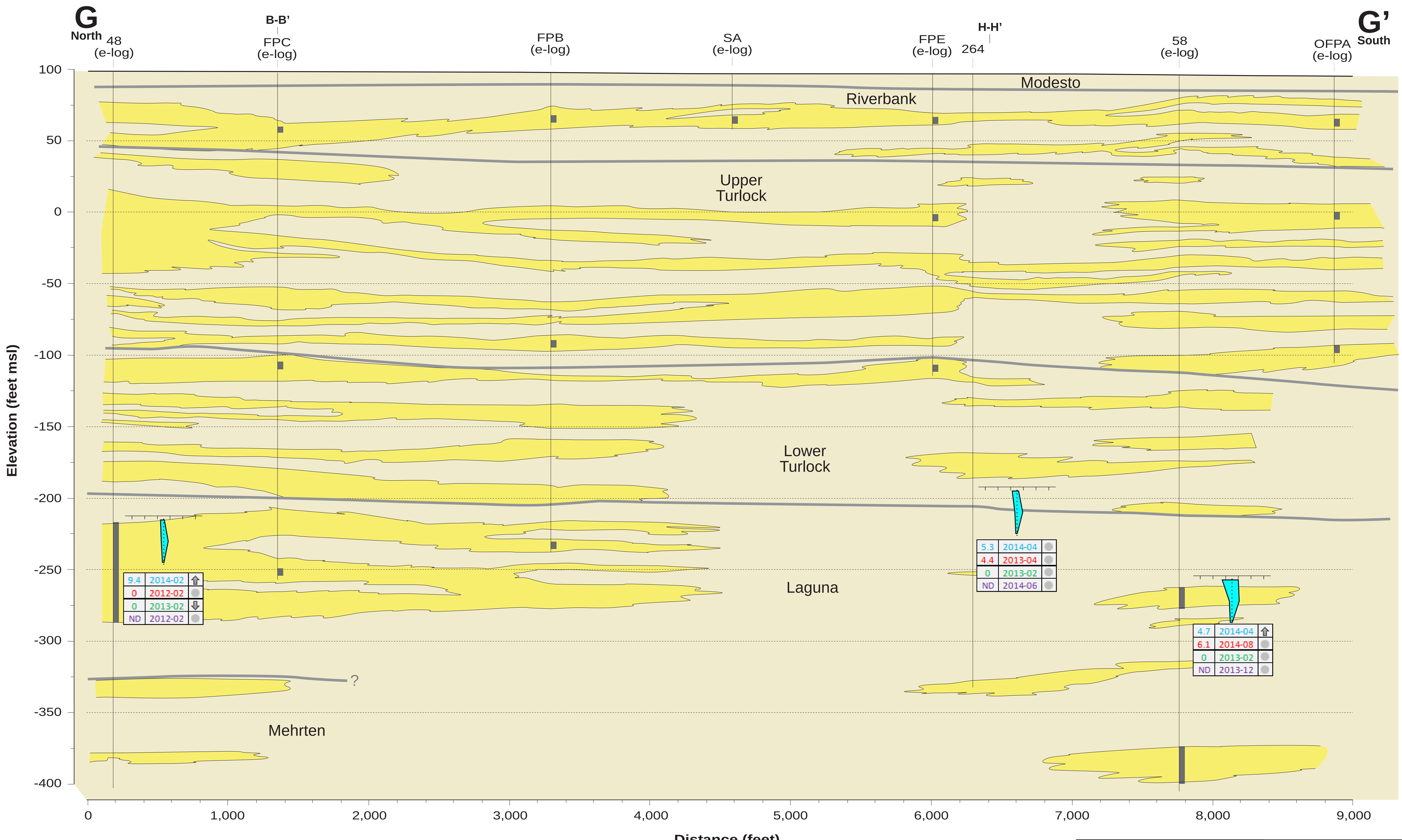
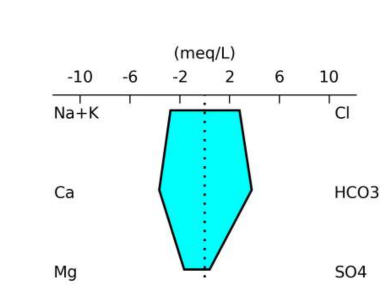
Figure 36
Cross Section F - F'
Water Quality



Note: Base of casing indicated by "—— " for some wells without screened intervals.

Analytes (bold and italicized when above respective MCL)	Date of Latest Reported Sample	Mann-Kendall Trend Result	
Nitrate (mg/L)		⇧	increasing
Arsenic (µg/L)		●	no trend
Uranium (pCi/L)		○	less than 4 samples
Dibromochloropropane (µg/L)		⇩	decreasing



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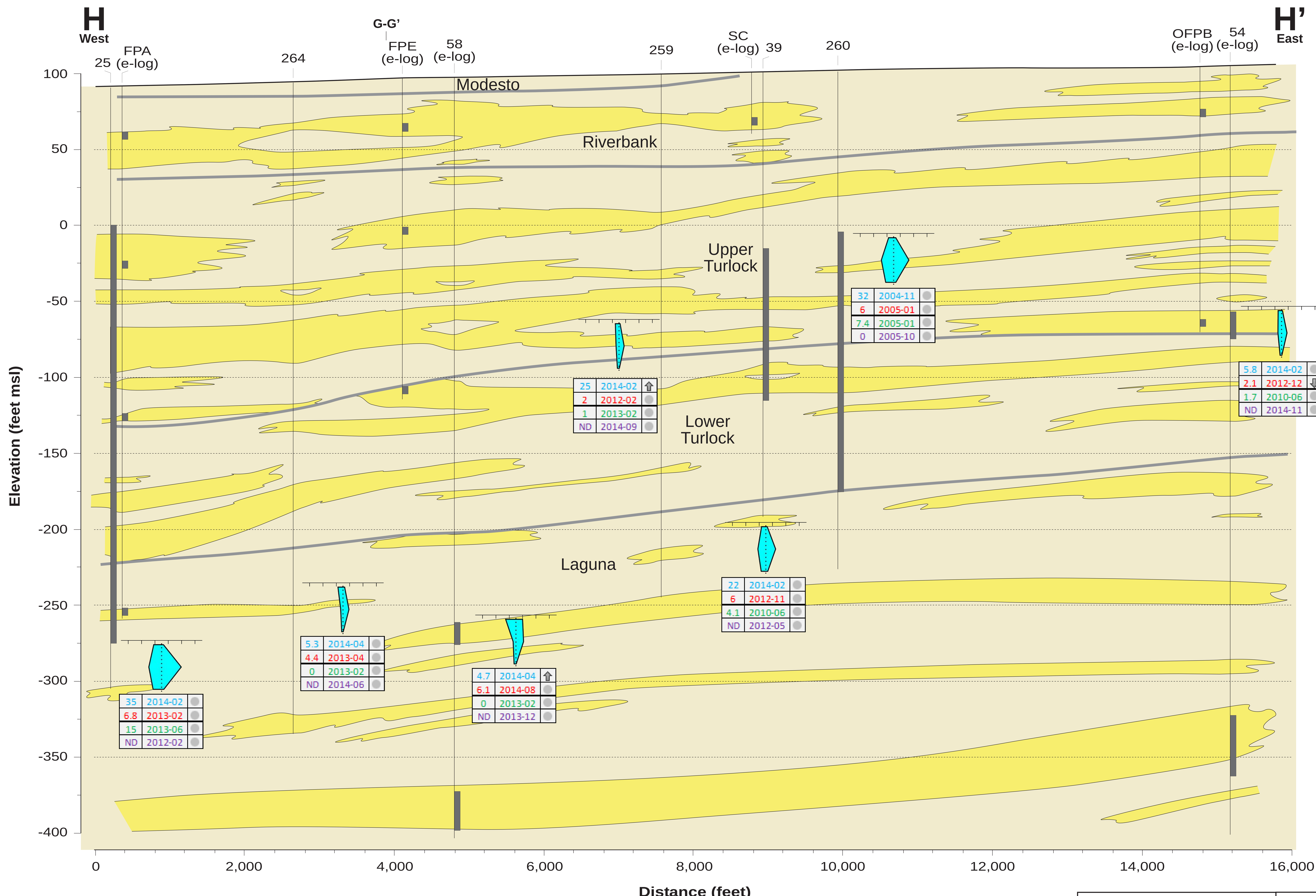
RMC water and environment

Figure 37
Cross Section G - G'
Water Quality



Note: Base of casing indicated by "——" for some wells without screened intervals.

Analytes (bold and italicized when above respective MCL)	Date of Latest Reported Sample	Mann-Kendall Trend Result
Nitrate (mg/L)		⇧ increasing
Arsenic (µg/L)		● no trend
Uranium (pCi/L)		○ less than 4 samples
Dibromochloropropane (µg/L)		⇩ decreasing

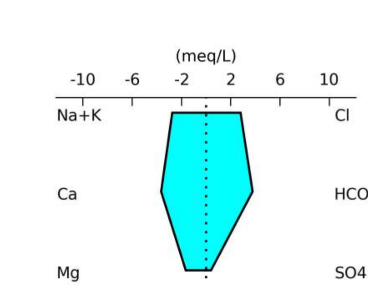


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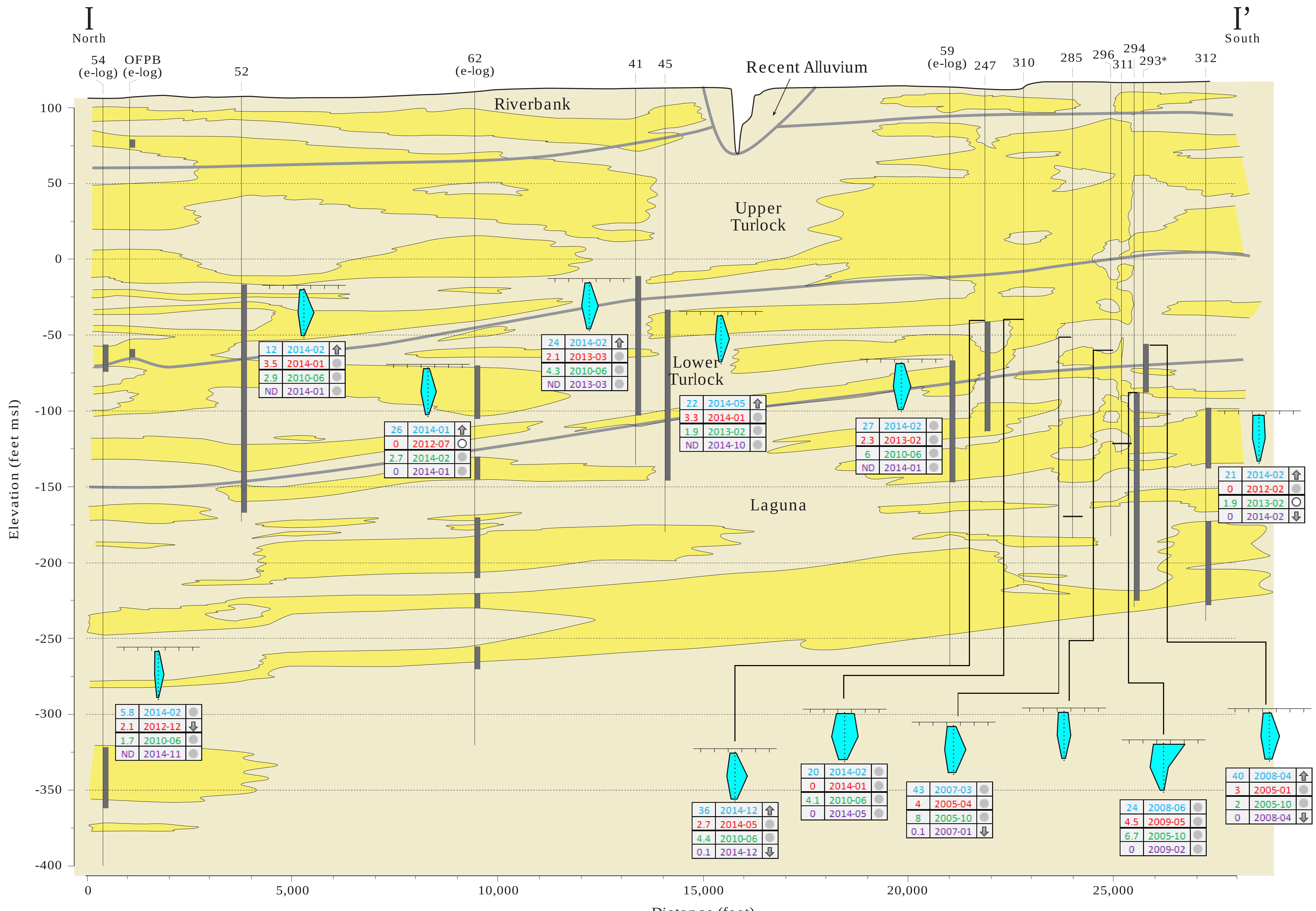
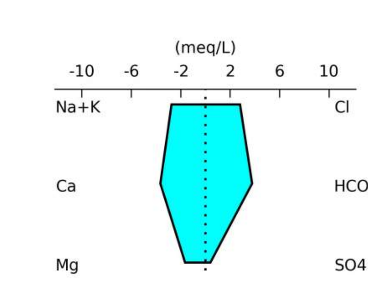
Figure 38
Cross Section H - H'
Water Quality



Notes: 1) Base of casing indicated by " —— " for some wells without screened intervals.
2) * Well 293: Driller's Report not available. Lithology inferred from adjacent wells.

