Appendix E

Groundwater Levels, Storage and Natural Recharge

Antelope Valley Area of Adjudication

Appendix E

Groundwater Levels, Storage and Natural Recharge

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Appendix E

Groundwater Levels, Storage and Natural Recharge

1 INTRODUCTION

This appendix of the Expert Report addresses groundwater levels, storage changes, and natural recharge within the Antelope Valley Groundwater Basin. A summary of this appendix is presented as Sections 4.3 and 4.5 in the main body of the Expert Report.

An estimate of the natural recharge of the Antelope Valley Groundwater Basin is required to manage groundwater resources effectively and, ultimately, to allocate those resources to the water users in the basin. Natural recharge was independently estimated by Durbin as described in Appendix C, using precipitation and runoff data; the results of that analysis are described in the Expert Report as the product of the yield-modeling approach. The analysis reported herein relies primarily on the observed change in groundwater storage from 1951 to 2005, with updates through 2009; its results are described in the Expert Report as the product of the change-in-storage method.

1.1 Objectives

The objectives of this analysis were to determine, using the best available data, the estimated changes in storage over the investigation period and the natural recharge to the Antelope Valley Groundwater Basin. This appendix describes the methods used to determine the change in groundwater storage and the components of the natural recharge equation. Natural recharge is estimated using the fundamental mass balance equation:

$$\text{Change in Storage} = \text{Inflow} - \text{Outflow} \tag{1.1}$$

where natural recharge, one of the components of total inflow, was calculated as the residual of all other components of the equation as described herein.

1.2 Outline of Remainder of Appendix

This appendix is organized as follows. Section 2 describes the method and data used to calculate the change in storage and provides a general description of the hydrogeologic properties of the Antelope Valley. Section 3 presents natural recharge using methods independent of those developed by Durbin (as summarized in Section 4.1 of the Expert Report and described in detail in Appendix C of the Expert Report). Section 4 lists the references used in this document.

1.3 Investigation Period

The investigation or base period for this effort is 1951 through 2005, with updates to groundwater storage change through 2009. This period was selected based on the availability of data, and independent assessment of hydrologic conditions, as indicated by long-term surface water runoff and long-term precipitation, as described in Appendix C and Section 4.7 of the Expert Report.

2 CHANGE IN GROUNDWATER STORAGE

The volume of groundwater in storage within an aquifer is a function of the volume of the aquifer materials and the fraction of pore space within the aquifer material that will readily yield water under the force of gravity, commonly known as its specific yield. The change in storage over a particular time period is determined by multiplying the water level change by the specific yield of the aquifer materials over which the water level change occurred for a unit area of aquifer.

2.1 Data Sources

All available data was used to calculate groundwater elevation changes as well as aquifer geometry and storage properties for the periods of interest. The primary groundwater level database used in this analysis was compiled by Luhdorff and Scalmanini primarily from data obtained from the National Water Information System: a web-based database that contains water and groundwater related data and is maintained by the US Geological Survey (USGS). This database contained over 38,000 records. These data were supplemented with information provided by the Antelope Valley-East Kern Water Agency, Edwards Air Force Base, Los Angeles County Waterworks and Palmdale Water District.

Aquifer storage and geometry data were derived from published reports and, as further described in Section 2.4, from over 2,500 well completion reports that were obtained from the Department of Water Resources.

2.2 Groundwater Occurrence and Flow

2.2.1 BASIN BOUNDARIES

The groundwater basin within the Antelope Valley area of adjudication is, for all practical purposes, a closed basin that comprises approximately 1,400 square miles in the western most part of the Mojave Desert. The basin is bounded on the south by the San Gabriel Mountains, on the west and northwest by the Tehachapi Mountains, on the north and northeast by the Rosamond and Bissell Hills, and on the east by low lying hills that separate the Antelope Valley from the Mojave River Groundwater Basin (Figures E2-1 and E2-2).

A more detailed discussion of the basin boundary and area of adjudication is presented in Section 2 of the Expert Report.

2.2.2 SUBBASINS

Thayer (1946) and Bloyd (1967) divided the groundwater basin into 13 subbasins (Thayer, 1946; Bloyd, 1967); eight of which are entirely within the boundary of the adjudicated basin, and two are partially within the adjudication boundary. The subbasins were established based upon known and exposed faults, faults inferred through groundwater level differences, and exposed bedrock along the basin perimeter and within the basin (Figure E2-2).

Further analysis of groundwater levels (see Section 2.3 below) indicates that the majority of basin subdivisions, which are based upon groundwater elevations, may not be necessary or even defensible. With the exception of the Willow Springs subbasin and the Finger Buttes subbasin, groundwater elevation contours can be continuously drawn across the subbasin boundaries that were proposed by Thayer and Bloyd. In the case of the Willow Springs subbasin, groundwater elevation differences across the Willow Springs and Neenach subbasins exceed 200 feet, requiring groundwater contours to be broken. The Finger Buttes subbasin simply does not have sufficient groundwater elevation data to draw groundwater elevation contours or to make an assessment regarding hydraulic communication across the subbasin boundaries proposed by Thayer and Bloyd.

2.2.3 RECHARGE, FLOW, AND DISCHARGE

Recharge to the groundwater basin occurs primarily along the San Gabriel and Tehachapi Mountains as streambed and soil infiltration. The majority of this recharge occurs along Big Rock and Littlerock Creeks in the San Gabriel Mountains and Cottonwood Creek in the Tehachapi Mountains. Precipitation that occurs on the valley floor is, from a practical standpoint, entirely consumed by evapotranspiration (ET). Section 4.1 of the Expert Report provides a detailed description of the groundwater basin recharge components.

Under pre-development conditions, groundwater flowed from the higher elevations along the mountain fronts to the lower elevations of the Rosamond, Buckhorn, and Rogers Dry Lakes (Figure E2-3). During this time, groundwater conditions were in a state of balance (Leighton, 2003), and recharge was balanced by discharge as rising groundwater. The rising groundwater was consumed by either direct evaporation or by riparian vegetation. Approximately 100 – 1,000 acre-feet/year (ft/yr) of groundwater moved north out of the Antelope Valley through a bedrock gap into the Freemont Valley Basin (Bloyd, 1967; Durbin, 1978).

Currently, groundwater flow is influenced by pumping in the urban centers of Lancaster and Palmdale and by agricultural pumping in the northwest and east parts of the basin. These pumping depressions have changed historical flow patterns and created anthropogenic groundwater divides. A north-south trending groundwater divide is created by a groundwater ridge that generally bisects the Lancaster subbasin into east and west halves. On the west side of this divide, groundwater moves concentrically toward the eastern corner of the Neenach subbasin. With the exception of two areas (Edwards AFB/North Muroc and east Lancaster subbasin), groundwater east of this divide generally moves concentrically toward the southeast into Palmdale. In the area of Edwards AFB and North Muroc, groundwater generally moves north and exits the basin through bedrock gaps and flows into the Freemont Valley Basin. On the eastern edge of the Lancaster subbasin, groundwater flows toward a small agricultural pumping depression.

The Willow Springs subbasin is hydraulically isolated from the adjacent Neenach subbasin and does not reflect the regional groundwater flow patterns. Groundwater flow in this area is to the southeast and has not changed from pre-development conditions. In pre-development conditions groundwater discharged as springs along the Willow Springs Fault (Leighton, 2003).

2.2.4 AQUIFER SYSTEMS

The Antelope Valley floor primarily comprises alluvial materials from the surrounding mountains, interspersed with outcrops of bedrock in various stages of decay. The alluvium, which comprises the primary water bearing material, is composed of unconsolidated to moderately indurated, poorly sorted gravel, sand, silt, and clay. The alluvium is divided into seven lithographic units (Dutcher & Worts, 1963), including older fan deposits, older alluvium, younger fan deposits, younger alluvium, lakeshore deposits, old wind-blown sand, and dune sand. Of these deposits, only the older alluvium, younger fan deposits, and younger alluvium yield significant quantities of groundwater.

A thick sequence of lacustrine deposits helps define the aquifer system primarily within the central part of the Lancaster subbasin. The lacustrine deposit extends laterally from the Rosamond, Rogers, and Buckhorn Dry Lakes in the north to the San Gabriel Mountains in the south, the Little Buttes to the west, and the east edge of Rogers Lake to the east. The lacustrine deposits are characterized by massive, often blue, clay deposits up to 100 feet thick with interbedded lenses of coarse-grained material up to 20 feet thick. The entire sequence of these deposits can reach 300 feet thick. At the southern end of the Lancaster subbasin, the lacustrine deposit is overlain by up to 800 feet of alluvium. The lacustrine deposit shallows in a northerly direction until it becomes exposed at the land surface around the Rosamond, Buckhorn, and Rogers Dry Lakes.

The historical conceptual model (Dutcher & Worts, 1963; Bloyd, 1967; Durbin, 1978) identified two primary aquifers within the basin: the principal (upper) aquifer and the deep aquifer. These aquifers are separated by the above-mentioned lacustrine deposit, which underlies a significant portion of the Lancaster subbasin. The principal aquifer is the alluvial deposit overlying the lacustrine deposit and is characterized as regionally unconfined with locally confined conditions that result from local aquitards. The deep aquifer is the portion of the alluvial deposit beneath the lacustrine deposit and is characterized as confined.

Leighton and Phillips (2003) refined the conceptual model of the aquifer into a three aquifer system: an upper, middle, and deep aquifer. The new conceptual model incorporates a chronostratigraphic approach to delineate aquifers, based on the premise that as alluvial deposits increase in age they decrease in their ability to store and transmit water. The upper aquifer is the saturated alluvium above 1,950 feet mean sea level (msl), the middle aquifer occurs between 1,950 and 1,550 feet msl, and the deep aquifer is that portion of the alluvial material between 1,550 feet msl and the basement complex or bedrock.

Chapter 3 of the Expert Report provides an updated and more detailed summary of the basin geology and aquifer system. It is based on previous studies and new analysis (e.g., geologic cross-sections) completed during preparation of the Expert Report.