Analytes (bold and italicized when above respective MCL)	Date of Latest Reported Sample	Mann-Kendall Trend Result
Nitrate (mg/L)		⇧ increasing
Arsenic (µg/L)		● no trend
Uranium (pCi/L)		○ less than 4 samples
Dibromochloropropane (µg/L)		⇩ decreasing



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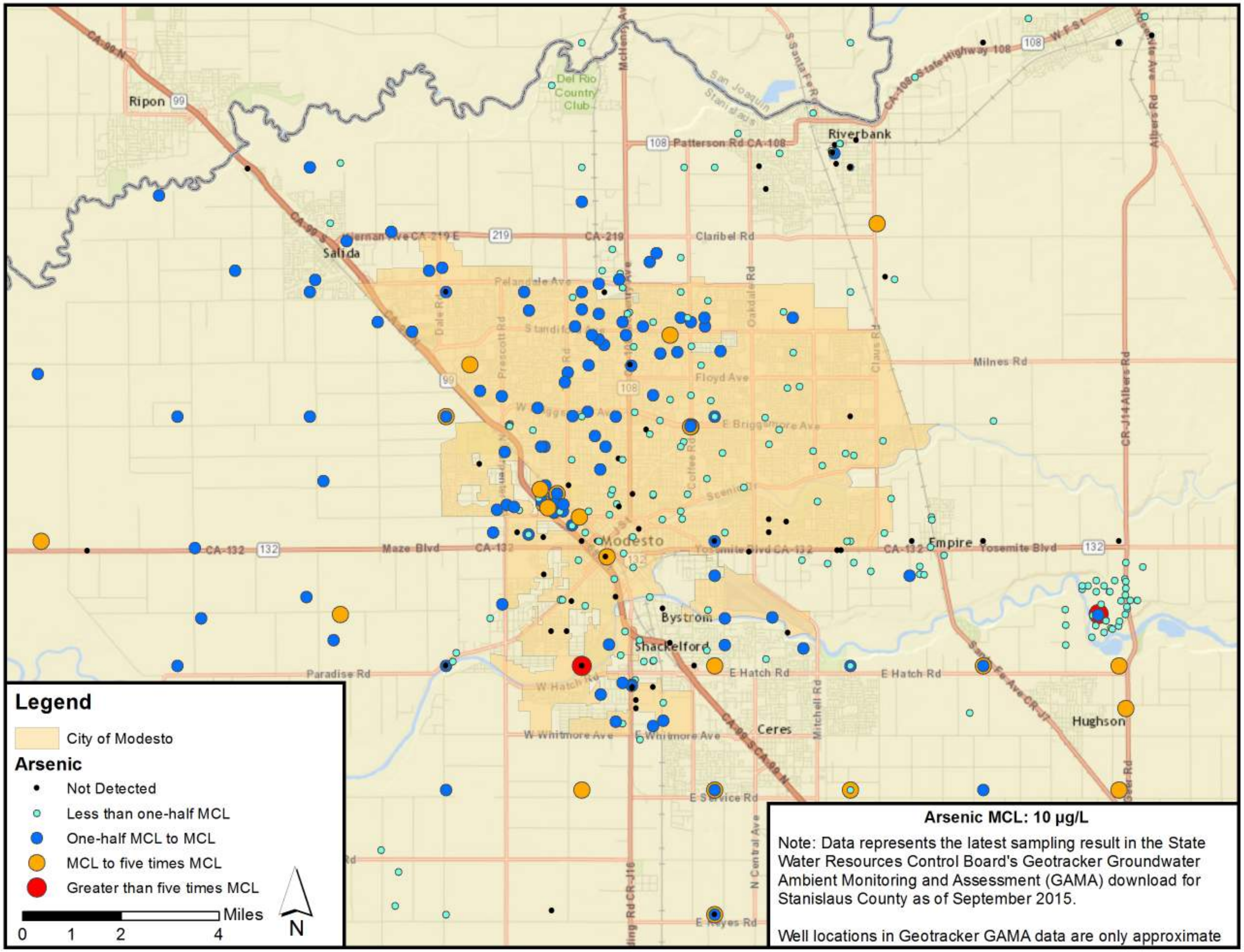
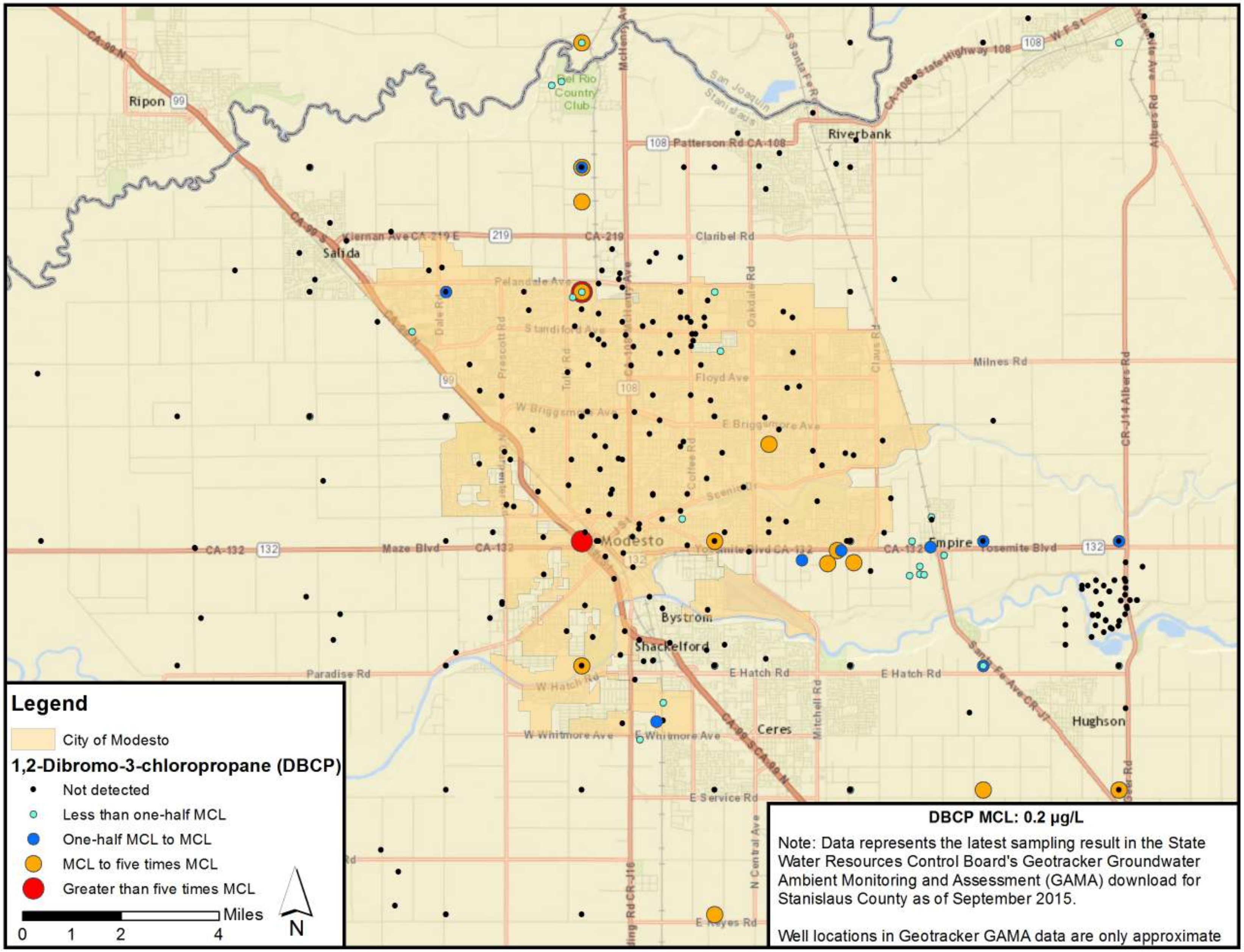
RMC water and environment

Figure 39
Cross Section I - I'
Water Quality



January 2016

Figure 40
Arsenic Concentrations



RMC water and environment

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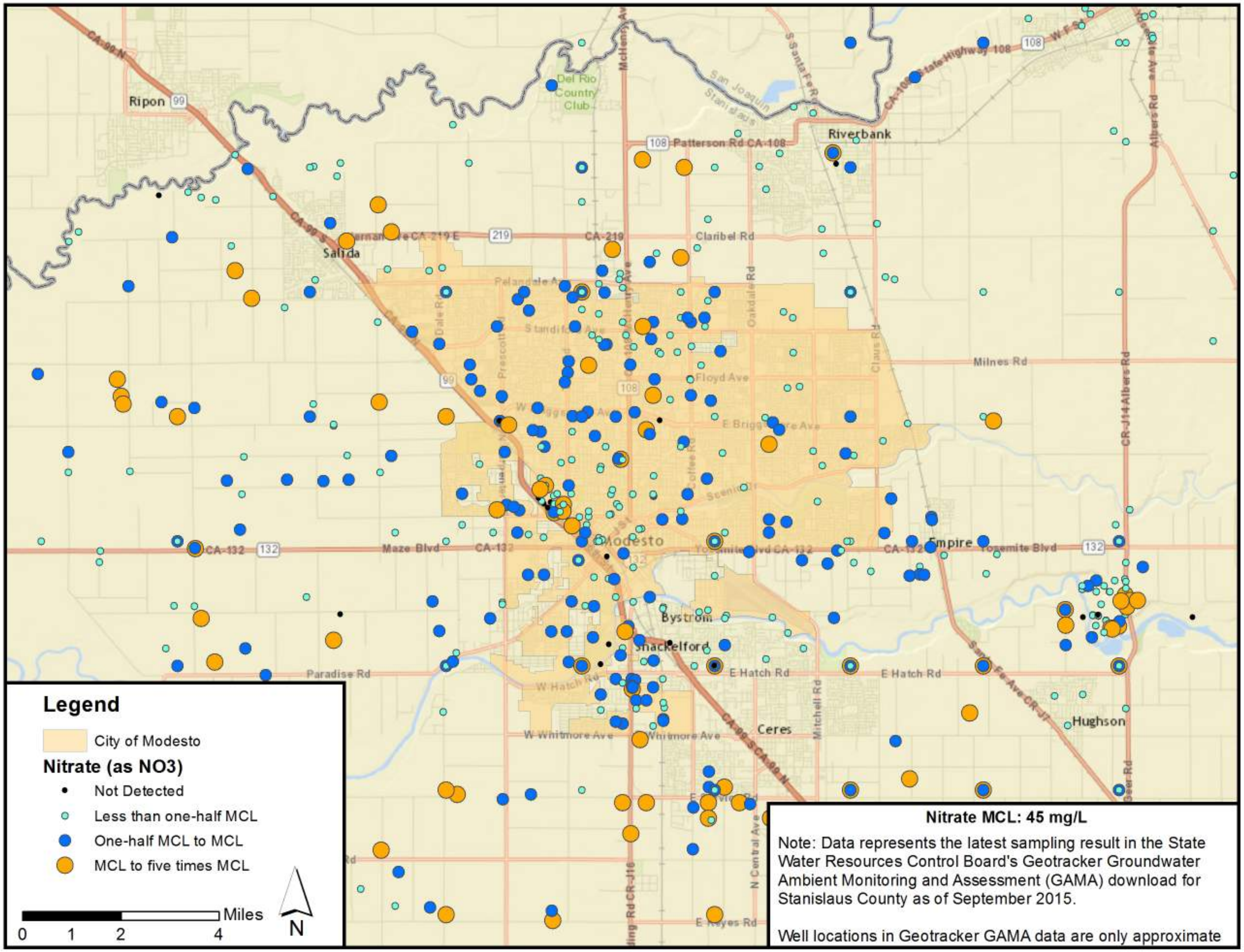
Figure 41
DBCP Concentrations



Legend

City of Modesto

Nitrate (as NO3)

- Not Detected
- Less than one-half MCL
- One-half MCL to MCL
- MCL to five times MCL

0 1 2 4 Miles

N

Nitrate MCL: 45 mg/L

Note: Data represents the latest sampling result in the State Water Resources Control Board's Geotracker Groundwater Ambient Monitoring and Assessment (GAMA) download for Stanislaus County as of September 2015.

Well locations in Geotracker GAMA data are only approximate

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Figure 42
Nitrate Concentrations

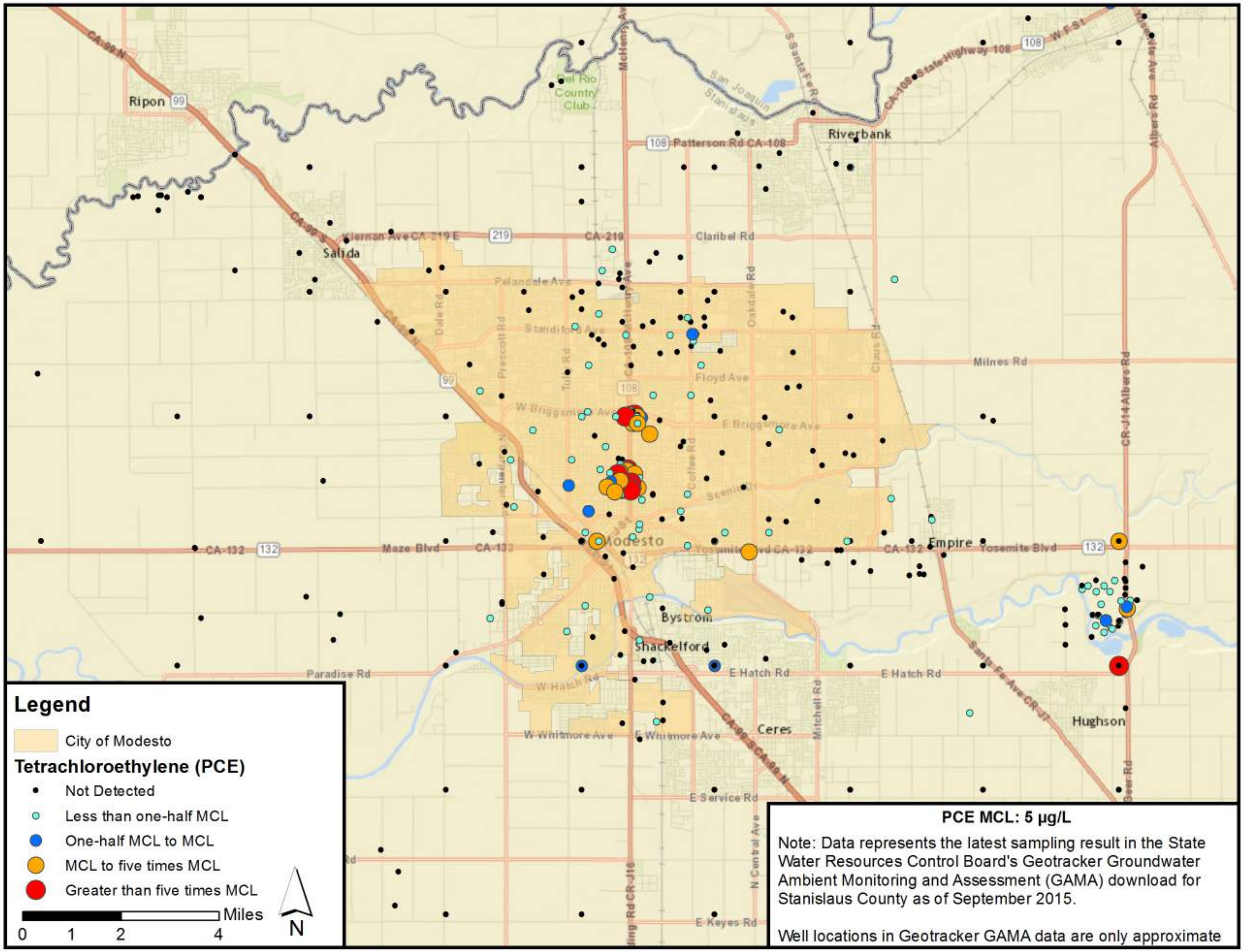

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Figure 43
PCE Concentrations

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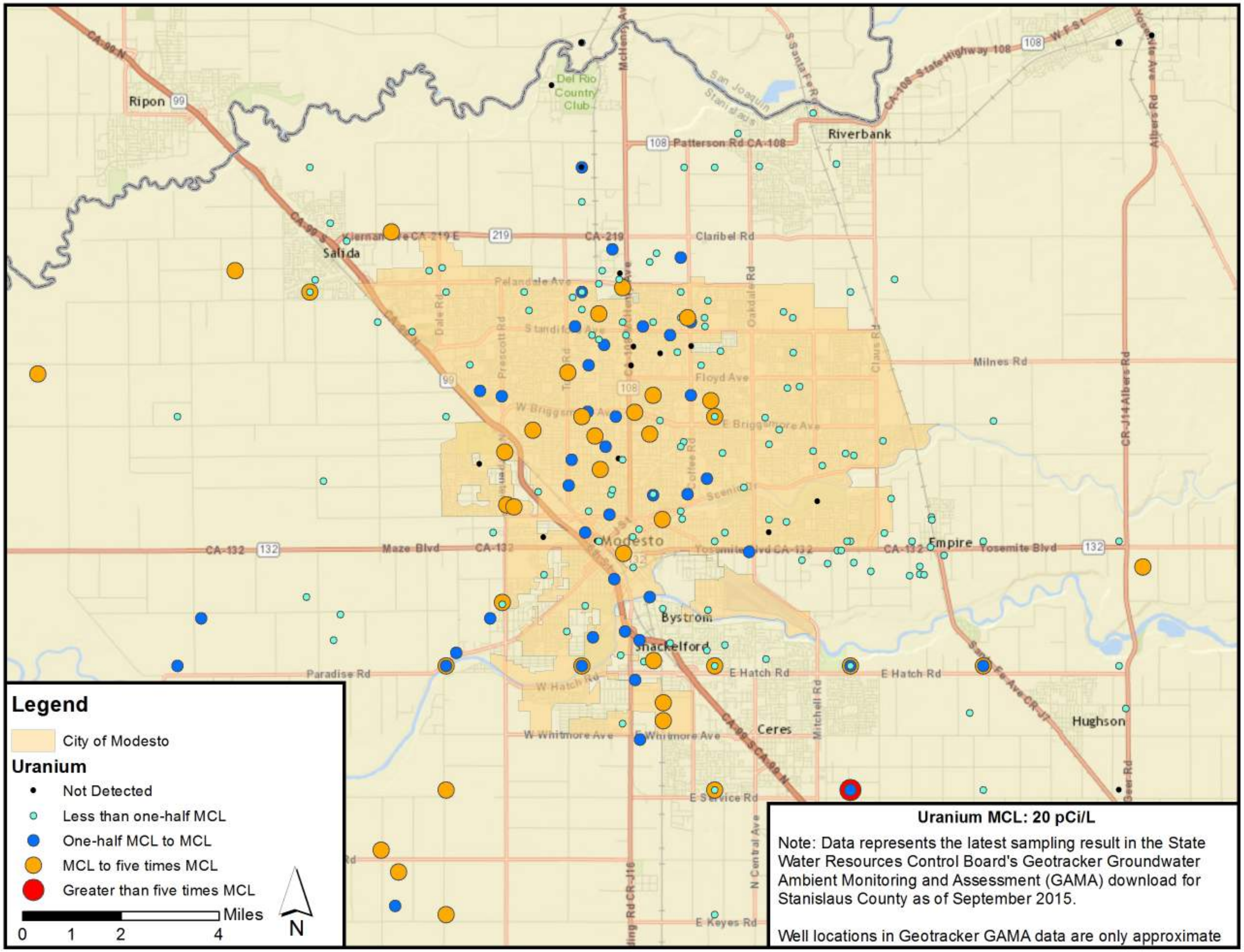

RMC water and environment

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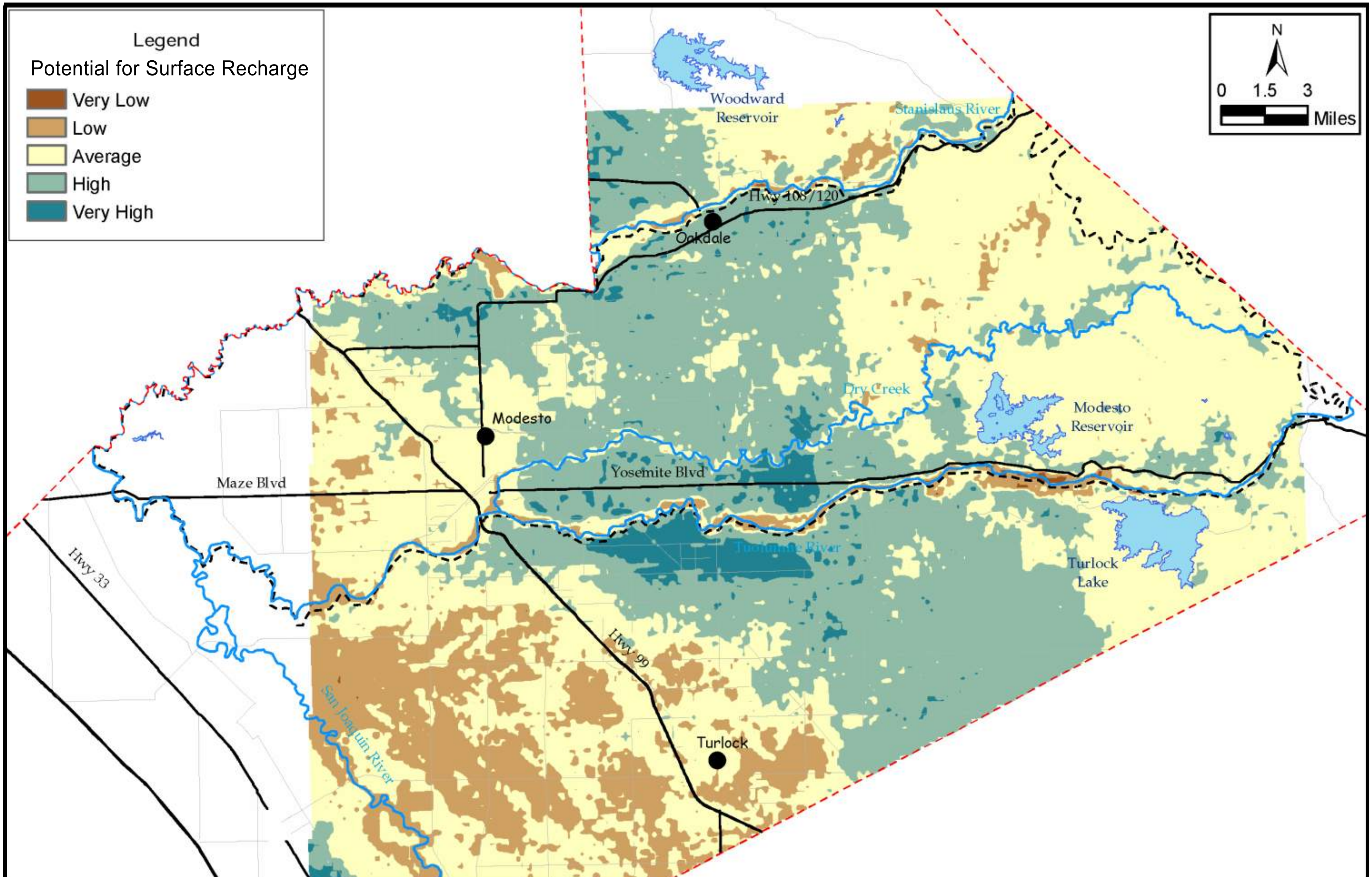
Figure 44
Uranium Concentrations



Adapted from: WRIME, 2007.

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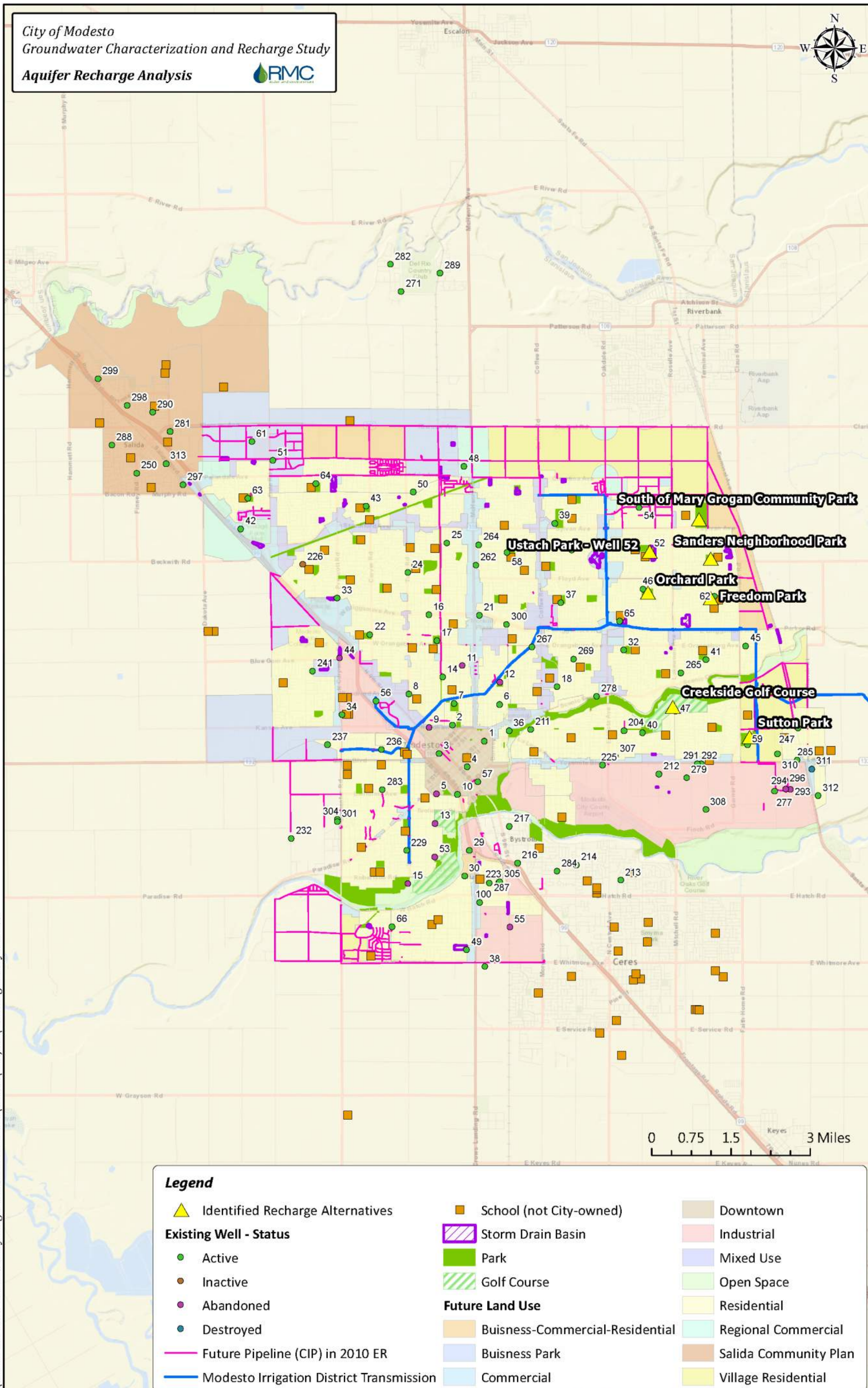
Figure 45
Potential for Surface Recharge



R:\0646-001 Todd-Modesto Hydrogeo Characterization\G. GIS\Project\RechargeAnalysis.mxd

Sources: Document Data Sources Here (i.e. ESRI Basemaps)

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Figue 46
City of Modesto Water Infrastructure, Land Use, and Recharge Alternative Locations

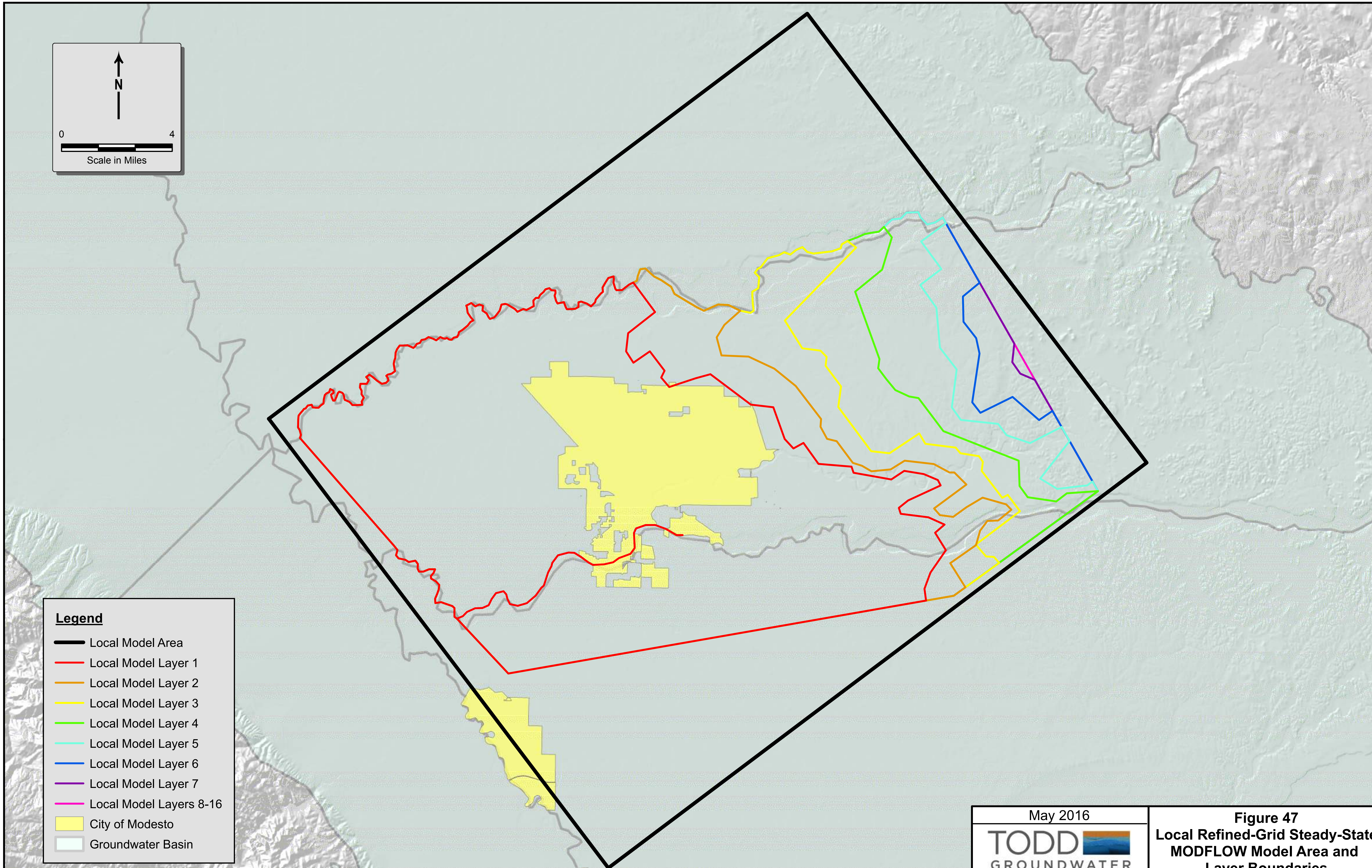

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Figure 47
Local Refined-Grid Steady-State MODFLOW Model Area and Layer Boundaries