2.3 Groundwater Levels and Trends

2.3.1 METHODS

A series of groundwater elevation contour maps were created to determine groundwater flow patterns and elevation trends within the basin and to estimate the change in storage over the investigation period. Groundwater elevations for a particular year were initially contoured using exclusively data from that year. If portions of the basin did not have any water level measurements during the year of interest, that portion was not initially contoured. In addition, water levels were initially contoured across “subbasin” boundaries (Thayer, 1946; Bloyd, 1967) when the data allowed. When contours could not be reasonably drawn across subbasin boundaries, the subbasin boundary was used to break the contours. Once a subbasin boundary was required in any year, contours in the other years were adjusted to also reflect the boundary. The only subbasin boundary (where sufficient data existed to draw groundwater elevation contours) that required a break in contours was the southwest side of the Willow Springs subbasin where groundwater elevations differ across the boundary in excess of 200 ft.

There was insufficient data to construct contours along the fringes of the basin, using only groundwater levels measured directly in the year of interest. The areas with insufficient data were primarily in the far east and west ends of the Antelope Valley. To augment the directly measured data, over 70 additional hydrographs were constructed, using the database described in Section 2.1, to fill in areas with limited water level data for the contoured year. These hydrographs were used to interpolate groundwater elevations for the contoured years, and the interpolated values were used to expand and refine contouring in areas with sparse data. An example of hydrographs analyzed is presented in Figure E2-4.

Groundwater elevation contour maps were prepared for 1951, 1963, 1971, 1979, 1985, 1992, 1998, 2005 and 2009, and are presented in Figures E2-5 through E2-13, respectively. Because of the paucity of data in the Finger Buttes and Oak Creek subbasins and along the fringes of the basin, these areas are excluded from groundwater elevation contouring and subsequent storage change calculations.

The investigation area was divided into four areas to characterize common trends in groundwater levels and storage. These areas are generally shown via colored symbols in Figure E2-4 and include the North Antelope Valley, Lancaster and Palmdale, West Antelope Valley, and East Antelope Valley areas. The groundwater level trends in these areas are described below.

2.3.2 NORTH ANTELOPE VALLEY

This area generally comprises Willow Springs, Rosamond, Edwards Air Force Base, and North Edwards. Over the period 1951 through 2009, groundwater levels in this area continuously declined up to approximately 100 feet (09N/13W-Q3). Unlike areas along the southern part of the basin, groundwater levels show no correlation to seasonal or drought-wet periods. Several factors most likely contribute to the declining groundwater level trends, including distance from the primary recharge areas along the southern part of the basin, continuous groundwater pumping for urban and agricultural uses, and negligible deep percolation of precipitation. The groundwater levels shown in Figures E2-5 through E2-13 suggest that this area is draining towards a pumping depression concentrated in the central part of the overall investigation area. This means that groundwater levels in this area are decreasing due to pumping from outside the local area.

2.3.3 SOUTH ANTELOPE VALLEY (LANCASTER AND PALMDALE)

Groundwater levels underlying the urban centers of Lancaster and Palmdale show continuous declines from the early 1950s through 2009. Declines in excess of 250 feet have occurred (06N/11W-19E6) and are primarily the result of heavy groundwater pumping to support the historical agricultural irrigation and subsequent municipal growth in these areas. Groundwater elevation contours from 1951 and 1963 (Figures E2-5 and E2-6, respectively) indicate that agricultural pumping to the northeast was the dominant influence on groundwater levels in this portion of the basin. By 1971 (Figure E2-7), pumping depression develop just northeast of Palmdale and in the vicinity of Lancaster. The depression has continued to develop in this area through the present and has become the dominant influence on groundwater movement within this portion of the basin.

2.3.4 WEST ANTELOPE VALLEY

This area includes the western portion of the Lancaster subbasin and the Neenach and West Antelope subbasins. Groundwater elevations in this area show similar trends of groundwater level decline from the early 1950s through the mid-1970s, followed by stabilizing and/or increasing groundwater elevations through approximately 2000. Since 2000, groundwater elevations have been generally declining. In general, groundwater levels have declined between 50 and 100 feet since 1951 with the greatest declines occurring in the agricultural areas of the eastern portion of the Neenach subbasin and the western portion of the Lancaster subbasin. Groundwater flow direction in this area is generally to the east and has not changed significantly since 1951.

2.3.5 EAST ANTELOPE VALLEY

This area includes the eastern portion of the Lancaster subbasin and the Buttes and Pearland subbasins. Groundwater elevations in this area show similar trends of groundwater level decline from the early 1950s through the mid-1970s, followed by stabilizing and/or increasing groundwater elevations through approximately the mid to late 1990's. Since the mid to late 1990's, groundwater elevations have been relatively stable, with only minor declines in the west Pearland basin (well 05N10W-06N1). Groundwater elevations within the Buttes and Pearland subbasins are very sensitive to precipitation and runoff, as the majority of the natural recharge to the groundwater basin occurs in this area at Littlerock Creek and Big Rock Creek. This is observed in the hydrographs (not presented in figures) from a number of shallow wells near the Littlerock and Big Rock creeks. In general, groundwater levels in the Buttes and Pearland subbasins have not changed significantly since 1951 and, in some cases, have risen (06N/10W-22D1). Groundwater flow direction in this area is generally to the west and has not changed significantly since 1951.

2.4 Lithology and Specific Yield

Specific yield, also known as the drainable porosity, is a property of aquifer materials that characterizes the capacity of an aquifer to release groundwater from storage in response to a decline in groundwater level. Moreover, specific yield is a ratio that indicates the volumetric fraction of the bulk aquifer volume that a given aquifer will yield when all the water is allowed to drain out of it under the forces of gravity:

$$Sy = V_{wd} / V_T \qquad (2.1)$$

Where:

V_{wd} is the volume of water drained, and

V_T is the total rock or material volume

The specific yield of the sediments was determined by analyzing a comprehensive library of over 2,500 well completion reports that were obtained from the DWR. After a thorough review of the well location information in these reports, the location of each well was determined to the accuracy of the available data. Well locations with only the township and range specified and records containing imprecise well location information were not included in this investigation.

Lithologic data in hardcopy format and from electronic PDF files were converted into electronic format through a data entry tool. Over 25,000 lines of data from the well completion reports were manually entered into a Microsoft Access database.

Lithologic descriptions for each well were reviewed by a geologist, and ambiguities in lithologic descriptions were eliminated. For example, decomposed granite underlain by clay is not typically found in an alluvial depositional sequence, and the lithologic description for such an entry was modified to a more reasonable lithology or the well was removed from the analysis. All lithologic descriptions were then assigned a specific yield value based on *Compilation of Specific Yields for Various Materials* (Johnson, 1967).

Specific yield values within the basin typically range from 0.25 (coarse sand) to 0.03 (clay). Table E2-1 summarizes the sediment types and associated specific yield values derived from Johnson (1967) and applied to the sediment callouts from each well completion report used in this analysis.

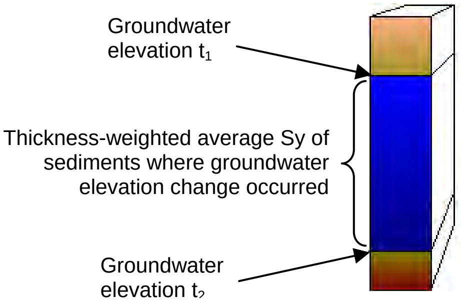
2.5 Computation of Storage Change from Sediments that Drain By Gravity

2.5.1 METHOD (STORAGE CHANGE MODEL)

A storage change model (Model) was developed to estimate the groundwater storage changes that occurred within the Antelope Valley Groundwater Basin during the investigation period (1951 through 2009).

The accuracy of the Model relates directly to the accuracy of the groundwater elevation contour maps created for each period and to the accuracy of the assignment of specific yield values to the unconfined aquifer materials where groundwater elevation changes occurred. The storage change for each period is calculated as follows:

$$\text{Change in Storage } (\Delta S) = \Delta WL \times Sy_{avg} \qquad (2.2)$$



Where ΔWL is the change in groundwater elevation for a specific period, and Sy_{avg} is the thickness-weighted average specific yield of the sediments where the groundwater elevation change occurred during a specific period.

The Model and the procedures for estimating storage change included the following steps:

- Develop groundwater elevation contour maps for each of the periods using the best available static (non-pumping or recovering) groundwater elevation data.
- Digitize the contour maps, and convert them to ArcGIS shapefiles.
- Create three-dimensional raster surfaces (ArcGIS grids) from the groundwater elevation contour maps for each period[1]. Groundwater elevations between contour lines and measured values were predicted using an ordinary kriging method of interpolation with kriging parameters held constant between periods. Control contours were used to allow the kriging of groundwater elevations beyond the available data.
- Create a point shapefile of all well sites with lithologic data that were included in the investigation, and extract groundwater elevation values to the point shapefile for each period. Export data to a Microsoft Excel spreadsheet for specific yield calculations.
- Calculate the average specific yield value at each well between the given groundwater elevations as follows:
    1. The groundwater elevation and lithology data for each well are extracted from the database and uploaded to a custom software code.
    2. The upper and lower elevations of each lithologic unit[2] are identified. Each lithologic unit is assigned a specific yield value based on the ranges found in literature (Table E2-1).
    3. The beginning and ending groundwater elevations for each period are identified.
    4. The lithologic units that are partially or completely within the zone defined by the beginning and ending groundwater elevations for each period are identified.
    5. The thickness-weighted average specific yield of each lithologic unit is calculated.
- Plot specific yield values as a point shapefile, and evaluate spatial trends for anomalies. Create a map of estimated specific yield values for areas between points using an ordinary kriging interpolation method.
- Create raster surfaces from all specific yield estimation maps (ArcGIS grids) to the extent of the Antelope Valley investigation area.
- Create a grid (polygon shapefile) composed of 400-meter by 400-meter cells (approximately 24,000 cells in the Model area), covering the geospatial extent of Antelope Valley.
- Assign attributes to each 400-meter grid cell:
    1. surface area of grid cell
    2. groundwater elevation surface for all periods analyzed
    3. change in groundwater elevation between periods

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[1] The Willow Springs subbasin was processed separately because it is hydraulically isolated from the primary groundwater basin along the Willow Springs Fault, which defines the southern subbasin boundary.

[2] A lithologic unit, as used in this study, is an individual layer or strata identified in well drilling reports that is bounded by strata with different physical characteristics (i.e. grain size and composition) and thus is assigned a different specific yield.

4. thickness-weighted average specific yield of sediments for each period

- Calculate storage change at each grid cell based on the following equation:

$$\Delta S = Sy_{timestep} \text{ x } \Delta WL \text{ x Area} \tag{2.3}$$

Where:

ΔS = the change in storage in cubic feet for a particular grid cell for the given period

$Sy_{timestep}$ = thickness-weighted average specific yield for a particular grid cell for the given period

ΔWL = change in groundwater elevation (in feet) for a particular grid cell for the given period

Area = the area of a grid cell (square feet)

The follow steps were taken to refine the change in storage calculation:

- The spatial limits of the calculation were constrained based on the availability and distribution of groundwater elevation and lithology data. This minimized the influence of bedrock in specific yield calculations and prevented "boundary effects" in the groundwater elevation kriging, which could cause mathematical artifacts in the storage change calculation (control contours/points were used only sparingly to avoid the introduction of cognitive bias).
- The Model used to calculate the change in storage is composed of 14,292 cells and covers approximately 875 square miles of alluvial basin or 63 percent of the area contained in the adjudicated boundary.
- Cells with incomplete raster data (i.e. cells at the fringe of the calculation boundary) and cells with unsupported interpolation/extrapolation trends were excluded from the storage change calculation. This step was important as it removed the possibility of including cells with unreliable groundwater elevation change values in the final storage change calculation.

2.5.1.1 Kriging Parameters

Kriging is a flexible method of stochastic interpolation, suited for creating prediction surfaces based on a dataset irregularly distributed in space. More specifically, Kriging is a generalized linear regression technique in which the value of a property at an unsampled location is estimated from values at neighboring locations (Davis, 2002) by minimizing an estimation variance defined from a prior model for a covariance (i.e. semivariogram).

Successful interpolation using a Kriging method is dependent on the following assumptions: 1) the dataset has a spatial trend and 2) an element of variability (i.e. a spatially auto-correlated random error). For example, the change in groundwater elevation across a basin from an area of high piezometric head to an area of low piezometric head can be represented by a linear trend that represents the regional hydraulic gradient. However, at any point between the two areas, the measured value of groundwater elevation is likely to be slightly above or below the trend value. This variability, or "auto-correlated random error," is assumed to be spatially dependent. While there are several Kriging methods commonly applied in the field of geostatistics, it was determined that "Ordinary Kriging" would be the most appropriate fit for modeling groundwater elevations across the Antelope Valley Basin. Ordinary Kriging assumes that the mean of the regionalized variable is constant throughout the area of interest. Ordinary Kriging is one function of ESRI's Geostatistical Analyst extension for ArcGIS v9.2. It was employed to interpolate the values of groundwater elevations in the investigation area.

Parameters were optimized by running a number of Ordinary Kriging model runs and visually analyzing a semivariogram. The outcomes of various model runs were analyzed using a number of validation statistics. The "mean standardized prediction error" was held as close to zero as possible to ensure that the predictions were unbiased. The "root-mean-squared prediction error" was minimized to ensure that predictions were as close to measured values as possible: the "root-mean-squared standardized error" was nearly equal to one, indicating that the variability of the predictions was not over- or under-estimated.

Once a good statistical fit was found for a typical set of groundwater elevation data, the same parameters were held constant when applied to other sets of data. The same validation statistics were reviewed to verify the applicability of the parameter set to each time period. The product was eight prediction surfaces, representative of each time period evaluated.

The three dimensional prediction surfaces for all time periods were plotted spatially and overlain on a grid of 400x400m cells. Each individual cell was populated with the average groundwater elevation as calculated from the individual prediction surfaces.

A similar process was used to create a prediction surface for the specific yield values across the basin as measured at boring sites.

2.5.2 PERIODS OF COMPUTATION

Change in storage estimates were calculated for nine periods, beginning in 1951 and ending in 2009:

- 1951 to 1962
- 1963 to 1970
- 1971 to 1978
- 1979 to 1984
- 1985 to 1991
- 1992 to 1997
- 1998 to 2005
- 2006 to 2009
- 1951 to 2009 (complete period)

These periods were selected based on the availability of water level data and the need to represent water levels in each decade within the complete period.

The 1951 through 2009 period almost completely overlays the period used by Durbin (1949-2005) in his analysis of natural recharge (see Appendix C).

2.5.3 RESULTS

The methods and data described above were used to estimate groundwater storage changes from gravity drainage that occurred within the investigation area for the period of 1951 through 2009. The change in storage by gravity drainage over this 59-year period is approximately -5,200,000 acre-ft. That is, the volume of groundwater in storage decreased by 5,200,000 acre-ft. The average specific yield of the cells included in the storage change calculation is approximately 14 percent. Figure E2-14 presents a graph of the cumulative and total change in storage and the components of the storage change (gravity drainage and compaction). Table E2-3 includes a summary of the calculated change in storage from gravity drainage for each period. Figures E2-15a and E2-15b show the regional distribution of storage change by gravity drainage for each period and for the entire period between 1951 and 2009.

Just as agricultural pumping peaked in the early 1960s, so did the change in groundwater storage. The storage change by gravity drainage between 1951 and 1962 was approximately -3,200,000 acre-feet or 60% of the total storage change over the entire investigation period. Groundwater storage decreased by about 1,200,000 acre-feet between 1963 and 1971. From 1972 to 2009, the cumulative decrease in storage was about 700,000 acre-feet. The only period to show significant increase in groundwater storage was during the 1992 to 1997 period, where storage increased by about 200,000 acre-feet.

2.6 Land Subsidence and Storage Change from Compaction

2.6.1 GROUNDWATER WITHDRAWALS AND LAND SUBSIDENCE

Land subsidence is the sinking of the Earth's surface due to the rearrangement of subsurface materials. In the United States alone, over 17,000 square miles in 45 states have experienced land subsidence (Galloway, 1999). In many instances, land subsidence is accompanied by adverse impacts at the land surface, such as sinkholes, earth fissures, encroachment of adjacent water bodies, modified drainage patterns, and others. In populated regions, these subsidence-related impacts can result in severe damage to man-made infrastructure and costly remediation measures.

Over 80% of all documented cases of land subsidence in the United States have been caused by groundwater extractions from underlying aquifer-systems (Galloway, 1999). Groundwater extraction is an especially well-documented cause of subsidence in the arid southwestern United States where aquifer-systems are typically composed of unconsolidated sediments that are susceptible to permanent compaction when groundwater is extracted. Some infamous examples include the San Joaquin and Santa Clara Valleys in California, the Las Vegas Valley in Nevada, the Houston-Galveston area in Texas, and several basins in Arizona. In many of these regions, fissuring occurred in areas of differential subsidence (i.e. where rates of subsidence vary over short horizontal distances).

Although the drawdown of water levels is the driving force that causes land subsidence, the geology of a groundwater basin also plays an important role. Clay layers within the aquifer-system are relatively compressible materials. Therefore, aquifer-systems that contain thick and/or numerous clay layers are more susceptible to permanent compaction and land subsidence when groundwater is extracted. In addition, faults that act as groundwater barriers can focus and augment drawdown in the aquifer-system when pumping wells are located nearby. When pumping and drawdown are concentrated on one side of a fault barrier, differential land subsidence and ground fissuring are a possible result.

The scientific model that describes the phenomenon of pumping-induced land subsidence is termed the aquitard-drainage model. This model has been successfully applied to numerous cases of land subsidence world-wide. It has been incorporated into the industry-standard computer models of groundwater flow and is increasingly recognized as critical to the understanding of aquifer-system hydraulics (flow and storage) and mechanics (deformation). The following is a brief summary of the aquitard-drainage model.

An aquifer-system consists of permeable sand and gravel layers (the aquifers) interbedded with less-permeable silt and clay layers (the aquitards). Pumping wells cause water level drawdowns in the aquifers that, in turn, cause aquitards to slowly drain into the aquifers. The draining allows aquitard pore pressures to decay toward equilibrium with the reduced heads in the adjacent aquifers. Since the pressure of the pore water provides some internal support for the sedimentary structure of the aquitards, this loss of internal support causes the aquitards to compress, resulting in a small amount of subsidence at the land surface. When the pumping wells turn off and water levels recover in the aquifers, groundwater migrates back into the aquitards and they expand, resulting in a small amount of rebound at the land surface. Over a limited range of seasonal water level fluctuations this process can occur in a purely elastic fashion. That is, a recovery of water levels to their original values causes the land surface to rebound to its original elevation. However, when drawdown falls below a certain "threshold" level, elastic compression transitions to a non-recoverable inelastic compaction of the aquitards. The “threshold” water level, referred to as the preconsolidation stress, is taken to be the maximum past stress to which the sedimentary structure had previously equilibrated under the gradually increasing load of accumulating sediments.

Drawdowns exceeding a previous threshold water level result in an increase in the value of maximum past stress and, thus, the establishment of a deeper threshold, accompanied by an increment of inelastic aquitard compaction. Concomitantly, the compaction results in a one-time irreversible mining of groundwater from the aquitards and the deformation and subsidence of the land surface.

2.6.2 LAND SUBSIDENCE IN THE ANTELOPE VALLEY

Historical land subsidence in the Antelope Valley is attributed to the lowering of groundwater levels beyond the preconsolidation stress of the underlying materials (Leighton, 2003). Figure E2-16 shows subsidence measured from 1930-1992 and the approximate extent of lacustrine (clay) deposits (Leighton, 2003), which are attributed to be the primary compressible material in the Antelope Valley (Ikehara & Phillips, 1994). Between 1930 and 1992, the ground surface subsided by a maximum of about 6.6 feet. The water derived from the compaction of aquitards is a non-renewable source of recharge to the aquifer-system.

The water derived from compaction of sediments must be accounted for in the water budget; otherwise, estimates of natural recharge would be artificially high. The estimates of the water derived from compaction are conservative in that the water from the compaction of sediments where subsidence was less than one foot is not accounted for in the water budget.