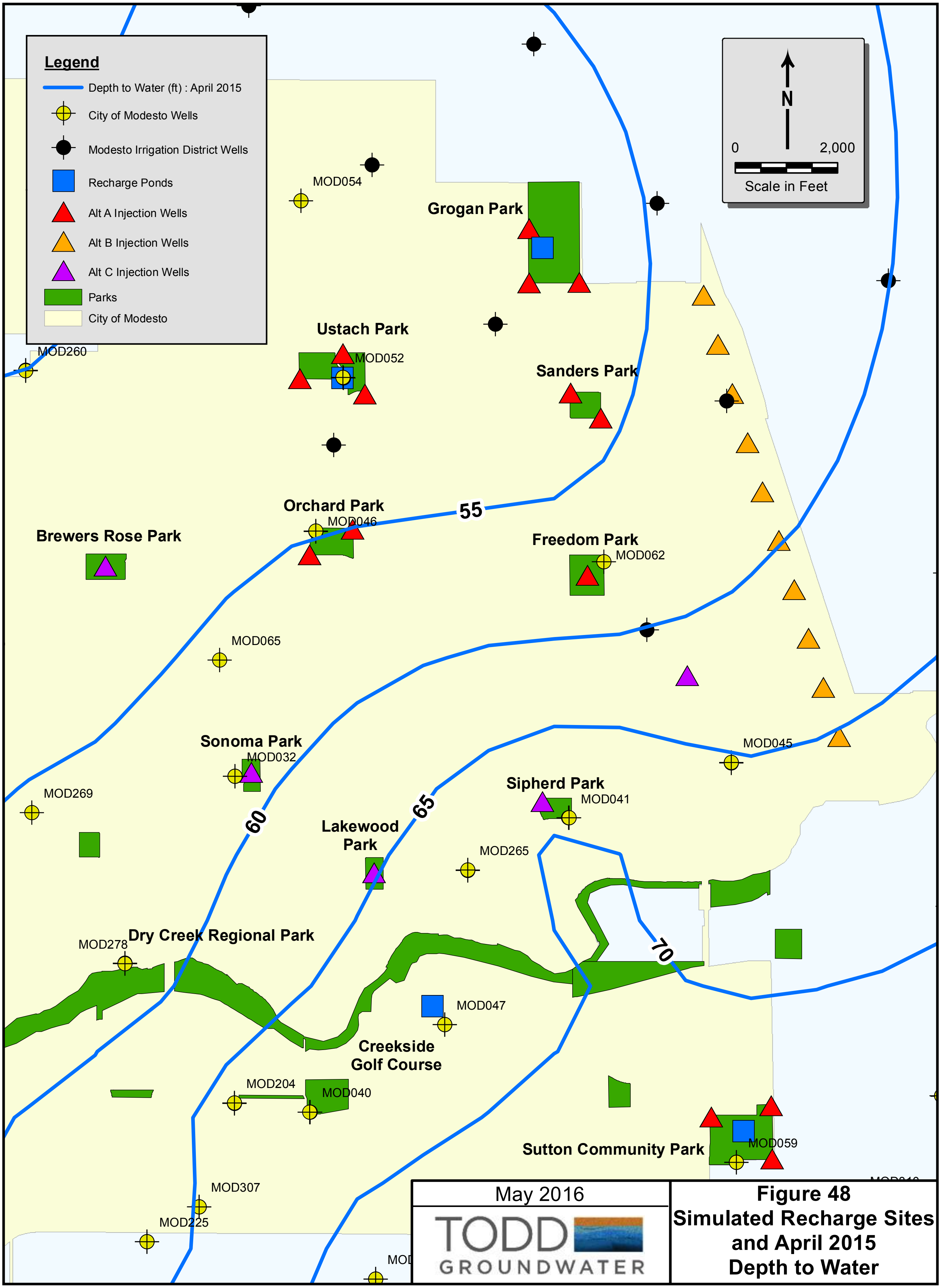
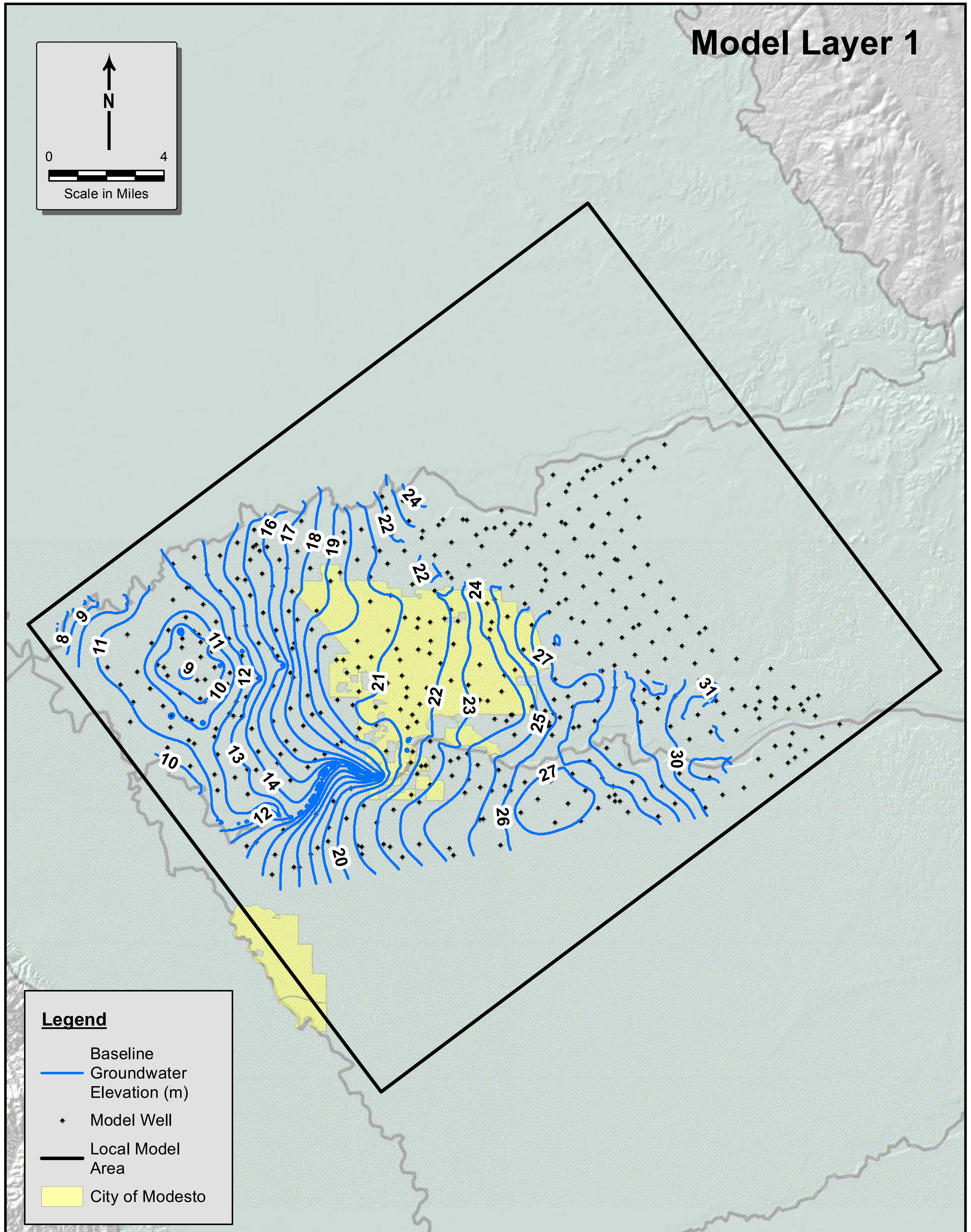


Figure 48
Simulated Recharge Sites and April 2015 Depth to Water



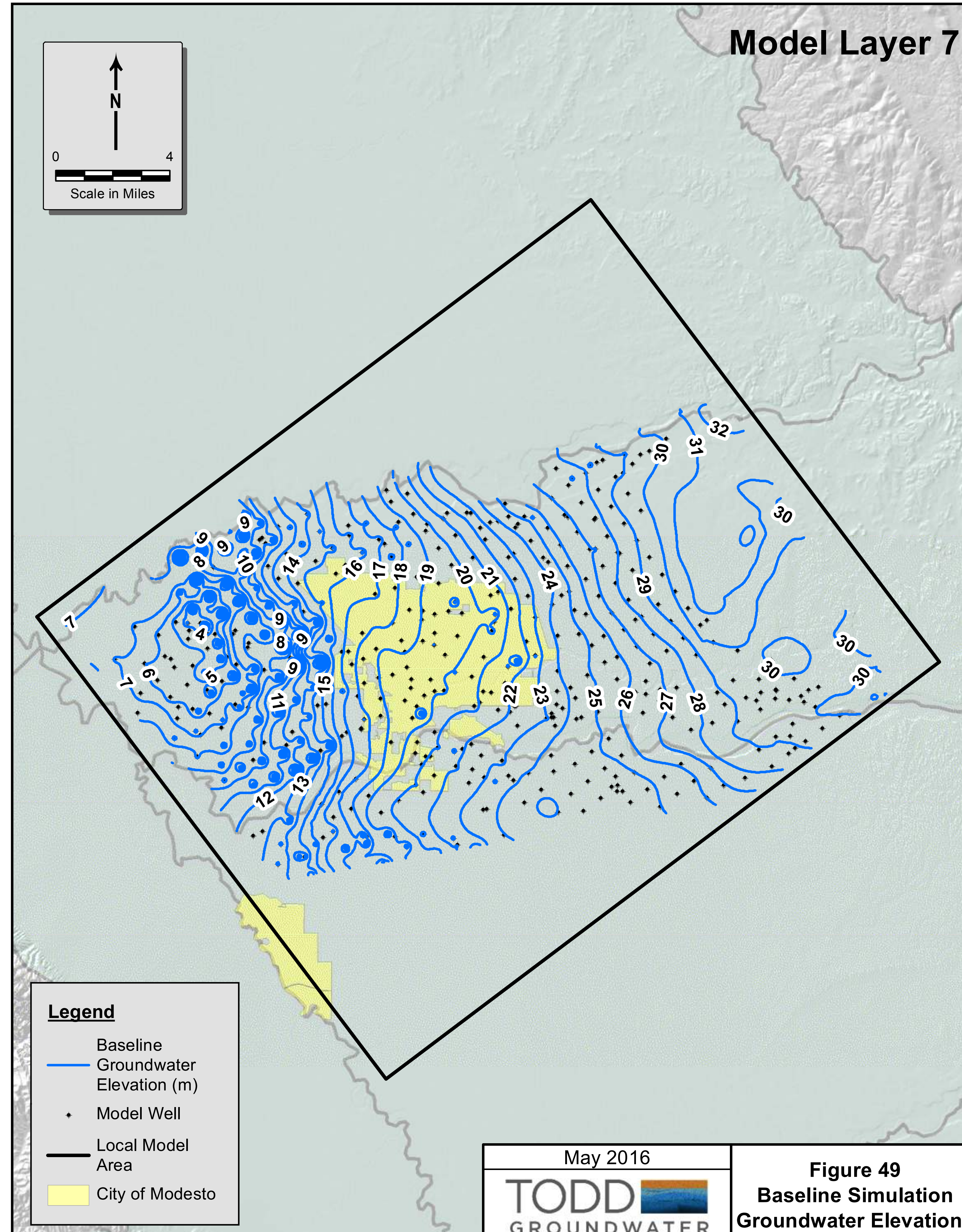


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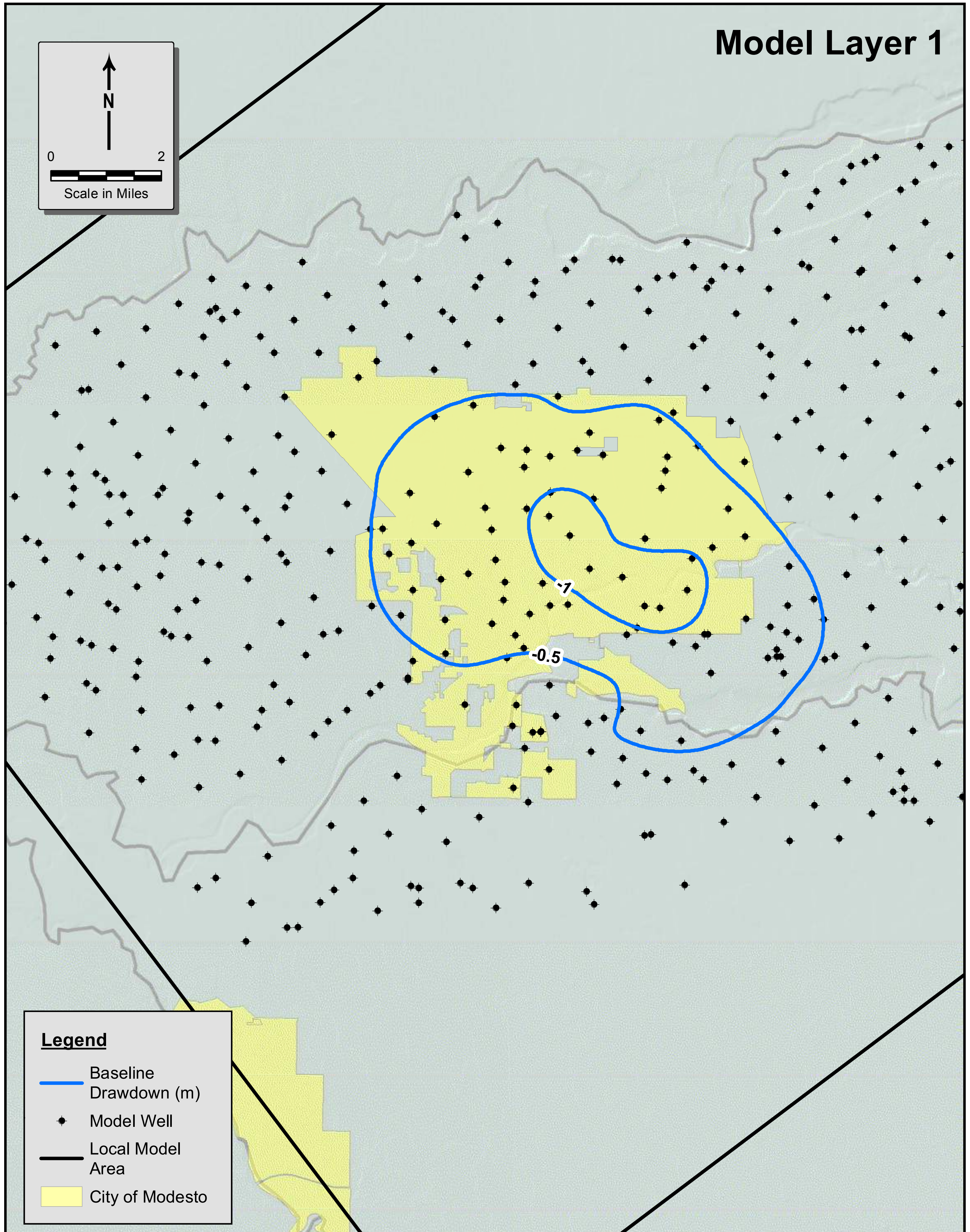
Figure 49
Baseline Simulation Groundwater Elevations