2.6.3 CALCULATION OF WATER DERIVED FROM COMPACTION

A GIS model was developed to estimate the volume of water that was derived from the compaction of sediments in the Antelope Valley. The model is based on the premise that the volume of water derived from compaction of aquitards is virtually equal to the volume of land subsidence. In 1994, Ikehara and Phillips published a paper: “Determination of Land Subsidence Related to Ground-Water-Level Declines using Global Positioning System and Leveling Surveys in Antelope Valley, Los Angeles and Kern Counties, California 1992.” This paper was the source of the data that were used in this volumetric calculation of subsidence. A series of contour maps (Ikehara, 1994) that show the average annual rate of subsidence in the Antelope Valley were produced for the following periods: 1957-62, 1962-65, 1965-72, 1972-75, 1975-81, and 1981-92. Post-1992 subsidence data for the Antelope Valley is lacking. The water derived from compaction from 1993 to 2005 was estimated based upon the annual subsidence rate in 1992. Estimates of the water derived from compaction from 2006 through 2009 were not made due to lack of publicly available data. The following steps were executed to calculate the volume of subsidence (i.e. water derived from the compaction of aquitards):

- Digitize the Ikehara average annual rate of subsidence contour maps and import files into ArcGIS as shapefiles.
- Create a polygon shapefile that surrounds the smallest contour (0.03 feet per year) for each time interval (hereafter, time interval extent polygon). This polygon becomes a conservative estimate of the extent of land affected by subsidence.
- Convert the “annual rate of subsidence contours” into “total amount of subsidence contours” for the natural recharge time periods. To accommodate the difference between the subsidence time interval and the natural recharge time intervals, 11 shapefiles were created.
- Create three-dimensional raster surfaces (ESRI grids) of the total amount of subsidence for each set of subsidence contours using an Ordinary Kriging method of interpolation. The rasters are clipped to the appropriate time interval extent polygon.

- Calculate the volume of subsidence for each time period using the Surface Analysis function within the 3D Analyst extension of ArcGIS.
- Sum the volume of subsidence over each natural recharge time period. These estimates of the volume of subsidence approximately equate to the volume of water derived from the compaction of the aquitards and are shown in Table E2-2 and Figure E2-17.

The volume of water derived from compaction between 1951 and 2005 is approximately 400,000 acre-feet. Figure E2-17 shows the cumulative volume of water derived from subsidence and clearly shows that the majority of the subsidence occurred between 1957 and 1981.

2.7 Total Change in Storage

The total change in storage from gravity drainage and compaction is shown in Table E2-3 and graphically in Figure E2-18. The total decrease in storage for the 1951 through 2009 investigation period is about 5,600,000 acre-ft with about 5,200,000 acre-ft from gravity drainage and about 430,000 acre-ft from compaction.

3 COMPUTATION OF NATURAL RECHARGE

An estimate of the natural recharge of the Antelope Valley Groundwater Basin is presented herein using the continuity equation, the change in storage developed in Section 2, and the hydrologic components developed by others and reported elsewhere in the Expert Report. The following equation was used to estimate natural recharge.

$$\text{Change in Storage } (\Delta S) = \text{Inflow (I)} - \text{Outflow (O)} \qquad (3.1)$$

Where

$I = \text{Natural Recharge } (I_{nr}) + \text{Artificial Recharge } (I_{ar}) + \text{Return Flows } (I_{rf.})$

$O = \text{Groundwater Pumping } (O_p) + \text{Subsurface Outflow } (O_{ss})$

This equation is algebraically rearranged to estimate natural recharge:

$$I_{nr} = \Delta S + O_p + O_{ss} - I_{ar} - I_{rf.} \qquad (3.2)$$

The variables on the right side of equation 3.2 have been estimated others, as described in the Expert Report, and can be substituted into this equation to yield estimates of natural recharge. The change in storage term is described in Section 2. Section 3.1 describes the outflow terms O_p and O_{ss}. Section 3.2 describes the inflow terms I_{ar} and I_{rf}. Section 3.3 presents the estimates of natural recharge over the study period and compares them to the independent natural recharge estimate developed by Durbin (Appendix C).

3.1 Outflows

The components of groundwater outflow used in this analysis are groundwater pumping and subsurface outflow to adjacent groundwater basins.

3.1.1 GROUNDWATER PUMPING

Groundwater has been pumped in the Antelope Valley since the 1800s (Leighton, 2003). Around 1915, the number of wells in the Antelope Valley increased significantly, and correspondingly, the amount of groundwater pumped from the basin also increased. Between 1920 and the early 1950s, groundwater production increased from less than 100,000 acre-ft/yr to a maximum of about 370,000 acre-ft/yr in 1951. The vast majority of the water pumped from the basin was for agricultural purposes. Between 1963 and 1990, groundwater pumping steadily decreased to a study-period low of approximately 88,000 acre-ft/yr as a result of significant decreases in agricultural water requirements and imported water supplies augmenting groundwater pumping. Groundwater production has since increased to approximately 150,000 acre-ft/yr (2005) to support increased agriculture as well as municipal and industrial (M&I) uses. A detailed analysis of groundwater pumping in the basin is provided in Appendix D. Table E3-1 presents all of the components of the Antelope Valley water balance, including groundwater pumping estimates developed by Luhdorff and Scalmanini (Appendix D).

3.1.2 SUBSURFACE OUTFLOW

In addition to groundwater pumping, there is a small volume (100 to 1,000 acre-ft/yr) of groundwater leaving the basin as subsurface outflow through bedrock gaps in the North Muroc area into the Freemont Valley Basin (Bloyd, 1967; Durbin, 1978). The volume of outflow assumed in this analysis is 300 acre-ft/yr over the investigation period.

3.2 Inflows

3.2.1 RETURN FLOWS

Return flows, as used in this analysis, are the portion of the water applied on or near the ground surface that recharges the underlying aquifer. Return flows in the Antelope Valley occur from irrigated agriculture, and urban/M&I uses (i.e. landscape irrigation, recycled water and septic systems).

3.2.1.1 Return Flows Types

Agricultural Irrigation

Since the early 1900s about 17,600,000 acre-feet of groundwater has been applied to grow crops in the Antelope Valley (Table E3-1 and Appendix D). The portion of the applied irrigation water infiltrated past the root zone is the return flow. The irrigation return flow is a function of both the irrigation efficiency and the crop water requirement. Between 1919 and 2009, the total volume of irrigation water returned to the groundwater basin as return flow is about 5,000,000 acre-feet. Tables E3-1 and E3-2 summarize the historical irrigation water requirements and return flows for agricultural and M&I users. Estimates of the water applied for irrigation and irrigation return flows were developed by Luhdorff & Scalmanini and are described in detail in Appendix D. Table E3-3 contains the time history of estimated agriculture acreage, the total applied water requirement, the average unit water requirement, the total return flow, and the unit return flow. The total water applied for agriculture during the investigation period was about 12,400,000 acre-ft, averages about 225,000 acre-ft/yr, and range from a high of about 363,000 acre-ft/yr to a low of about 68,000 acre-ft/yr. Using a 15 year lag time, the total return flow from agriculture irrigation to the vadose zone during the investigation period is about 4,000,000 acre-ft, averages about 72,000 acre-ft/yr, and range from a high of about 109,000 acre-ft/yr to a low of about 15,000 acre-ft/yr.

Urban/Municipal and Industrial (M&I)

Urban/M&I return flows derive from outside irrigation, recycled water and septic system returns. Derivation of the return flow estimates for these areas are described in detail in Appendices D and G. Of the three sources of Urban/M&I return flows, only the outside irrigation is lagged. Using a 15 year lag time, the total return flow derived from irrigation during the investigation period is approximately 150,000 acre-feet, averages about 2,800 acre-ft/yr, and ranges from a high of about 8,000 acre-ft/yr to a low of about 800 acre-ft/yr. Recycled water and septic system effluent effectively reach the aquifer in the year applied. Over the investigation period the total recycled water return flow is about 133,000 acre-feet, averages about 2,000 acre-ft/yr, and ranges from a high of about 8,000 acre-ft/yr to zero during the beginning of the period. Septic system returns over the investigation period are about 460,000 acre-feet, average about 8,000 acre-ft/yr, and range from a high of about 20,000 acre-ft/yr to a low of about 1,000 acre-ft/yr. Table E3-1 summarizes all return flows on an annual basis.

3.2.1.2 Return Flow Lag Time

The return flows from irrigation (agriculture and Urban/M&I) may take many years to reach the phreatic zone. The length of time between the application of irrigation water and the arrival (at the water table) of irrigation water applied in excess of vegetative water requirements is referred to herein as lag time. This section describes the methods used to determine lag time and the results of the analysis. Return flows from non-agricultural recycled water and septic system discharge are not lagged in this analysis as the moisture content in the soil column beneath discharge sites becomes very high which leads to high vertical seepage velocities. For the purposes of this analysis, it is assumed that the portion of recycled water and septic system effluent that becomes deep percolation effectively reaches the phreatic zone in the year of application. The same would be true for any artificial recharge of water that is either long term or large relative to the area of application.

As used herein, lag time is defined as the average travel time for irrigation returns from the root zone to the phreatic zone. Lag time is a function of the volume of return flows at the root zone, the thickness of the vadose zone, and the hydraulic properties of the vadose zone. Wildermuth Environmental, Inc. (WEI) used different methods to derive an average lag time estimate for Antelope Valley. Initially, the HYDRUS2 model was applied to develop a range of lag time estimates at specific locations in the valley. However, in working with the model and the available data, it became clear that the accuracy of the data greatly limited the use of the HYDRUS2 model for this area. The average lag time for the valley that was assumed herein ranged from 15 to 20 years. The sensitivity of the natural recharge estimate to the lag time is demonstrated below.

3.2.2 ARTIFICIAL RECHARGE

Artificial recharge is defined in this study as the purposeful recharge of imported water through spreading basins, pits, stream channels, and injection wells, and the enhancement of natural groundwater recharge by modification of stream channels for stream water retention. The volume of water artificially recharged to the groundwater basin is relatively insignificant when compared to return flows. The total volume of water artificially recharged to the groundwater basin is approximately 6,464 acre-feet during the period 1951 through 2005. Table E3-1 lists the time history and type of artificial recharge during the investigation period.

3.3 Natural Recharge Estimate

The results of the natural recharge calculation are summarized in Tables E3-4a and E3-4b for the average lag times of 15 and 20 years, respectively. These tables show the estimated natural recharge for the following periods:

- 1951 to 1962
- 1963 to 1970
- 1971 to 1978
- 1979 to 1984
- 1985 to 1991
- 1992 to 1997
- 1998 to 2005
- 1951 to 2005

The natural recharge for the 1951 through 2005 period is about 57,000 acre-ft/yr and 55,000 acre-ft/yr for the 15 and 20-year lag times, respectively. These estimates of natural recharge are very close to Durbin's independently developed natural recharge estimate of 58,000 acre-ft/yr for the 1951 to 2005 period. Recall that Durbin's natural recharge estimate is based on precipitation and the subsequent recharge of runoff from precipitation: it does not depend on any of the information used to develop the natural recharge estimates provided in Tables E3-4a and E3-4b.

Figure E3-1 shows the total inflows and outflows based on the hydrologic components described above and the WEI change in storage. Figure E3-1 also shows the change in storage that would occur if the change in storage was computed from the following equation:

$$\Delta S = I_{nr} + I_{ar} + I_{rf} - O_{p} - O_{ss} \tag{3.3}$$

where the change in storage is now the dependent variable and I_{nr} is the natural recharge estimated by Durbin. The change in storage developed by WEI and described in Section 2 of this appendix closely tracks the change in storage developed with Durbin's natural recharge estimates. Figure E3-2 shows the cumulative change in storage ("calculated") based on Durbin's estimate of natural recharge and the changes in storage ("measured") developed by WEI.

Finally, Figure E3-3 shows the relationship of the assumed average lag time for irrigation return flows on the computed natural recharge for each period and for the 1951 through 2005 period. Average lag times of ten years or less produce negative natural recharge values in the period 1951 through 1962. These negative values are not possible. The explanation for the negative values lies in the short lag time. In the 1951 through 1962 period, lag times of ten years or less result in larger return flows from irrigation than lag times of 15 or more years. Review of equation 3.2 shows that if all the other independent variables are held constant, increasing the return flow volume will decrease the natural recharge. Figure E3-3 also shows the period natural recharge estimates developed by Durbin. The natural recharge estimates based on equation 3.2 are more consistent with Durbin's estimates with average lag times of 15 and 20 years. Based on these considerations and given all the information available at this time, an appropriate average lag time for irrigation return flow ranges between 15 and 20 years.

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Table E2-1: Specific Yield of Sediment Types

Lithology ID	Lithology Code	Lithology Description	Specific Yield
1	PEAFILL	Aggregate base	0.25
2	ASPHALT	Asphalt	0
3	BASALT	Basalt	0.03
4	B	Boulders/cobbles	0.25
5	B-C	Boulders/cobbles with Clay	0.05
6	B-G	Boulders/cobbles with Gravel	0.25
7	B-GC	Boulders/cobbles with Gravel and Clay	0.05
8	B-GS	Boulders/cobbles with Gravel and Sand	0.25
9	B-GM	Boulders/cobbles with Gravel and Silt	0.1
10	B-GSC	Boulders/cobbles with Gravel, Sand and Clay	0.1
11	B-GSM	Boulders/cobbles with Gravel, Sand and Silt	0.1
12	B-GSMC	Boulders/cobbles with Gravel, Sand, Silt and Clay	0.1
13	B-GMC	Boulders/cobbles with Gravel, Silt and Clay	0.05
14	B-S	Boulders/cobbles with Sand	0.25
15	B-SC	Boulders/cobbles with Sand and Clay	0.1
16	B-SM	Boulders/cobbles with Sand and Silt	0.1
17	B-SMC	Boulders/cobbles with Sand, Silt and Clay	0.05
18	B-M	Boulders/cobbles with Silt	0.1
19	B-MC	Boulders/cobbles with Silt and Clay	0.05
20	BRECCIA	Breccia	0.05
21	CHALK	Chalk	0.05
22	C	Clay	0.03
23	C-G	Clay with Gravel	0.05
24	C-GS	Clay with Gravel and Sand	0.1
25	C-GM	Clay with Gravel and Silt	0.05
26	C-GSM	Clay with Gravel, Sand and Silt	0.1
27	C-S	Clay with Sand	0.1
28	C-SM	Clay with Sand and Silt	0.05
29	C-M	Clay with Silt	0.05
30	CLAYSTONE	Claystone	0.03
31	COAL	Coal	0.01
32	CONCRETE	Concrete	0
33	CONGLOM	Conglomerate	0.05
34	CALICHE	Caliche	0.05
35	CRYSTALINE BEDROCK	Crystaline Bedrock	0
36	DG	Decomposed Granite	0.03
37	FILL	Fill (made ground)	0.05
38	FRACTURED BASALT	Fractured Basalt	0.1
39	FB	Fractured Bedrock	0.01
40	FG	Fractured Granite	0.01
41	TILL	Glacial Till	0.1
42	GRANITE	Granite	0
43	G	Gravel	0.25
44	G-C	Gravel with Clay	0.05
45	G-S	Gravel with Sand	0.25
46	G-SC	Gravel with Sand and Clay	0.1
47	G-SM	Gravel with Sand and Silt	0.1
48	G-SMC	Gravel with Sand, Silt and Clay	0.1
49	G-M	Gravel with Silt	0.1
50	G-MC	Gravel with Silt and Clay	0.05
51	GYPSUM	Gypsum, Rocksalt, etc.	0.01
52	SAND/SILTSTONE	Interbedded Sandstone/Siltstone	0.05
53	LIMESTONE	Limestone	0.01
54	PEAT	Peat	0.03
55	PUMICE	Pumice	0.1
56	S	Sand	0.25
57	S-C	Sand with Clay	0.1
58	S-G	Sand with Gravel	0.25
59	S-GC	Sand with Gravel and Clay	0.1
60	S-GM	Sand with Gravel and Silt	0.1
61	S-GMC	Sand with Gravel, Silt and Clay	0.1
62	S-M	Sand with Silt	0.1
63	S-MC	Sand with Silt and Clay	0.1
64	SANDSTONE	Sandstone	0.05
65	SCHIST	Schist or mica schist	0
66	SEDIMENTARY BEDROCK	Sedimentary Bedrock	0.05
67	SHALE	Shale	0.03
68	M	Silt	0.05
69	M-C	Silt with Clay	0.05
70	M-G	Silt with Gravel	0.05
71	M-GC	Silt with Gravel and Clay	0.05
72	M-GS	Silt with Gravel and Sand	0.1
73	M-GSC	Silt with Gravel, Sand and Clay	0.1
74	M-S	Silt with Sand	0.1
75	M-SC	Silt with Sand and Clay	0.05
76	SILTSTONE	Siltstone	0.05
77	TOPSOIL	Topsoil	0.05
78	VOLCANIC ASH	Volcanic Ash	0.05
79	WEATHERED BEDROCK	Weathered Bedrock	0.03

Table E2-2: Summary of Water Derived from Compaction 1930 - 2005

Subsidence Rate Time Period	Period Length (years)	Volumetric Rate of Subsidence (acre feet/year)	Water Derived from Compaction (acre feet)	Natural Recharge Time Period	Water Derived from Compaction (acre feet)
1951-57[1]	6	2,978	17,868	1951-63[3]	116,976
1957-62	5	17,737	88,683		
1962-63	1	10,425	10,425		
1963-65	2	41,994	83,988	1963-71	141,222
1965-71	6	9,539	57,234		
1971-72	1	19,078	19,078	1971-85	140,349
1972-75	3	18,870	56,611		
1975-81	6	9,778	58,667		
1981-85	4	1,498	5,993		
1985-92	7	1,498	10,488	1985-92	10,488
1992	1	1,498	1,498	1992-98[2]	8,988
1993-98[2]	5	1,498	7,490		
1998-05[2,4]	8	1,498	11,984	1998-05[2]	11,984

Notes:

1) Values derived from the average rate of subsidence from 1930-1957 (2,978 af/yr).

2) Estimates based upon the assumption that water from compaction remains stable at 1992 rates (1,498 af/yr) over the time periods 1992-1998 and 1998-2005.

3) The sum of the measured subsidence from 1957-1963 (99,108 af) and the average rate of subsidence from 1930-1957 (2,978 af/yr) over the period 1951-1957 (2,978 af/yr x 6 yrs).