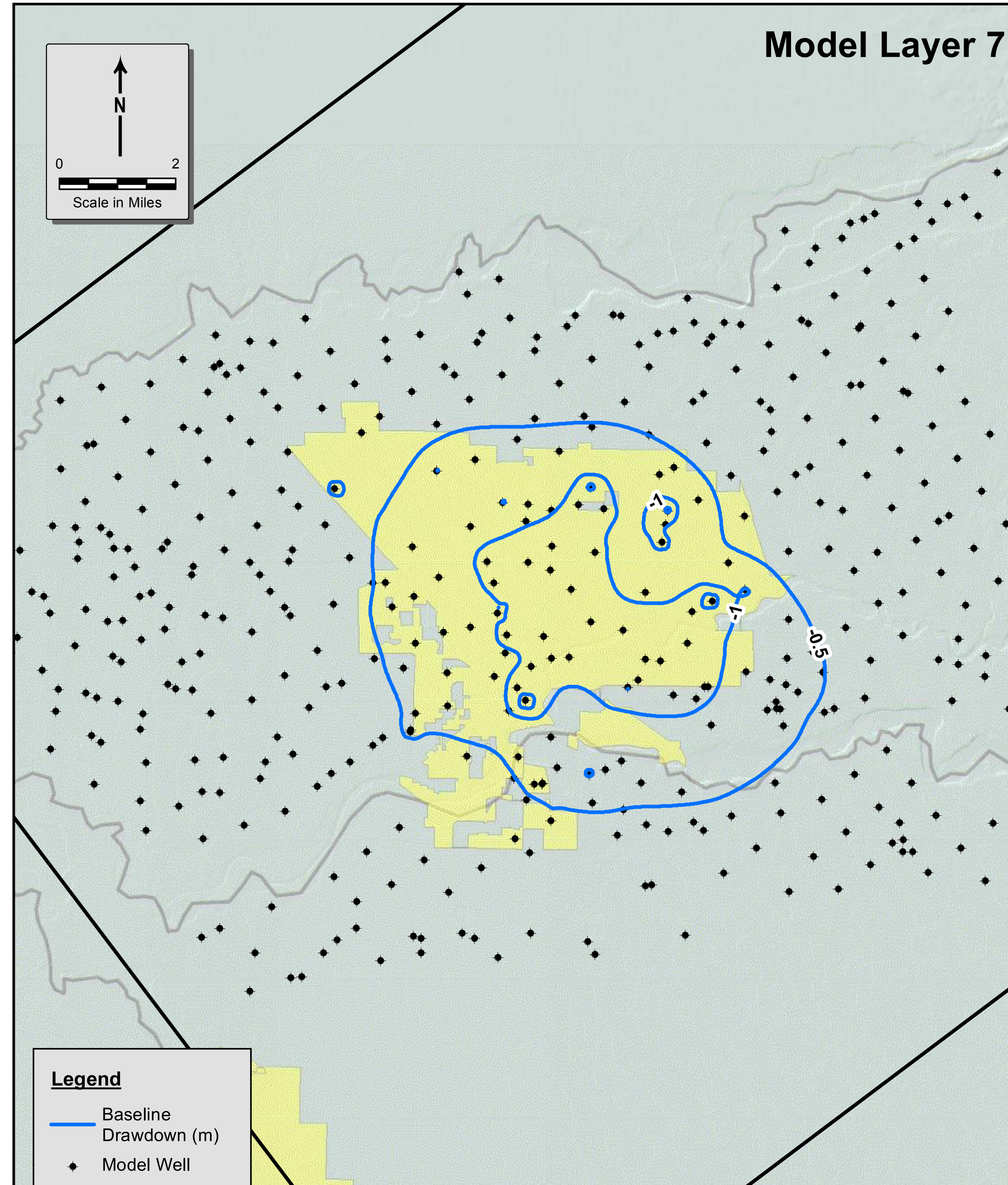


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Figure 50
Baseline Simulation Drawdown

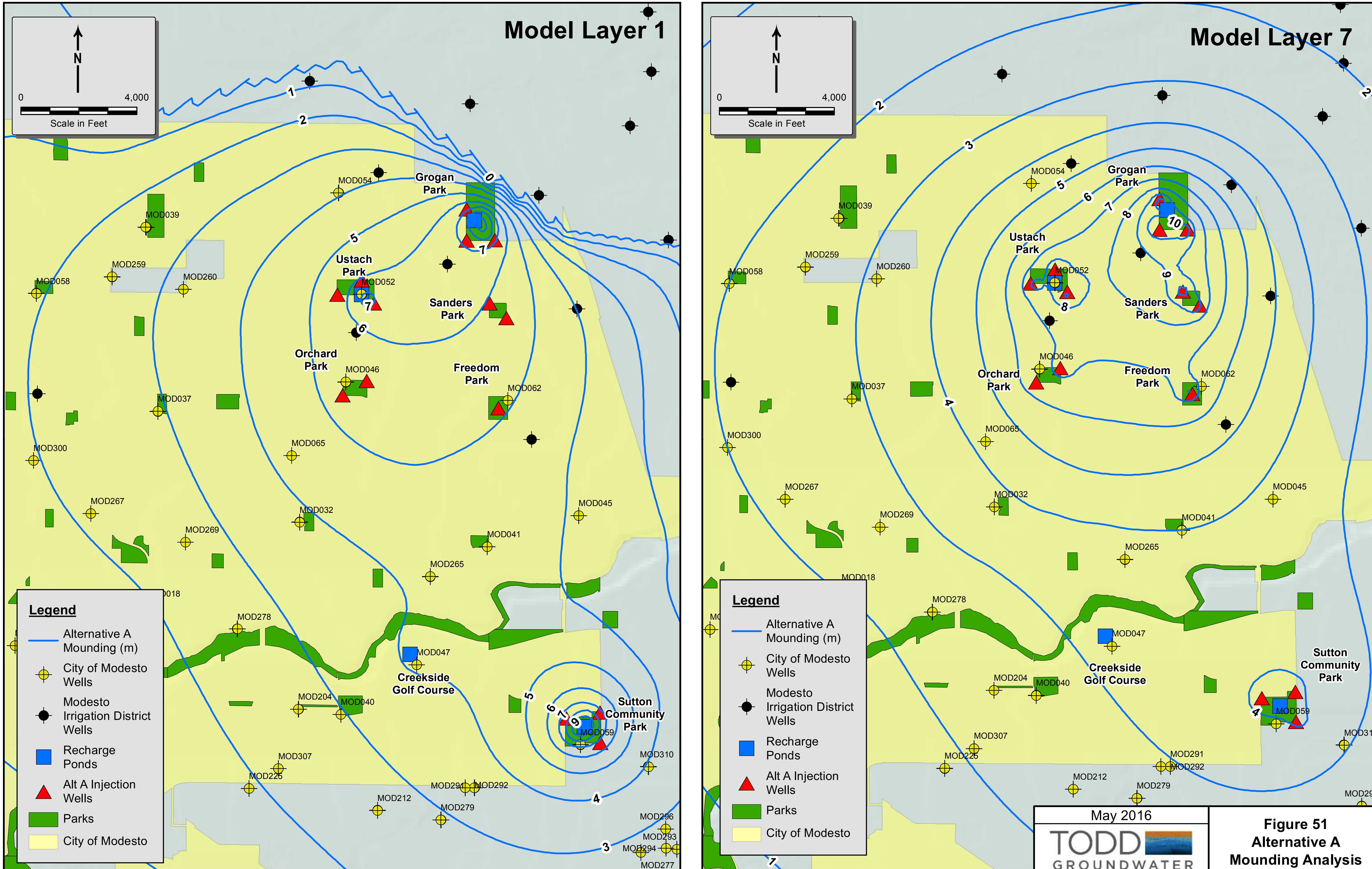

Figure 51
Alternative A
Mounding Analysis

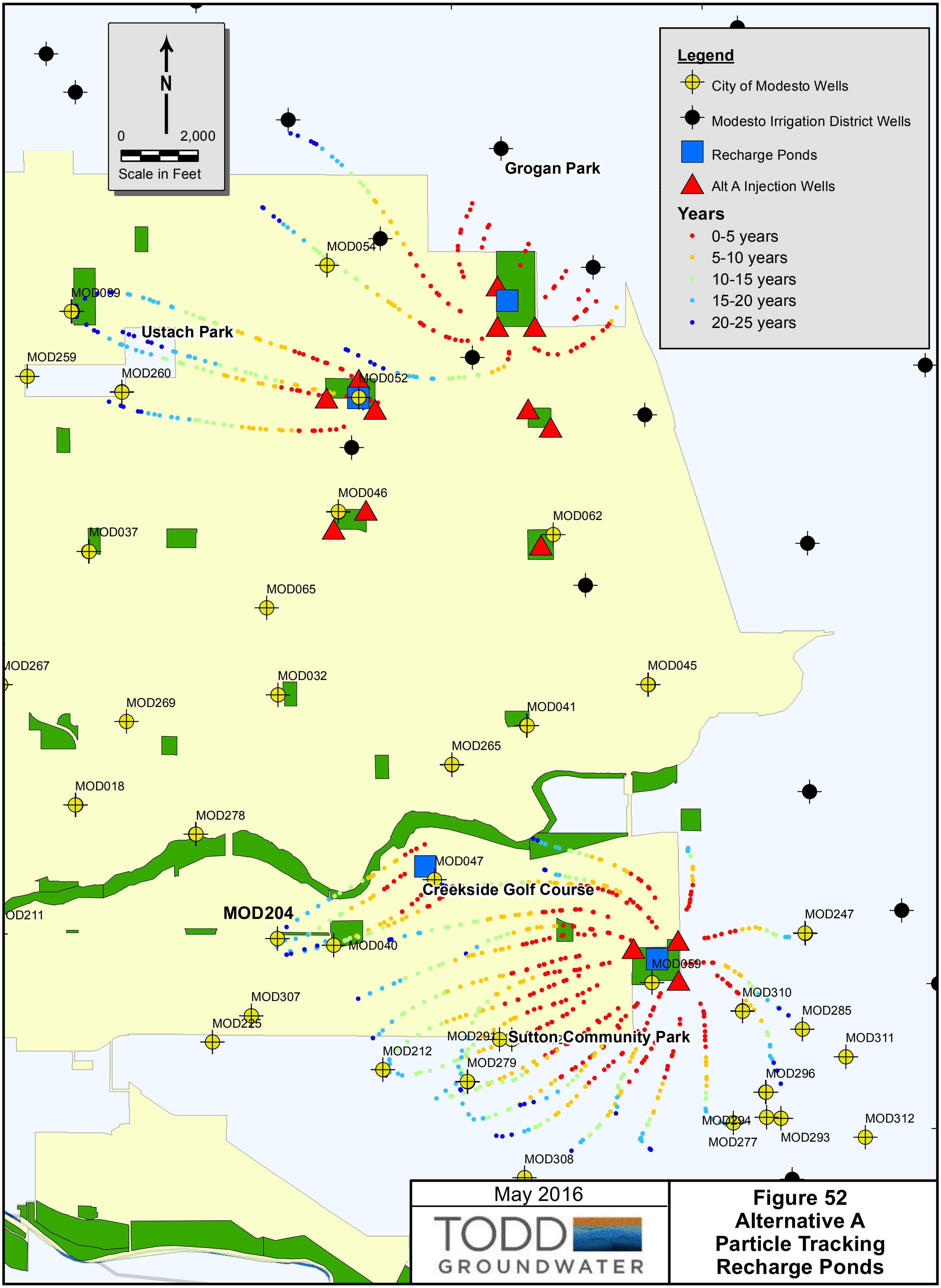

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Figure 52
Alternative A
Particle Tracking
Recharge Ponds

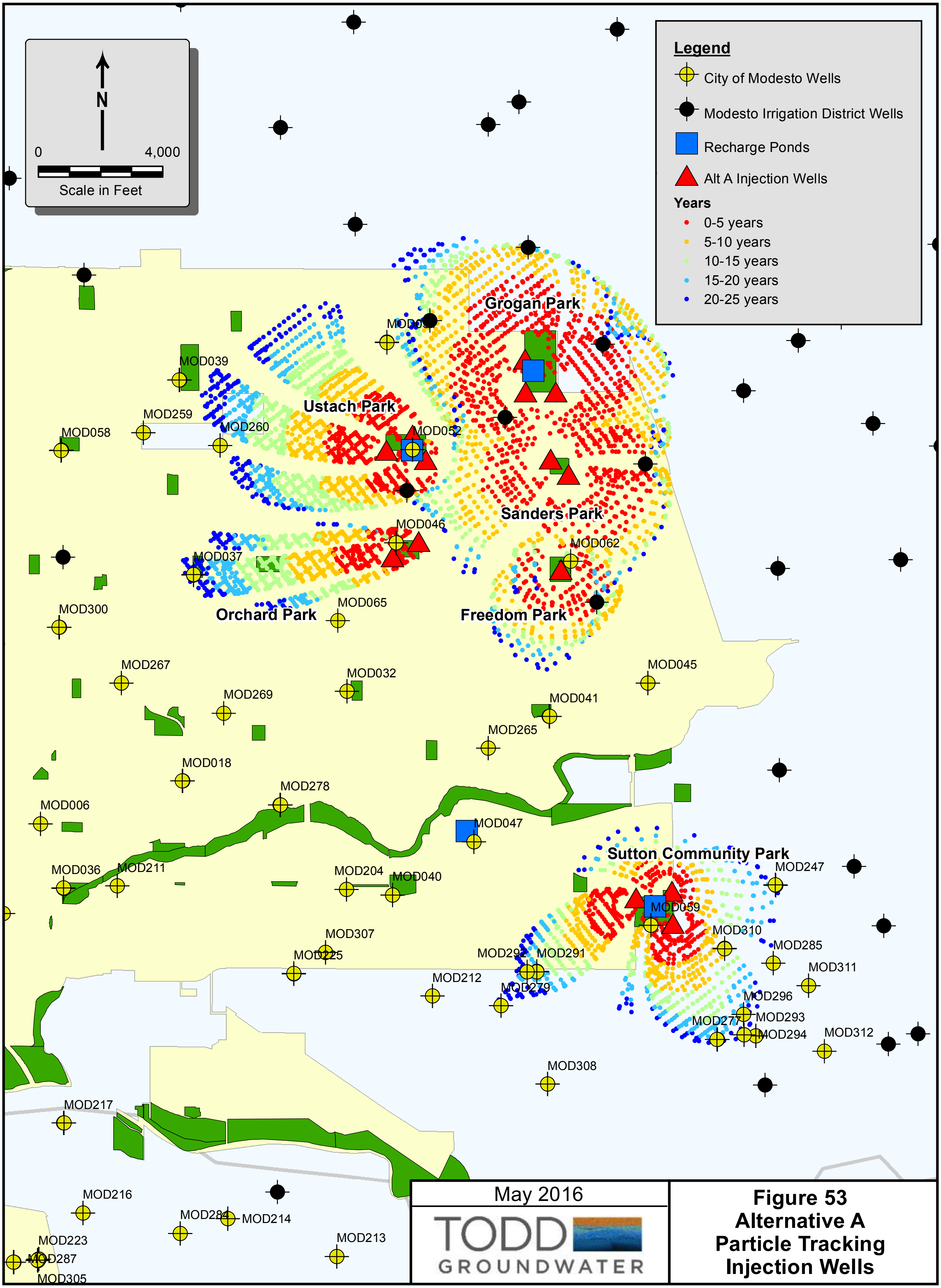

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Figure 53
Alternative A
Particle Tracking
Injection Wells

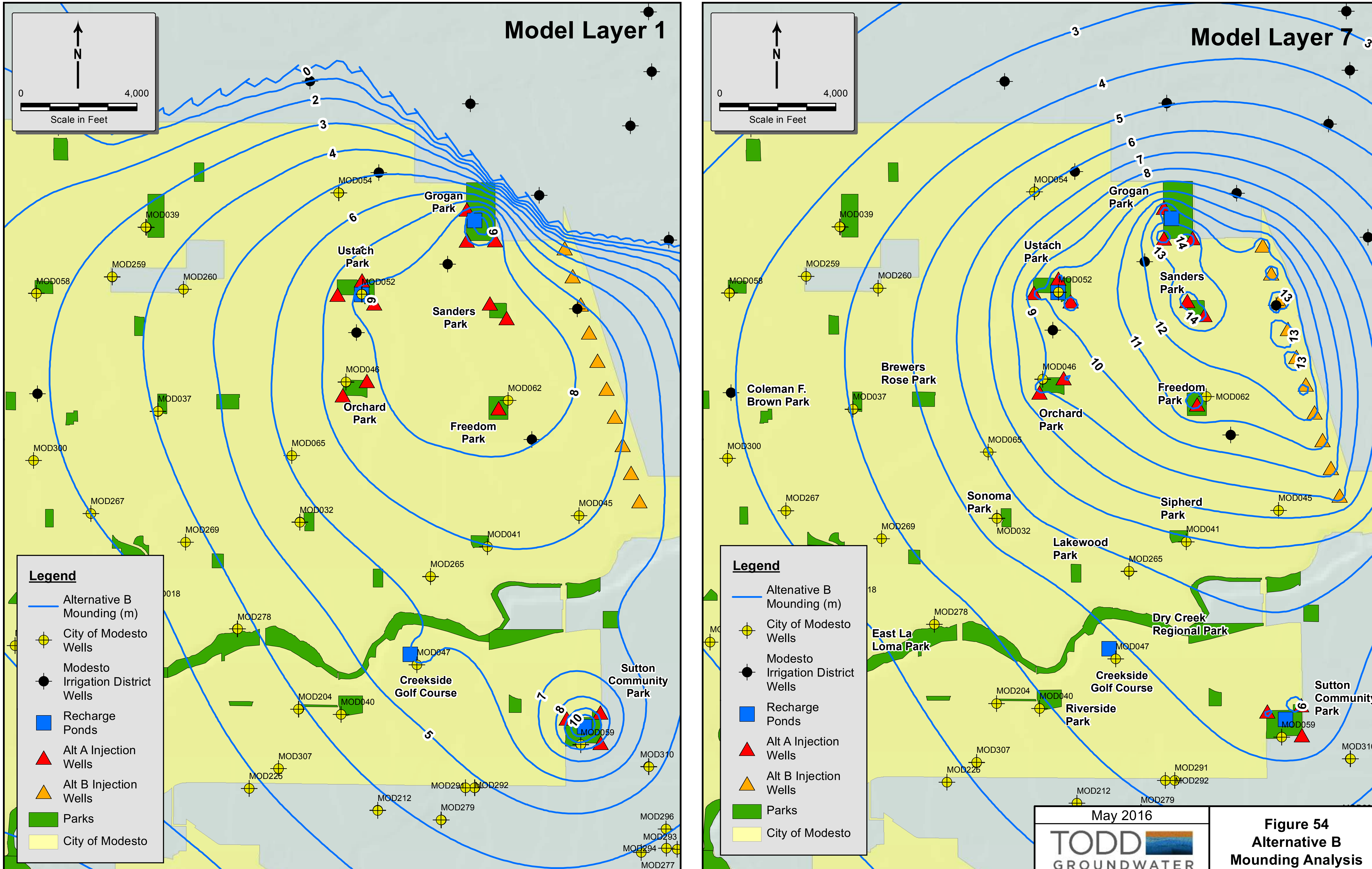

Figure 54
Alternative B
Mounding Analysis

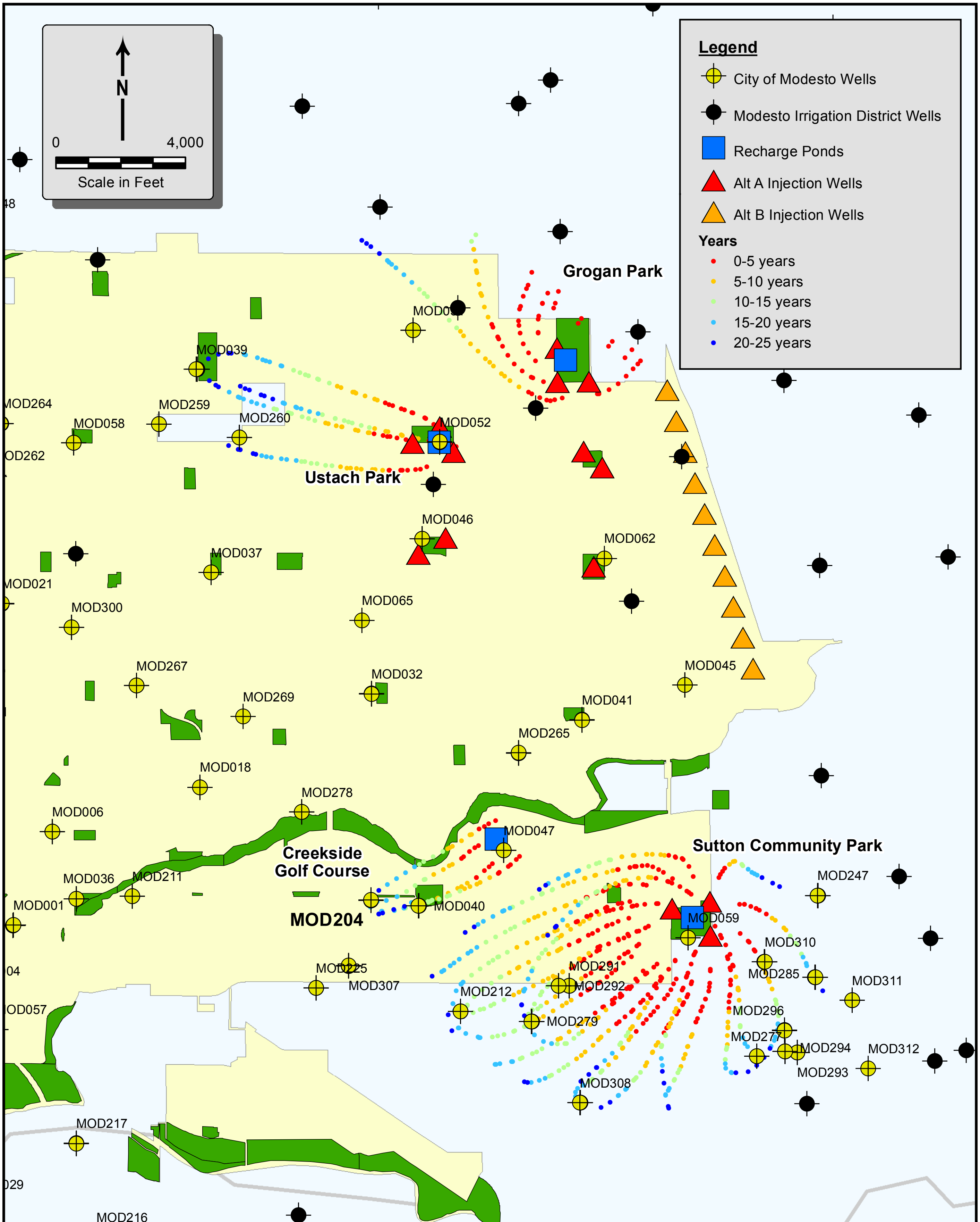

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Figure 55
Alternative B
Particle Tracking
Recharge Ponds

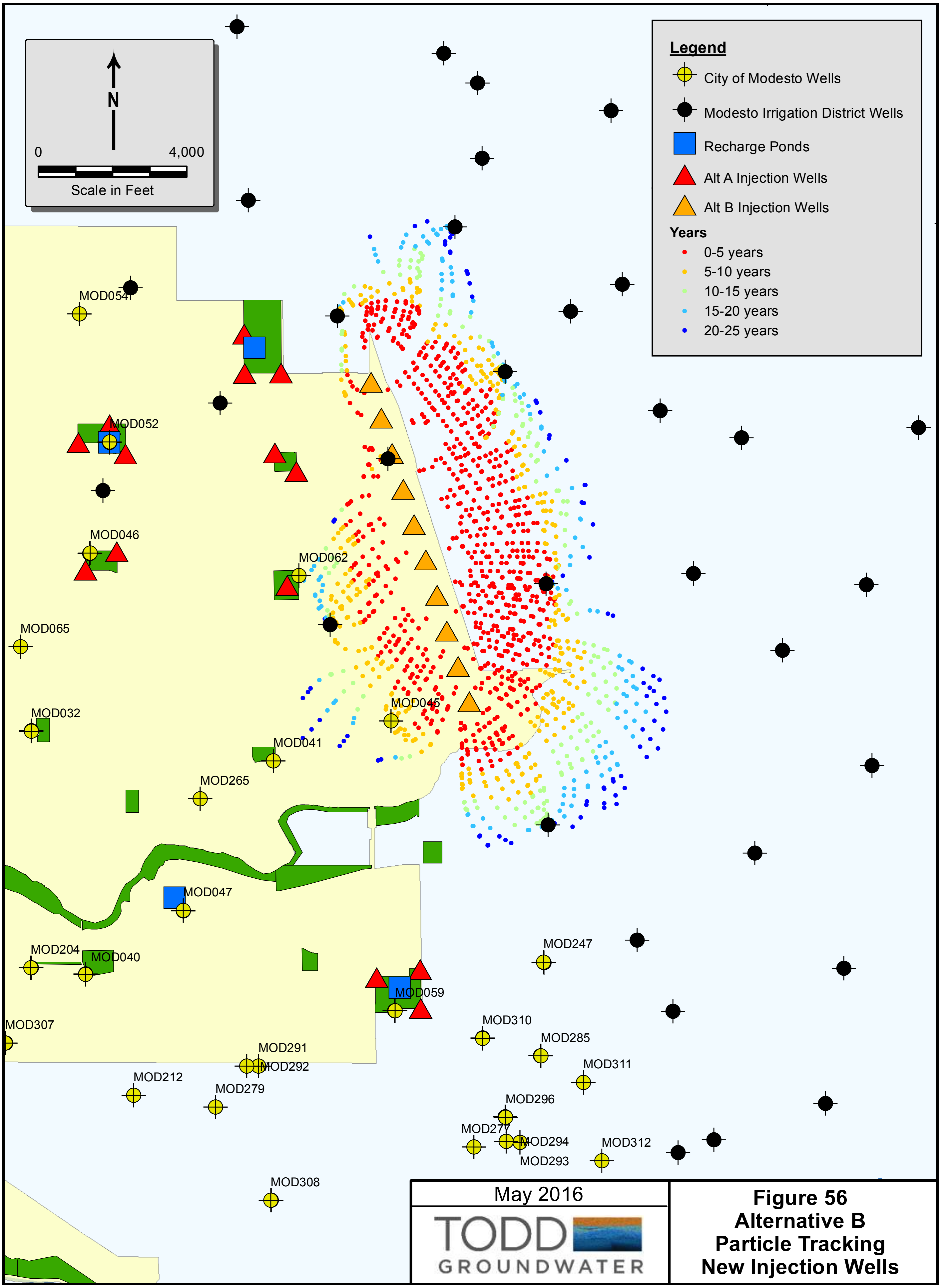

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Figure 56
Alternative B
Particle Tracking
New Injection Wells