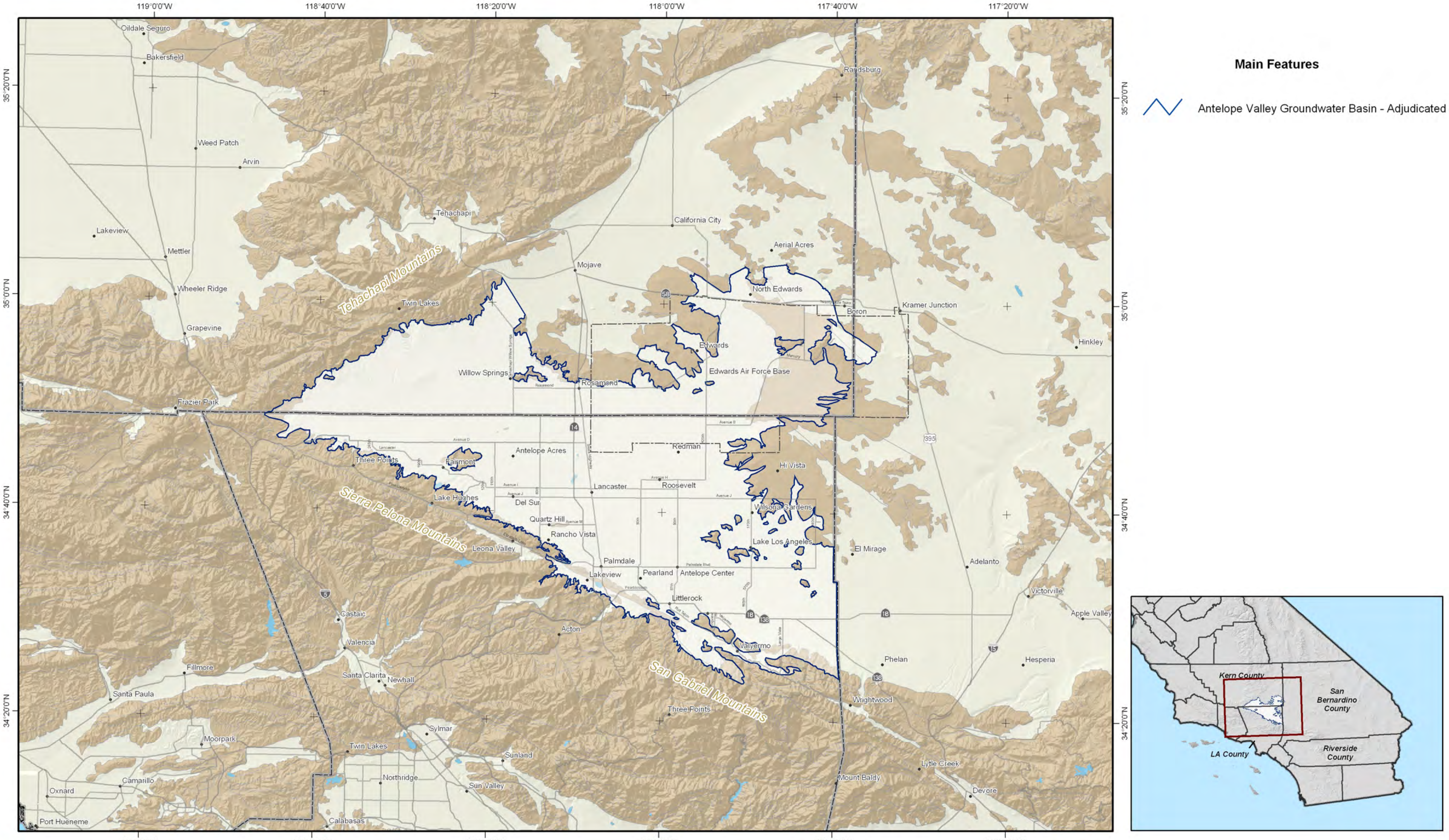
4) The 1998-2005 time period extends through the end of 2005.

Table E2-3: Change in Storage for 1951 - 2009

Period	Storage Change				
	Gravity Drainage (acre-ft)	Compaction (acre-ft)	Total (acre-ft)	Gravity Drainage	Compaction
1951-1962	-3,229,489	-117,000	-3,346,489	62%	27%
1963-1970	-1,220,748	-141,000	-1,361,748	24%	33%
1971-1978	-361,432	-80,000	-441,432	7%	19%
1979-1984	31,751	-60,000	-28,249	-1%	14%
1985-1991	24,971	-10,000	14,971	0%	2%
1992-1997	209,801	-9,000	200,801	-4%	2%
1998-2005	-485,163	-12,000	-497,163	9%	3%
2006-2009	-153,400	N/A	-153,400	3%	
1951-2009	-5,183,709	-429,000	-5,612,709		

Notes:

N/A - Not analyzed owing to lack of subsidence data for the 2006 to 2009 time period.



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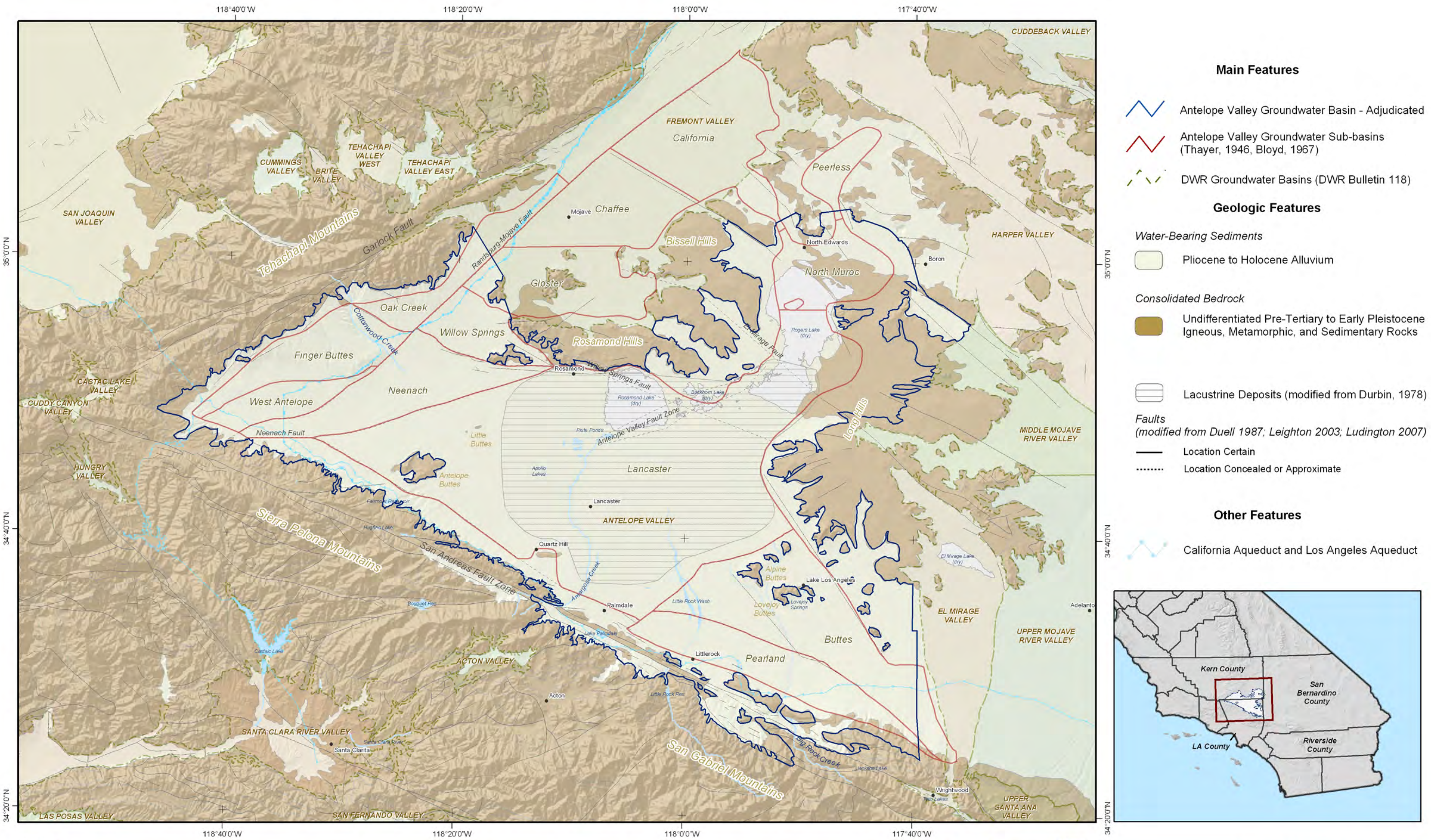
Study Area

Antelope Valley Groundwater Basin

Figure E2-1



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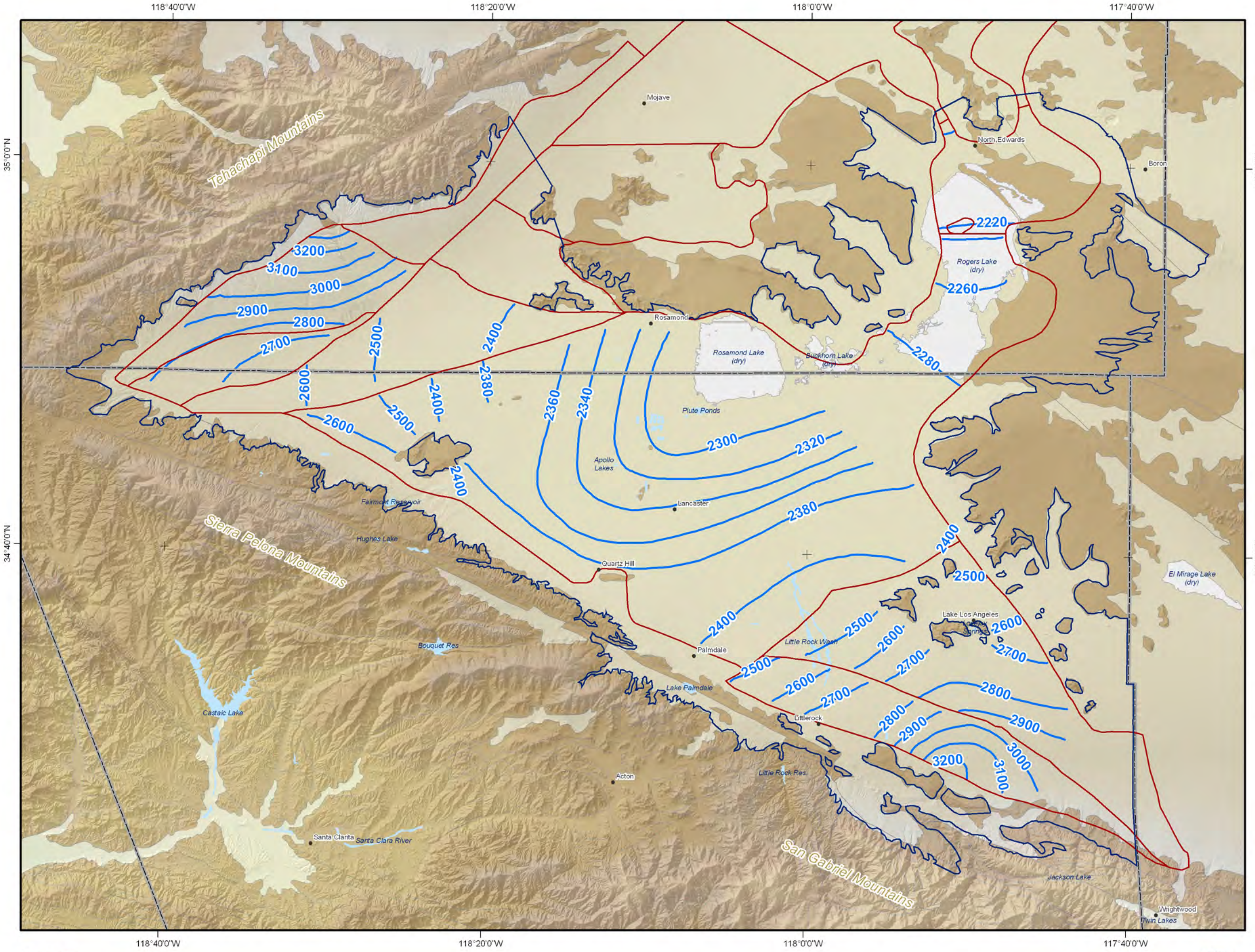
General Geologic Setting
Antelope Valley Groundwater Basin