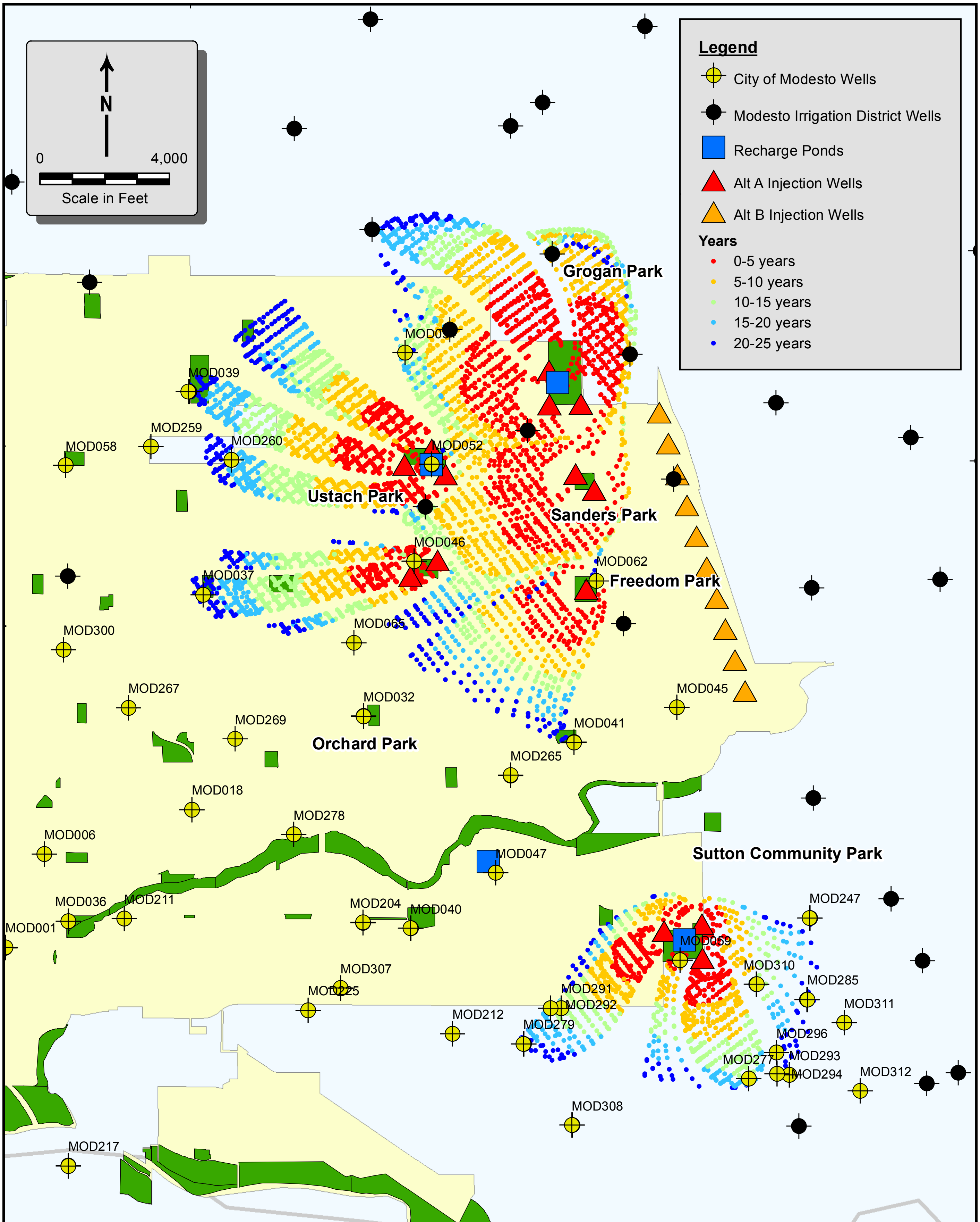

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Figure 57
Alternative B
Particle Tracking
Alt A Injection Wells

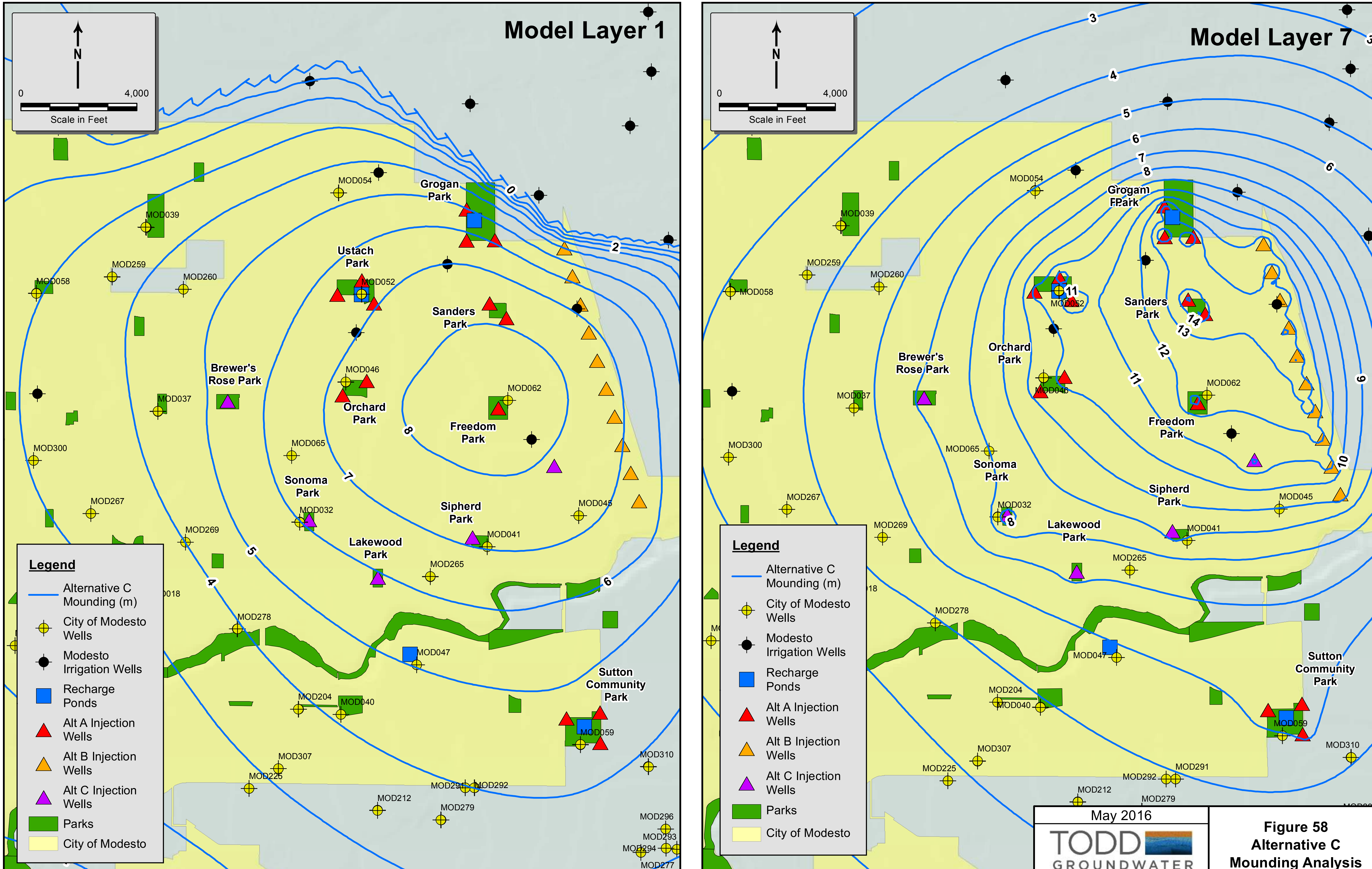

Figure 58
Alternative C
Mounding Analysis

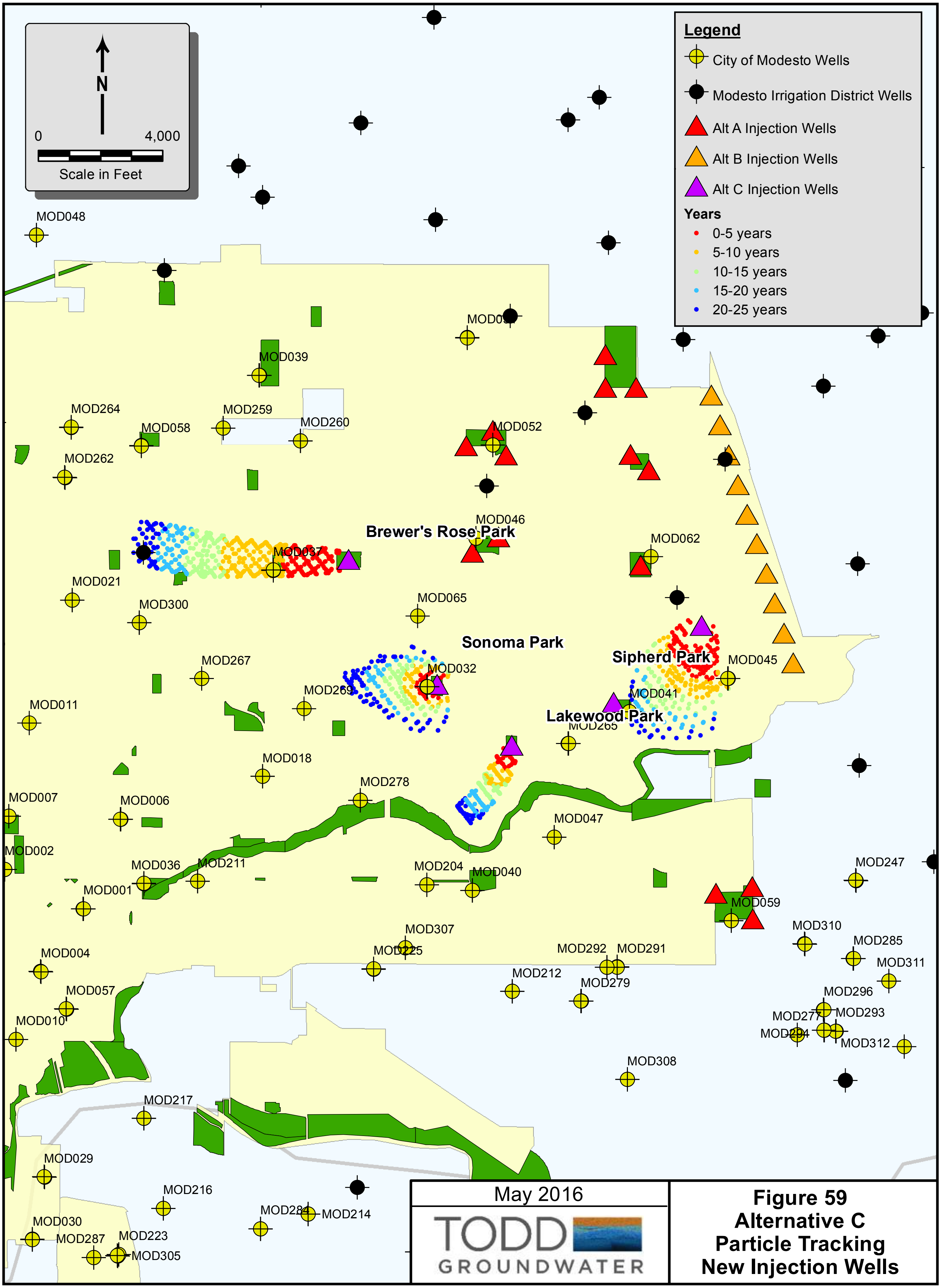

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Figure 59
Alternative C
Particle Tracking
New Injection Wells

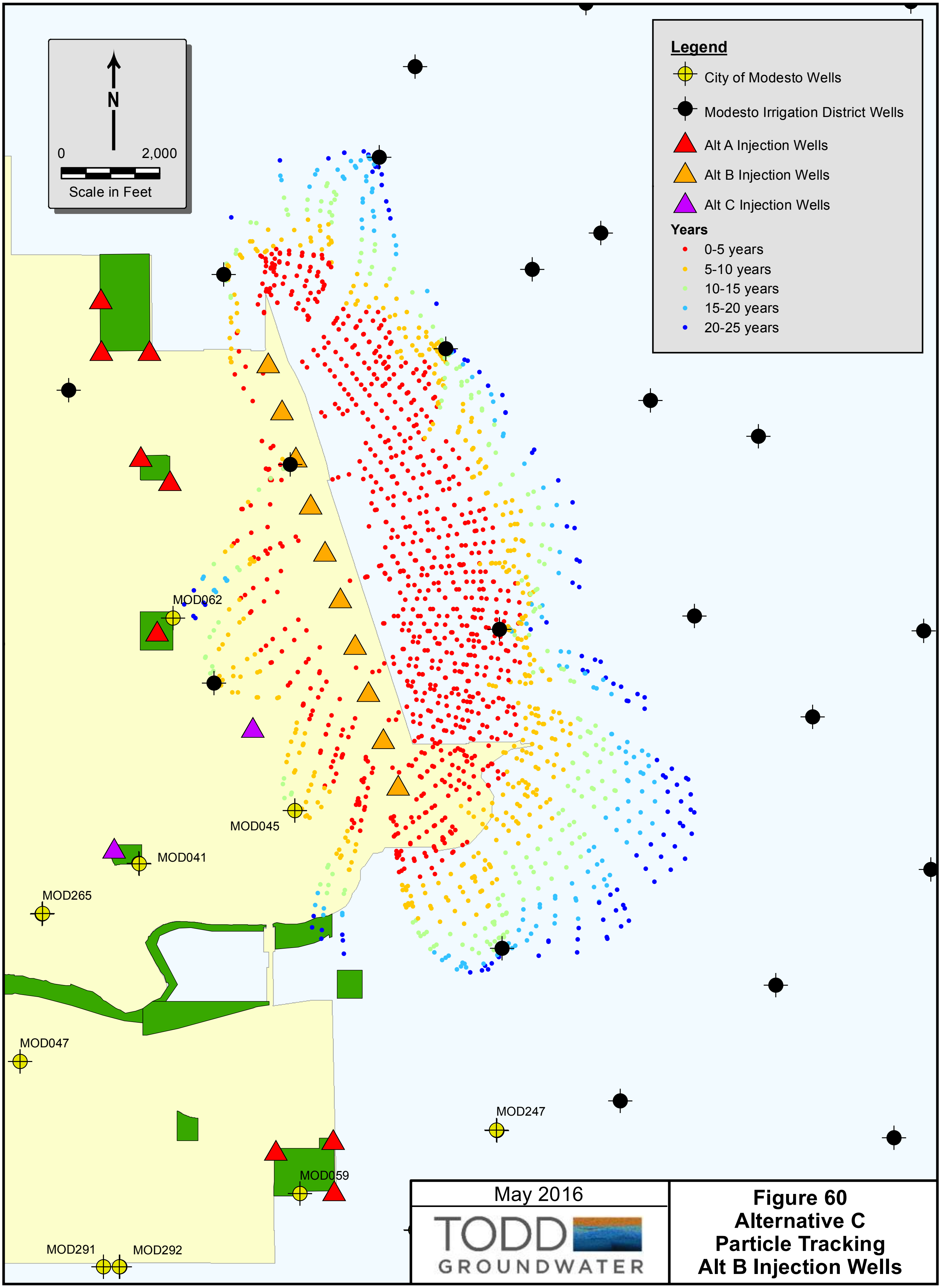

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Figure 60
Alternative C
Particle Tracking
Alt B Injection Wells

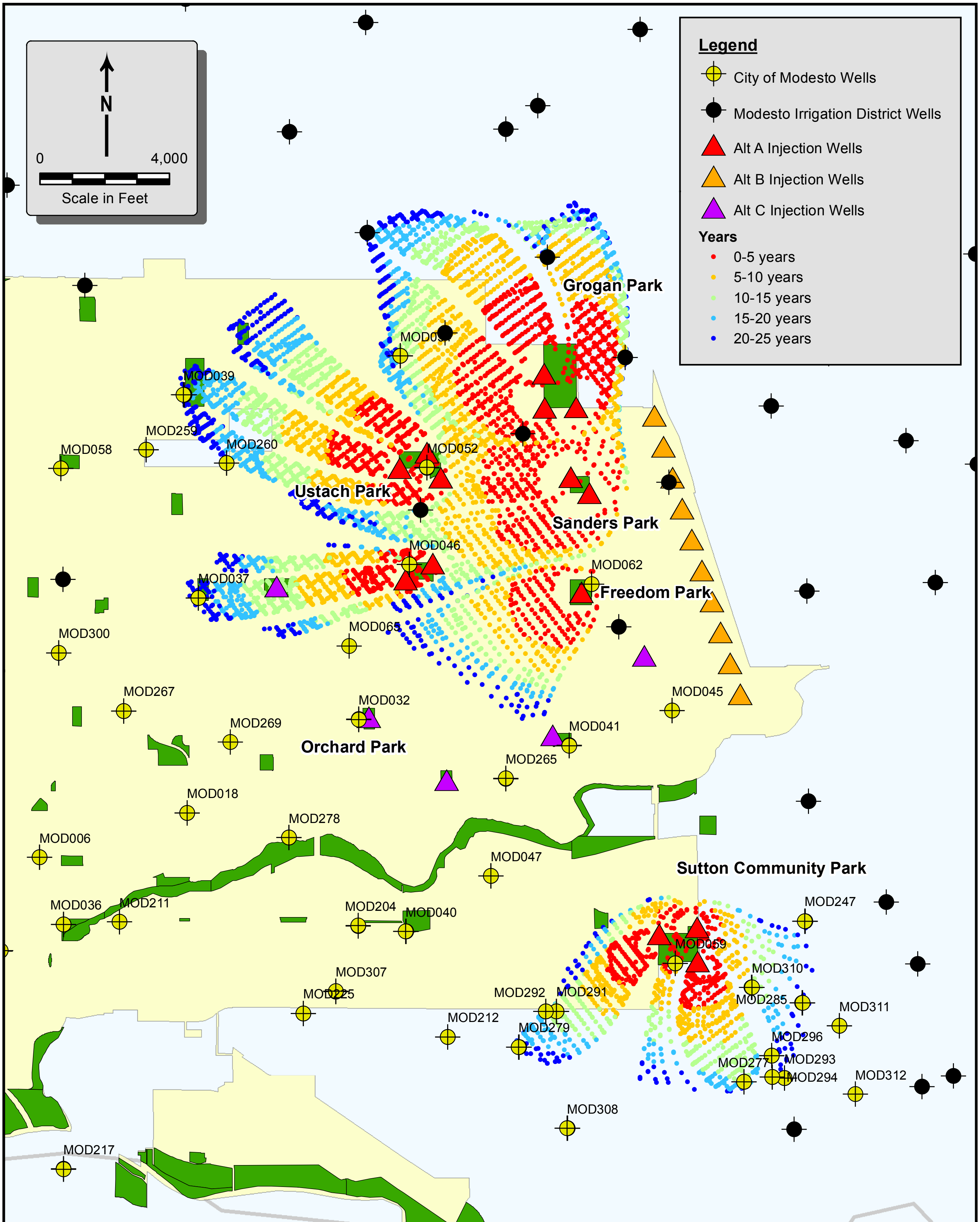

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Figure 61
Alternative C
Particle Tracking
Alt A Injection Wells

Appendix A

Table A-1 - Aquifers Screened in City Wells

Well	Total Depth (ft bgs)	Top of Screen (ft bgs)	Bottom of Screen (ft bgs)	No Screen (base of casing)	On Cross Section(s)?	Transect(s)	Formation(s) Screened	Aquifer Category	Specific Capacity (gpm/foot)	Production July 2014 - June 2015 (AFY)
1	224	79	99		x	D-D'	Upper Turlock	shallow	167	258
2	255	92	216		x	A-A', D-D'	Upper Turlock, Lower Turlock	intermediate		0
3	138	-	-	x	x	A-A'	Upper Turlock	shallow	16	0
4	225	155	225		x	A-A', D-D'	Upper Turlock, Lower Turlock	intermediate		72
6	234	-	-					intermediate		38
7	260	160	210		x	D-D'	Upper Turlock, Lower Turlock	intermediate		168
8	220	121	149		x	A-A', F-F'	Upper Turlock	shallow	14	0
10	110	-	-	x	x	C-C', D-D'	Upper Turlock	shallow		198
11	125	-	-	x	x	D-D', F-F'	Upper Turlock	shallow		--
14	263	-	-	x	x	D-D', F-F'	Lower Turlock	intermediate		0
16	312	101	274		x	D-D'	Upper Turlock, Lower Turlock	intermediate	41	574
17	232	116	120		x	D-D'	Upper Turlock	shallow	37	147
18	250	104	232		x	E-E'	Upper Turlock, Lower Turlock	intermediate	56	72
19	240	-	-	x	x	D-D'	Corcoran Clay	intermediate	9	--
21	320	144	294		x	E-E'	Upper Turlock, Lower Turlock	intermediate	53	26
22	280	130/222	136/230		x	A-A'	Upper Turlock, Lower Turlock	intermediate	57	0
24	220	74	272		x	D-D', E-E'	Upper Turlock, Lower Turlock	intermediate	54	0
25	395	91	366		x	H-H'	Upper Turlock, Lower Turlock, Laguna	deep	43	292
29	144	-	-	x	x	C-C', D-D'	Upper Turlock	shallow	18	65
30	123	-	-					shallow	17	58
32	216	-	-		x	C-C'	Lower Turlock	intermediate		0
33	380	96	278		x	A-A'	Upper Turlock, Corcoran Clay, Lower Turlock	intermediate	50	315
34	112	-	-	x	x	F-F'	Upper Turlock	shallow	33	0
36	252	128/156	144/192					intermediate		0
37	233	102	214		x	F-F'	Upper Turlock, Lower Turlock	intermediate	55	0
38	258	105	213					intermediate	33	169
39	292	116	216		x	H-H'	Upper Turlock, Lower Turlock	intermediate	46	1,333
40	275	97	229		x	E-E'	Upper Turlock, Lower Turlock	intermediate		256
41	248	124	216		x	I-I'	Upper Turlock, Lower Turlock	intermediate	28	1,380
42	430	144	264		x	A-A'	Upper Turlock, Corcoran Clay, Lower Turlock	intermediate	42	436
43	332	151	303		x	E-E'	Upper Turlock, Lower Turlock	intermediate	36	871
44	245	110	202		x	A-A'	Upper Turlock, Corcoran Clay	intermediate	63	0
45	292	146	258		x	I-I'	Lower Turlock, Laguna	deep		870
46	329	129	241		x	F-F'	Upper Turlock, Lower Turlock	intermediate		533
47	280	134	246					intermediate	35	173
48	500	315	385		x	B-B', G-G'	Laguna	deep		892
49	266	109	221					intermediate	138	122
50	275	200	292		x	B-B', D-D'	Lower Turlock	intermediate	51	951
51	470	190	410		x	B-B', E-E'	Lower Turlock, Laguna	deep	30	195
52	280	124/259	259/274		x	F-F', I-I'	Upper Turlock, Lower Turlock, Laguna	deep		1,655
53	520	132/210/230	162/220/250		x	C-C'	Upper Turlock, Corcoran Clay, Lower Turlock	intermediate		--
54	505	162/427	180/467		x	B-B', H-H', I-I'	Upper Turlock, Laguna	deep		1,116

Table A-1 - Aquifers Screened in City Wells

Well	Total Depth (ft bgs)	Top of Screen (ft bgs)	Bottom of Screen (ft bgs)	No Screen (base of casing)	On Cross Section(s)?	Transect(s)	Formation(s) Screened	Aquifer Category	Specific Capacity (gpm/foot)	Production July 2014 - June 2015 (AFY)
55	265	125/196	155/260		x	D-D'	Upper Turlock, Corcoran Clay	intermediate		0
56	250	174	240		x	F-F'	Corcoran Clay, Lower Turlock	intermediate		1,392
57	200	165	195		x	A-A', C-C', D-D'	Upper Turlock	shallow		1,052
58	500	358/469	373/495		x	G-G', H-H'	Laguna	deep		799
59	265	180	260		x	I-I'	Lower Turlock, Laguna	deep		1,027
61	430	195/260/280/350	240/270/305/410		x	B-B', E-E'	Lower Turlock, Laguna	deep	18	250
62	390	180/240/280/330/365	215/255/320/340/380		x	C-C', I-I'	Lower Turlock, Laguna	deep		1,403
63	470	200/364/422	266/396/456		x	A-A'	Lower Turlock, Laguna	deep		590
64	430	180/240/300/340/380	200/260/320/360/420		x	E-E'	Upper Turlock, Lower Turlock, Laguna	deep		335
65	379	165/199/232/290/349	174/215/243/320/374		x	F-F'	Lower Turlock, Laguna	deep		551
66	460	210/400	270/450		x	C-C'	Corcoran Clay, Laguna	deep	13	54
100	127	-	-	x	x	D-D'	Riverbank	shallow		100
204	256	116	120		x	E-E'	Upper Turlock	shallow	50	183
211	215	120	204		x	C-C'	Upper Turlock	shallow	31	410
212	169	-	-	x	x	E-E'	Lower Turlock	intermediate		416
213	193	-	-					intermediate	33	51
214	162	-	-					intermediate		9
216	200	68	192		x	D-D'	Riverbank, Corcoran Clay, Upper Turlock	shallow		317
217	232	-	-	x	x	D-D'	Lower Turlock	intermediate	14	75
223	134	-	-	x	x	D-D'	Upper Turlock	shallow	81	170
225	320	145	305					intermediate		1,634
226	290	-	-	x	x	A-A'	Lower Turlock	intermediate	36	0
229	230	174	226		x	C-C'	Corcoran Clay	intermediate		6
232	81	-	-					shallow		40
236	224	97	206					intermediate		121
237	293	-	-	x	x	F-F'	Lower Turlock	intermediate		11
241	210	-	-					intermediate		97
242	295	-	-					deep		71
244	250	-	-					intermediate		42
245	300	-	-					deep	114	105
247	225	153	225		x	I-I'	Lower Turlock, Laguna	deep	17	703
250	246	-	-					intermediate		55
255	348	182/246	198/262					deep		78
256	208	-	-					intermediate		34
259	344	-	-	x	x	H-H'	Laguna	deep	11	339
260	327	106	277		x	H-H'	Upper Turlock, Lower Turlock	intermediate	9	0
262	195	-	-					intermediate		263
264	428	-	-	x	x	G-G', H-H'	Laguna	deep		536
265	300	110	296					intermediate	35	305
267	270	140	194		x	E-E', F-F'	Upper Turlock, Lower Turlock	intermediate		423
269	265	-	-	x	x	E-E'	Lower Turlock	intermediate	36	155

Table A-1 - Aquifers Screened in City Wells

Well	Total Depth (ft bgs)	Top of Screen (ft bgs)	Bottom of Screen (ft bgs)	No Screen (base of casing)	On Cross Section(s)?	Transect(s)	Formation(s) Screened	Aquifer Category	Specific Capacity (gpm/foot)	Production July 2014 - June 2015 (AFY)
271	284	124	284					intermediate		12
272	332	-	-					deep	17	124
274	168	120	140					shallow	13	58
275	272	180	252					intermediate		148
277	257	139	251					intermediate		1,134
278	270	176/189	188/253		x	C-C', E-E'	Lower Turlock	intermediate		617
279	208	156	172		x	E-E'	Lower Turlock	intermediate		1,148
281	365	128	276	x	x	A-A', B-B'	Upper Turlock, Corcoran, Lower Turlock	intermediate	263	0
282	192	139	271					intermediate		151
283	165	-	-					intermediate		178
284	224	127	191					intermediate		531
285	300	-	-	x	x	I-I'	Upper Turlock, Lower Turlock	intermediate		0
286	311	200	292					intermediate		226
287	248	-	-	x	x	D-D'	Corcoran Clay	intermediate		61
288	230	-	-	x	x	B-B'	Lower Turlock	intermediate	24	149
289	368	-	-					deep		454
290	304	164	276		x	A-A', B-B'	Corcoran Clay, Lower Turlock	intermediate	215	96
291	268	-	-	x	x	E-E'	Lower Turlock	intermediate	30	159
292	267	-	-	x	x	E-E'	Laguna	deep	29	305
293	256	172	204		x	I-I'	Lower Turlock, Laguna	deep		0
294	345	204	341		x	I-I'	Laguna	deep		0
295	336	156/252	192/328					deep		115
296	298	-	-		x	I-I'	Laguna	deep		0
297	272	-	-		x	A-A'	Lower Turlock	intermediate	29	615
298	286	-	-	x	x	A-A', B-B'	Lower Turlock	intermediate		150
299	258	-	-	x	x	A-A'	Lower Turlock	intermediate		44
300	368	-	-	x	x	E-E', F-F'	Laguna	deep		174
301	156	126	156					shallow	8	137
302	237	-	-					intermediate		157
303	271	-	-					intermediate		559
304	172	132	164					shallow		125
305	344	-	-	x	x	D-D'	Lower Turlock	intermediate		289
306	332	200/200/260/300	210/240/280/320					intermediate		3
307	264	176	236					intermediate		178
308	252	-	-					intermediate		334
309	445	-	-					deep	22	40
310	326	-	-	x	x	I-I'	Laguna	deep	73	607
311	244	-	-	x	x	I-I'	Laguna	deep		--
312	355	215/290	255/345		x	I-I'	Laguna	deep		1,101
313	322	171/225/307	187/235/322		x	A-A'	Lower Turlock, Laguna	deep		191