Figure E2-2



Main Features

Groundwater Elevation Contour (feet above msl)

Antelope Valley Groundwater Basin - Adjudicated

Antelope Valley Groundwater Sub-basins

Geologic Features

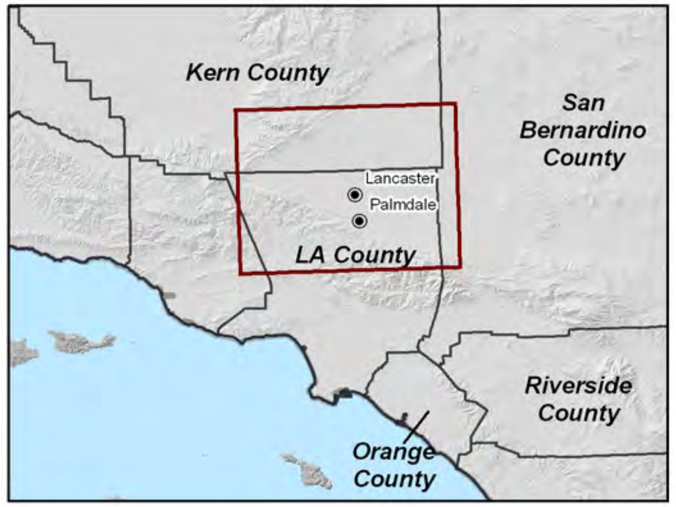
Water-Bearing Sediments

Pliocene to Holocene Alluvium

Consolidated Bedrock

Undifferentiated Pre-Tertiary to Early Pleistocene Igneous, Metamorphic, and Sedimentary Rocks

Note: Groundwater elevation contours from Durbin, 1978.



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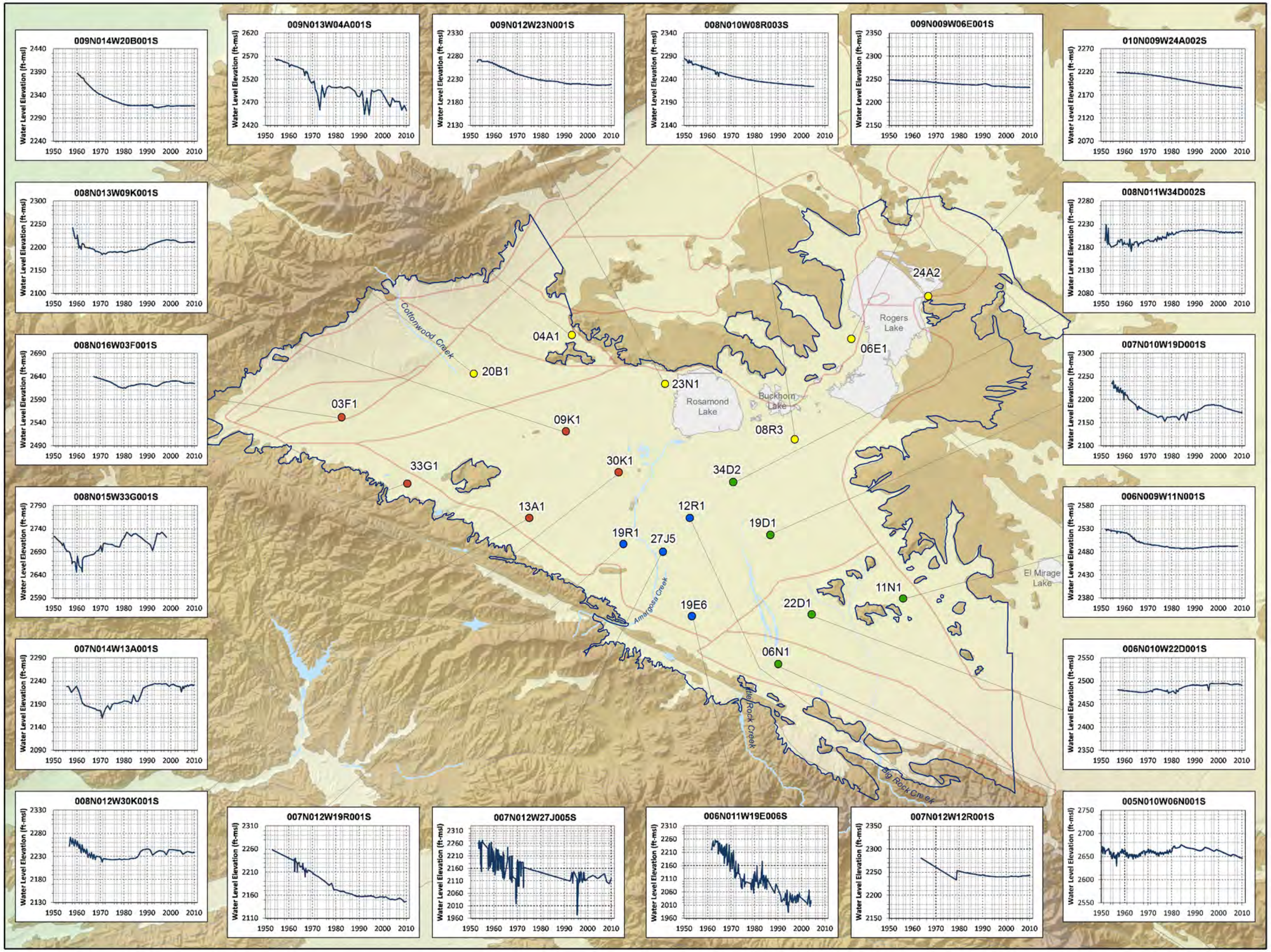
Groundwater Elevation Contours - 1915

Antelope Valley Groundwater Basin

Figure E2-3



Main Features

- 🔴 West Antelope Valley
- 🟢 East Antelope Valley
- 🟡 North Antelope Valley
- 🔵 South Antelope Valley

╱╲ Antelope Valley Groundwater Basin - Adjudicated

╱╲ Antelope Valley Groundwater Sub-basins

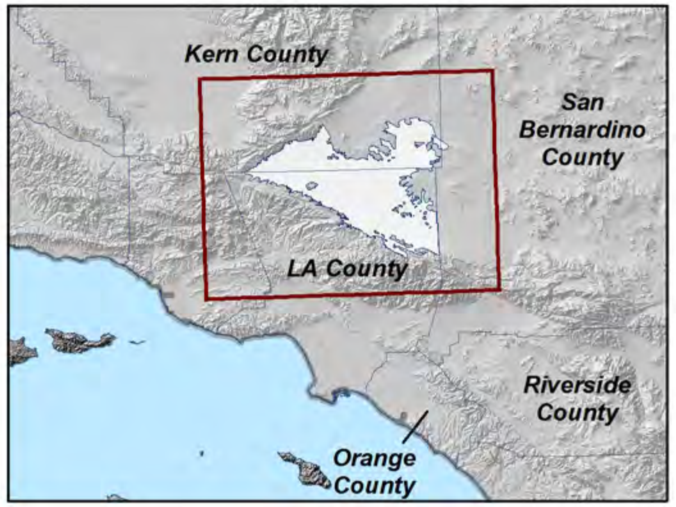
Geologic Features

Water-Bearing Sediments

▭ Pliocene to Holocene Alluvium

Consolidated Bedrock

▨ Undifferentiated Pre-Tertiary to Early Pleistocene Igneous, Metamorphic, and Sedimentary Rocks



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File: hydrograph_analysis_report.mxd

0 10 20 Miles
0 10 20 Kilometers

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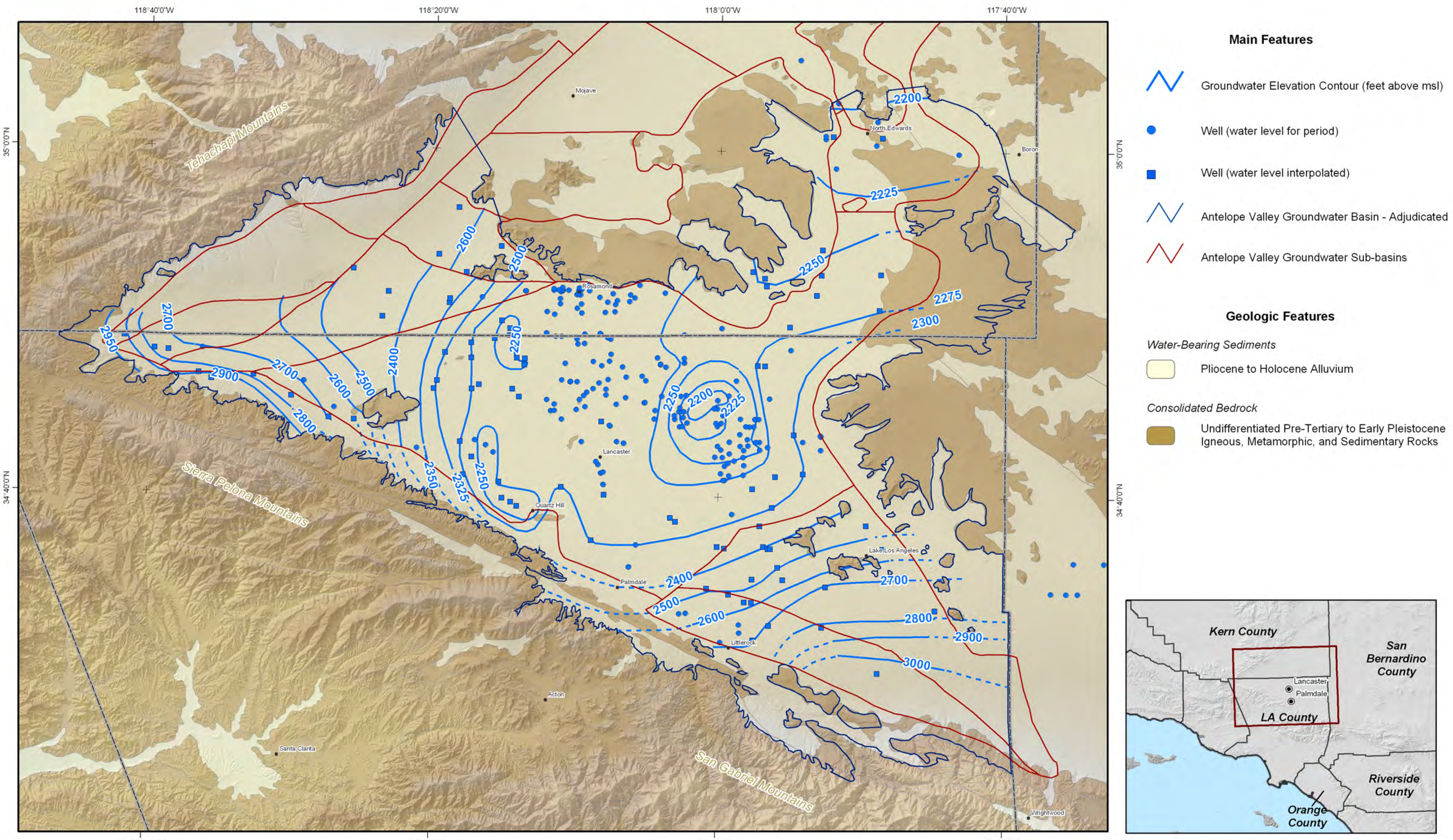
Groundwater Elevation Trends

Antelope Valley Groundwater Basin

Figure E2-4



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File: 1951_wl.mxd

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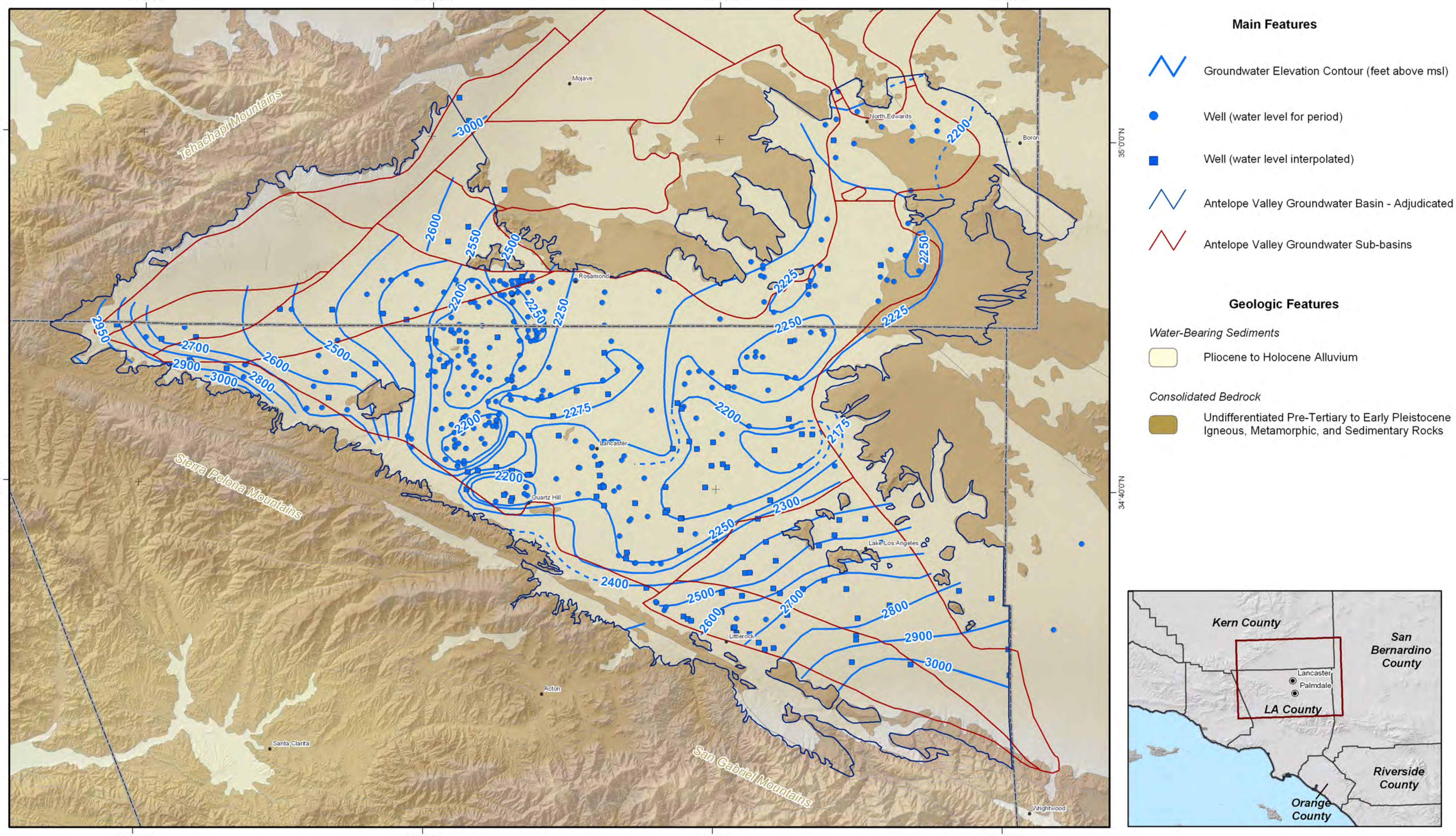
Groundwater Elevation Contours - 1951

Antelope Valley Groundwater Basin

Figure E2-5



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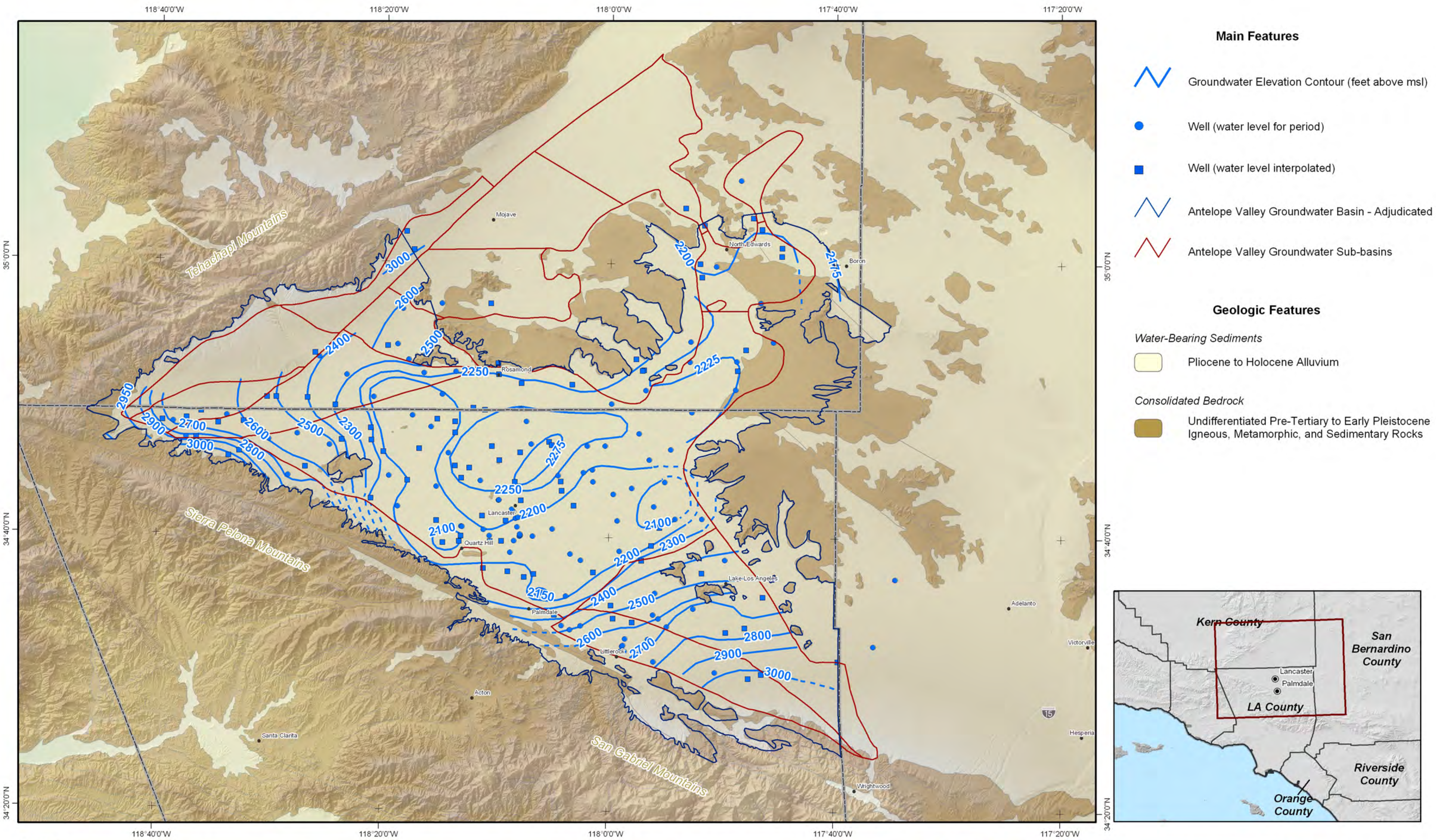
Groundwater Elevation Contours - 1963

Antelope Valley Groundwater Basin

Figure E2-6



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0 6 12 Miles
0 10 20 Kilometers

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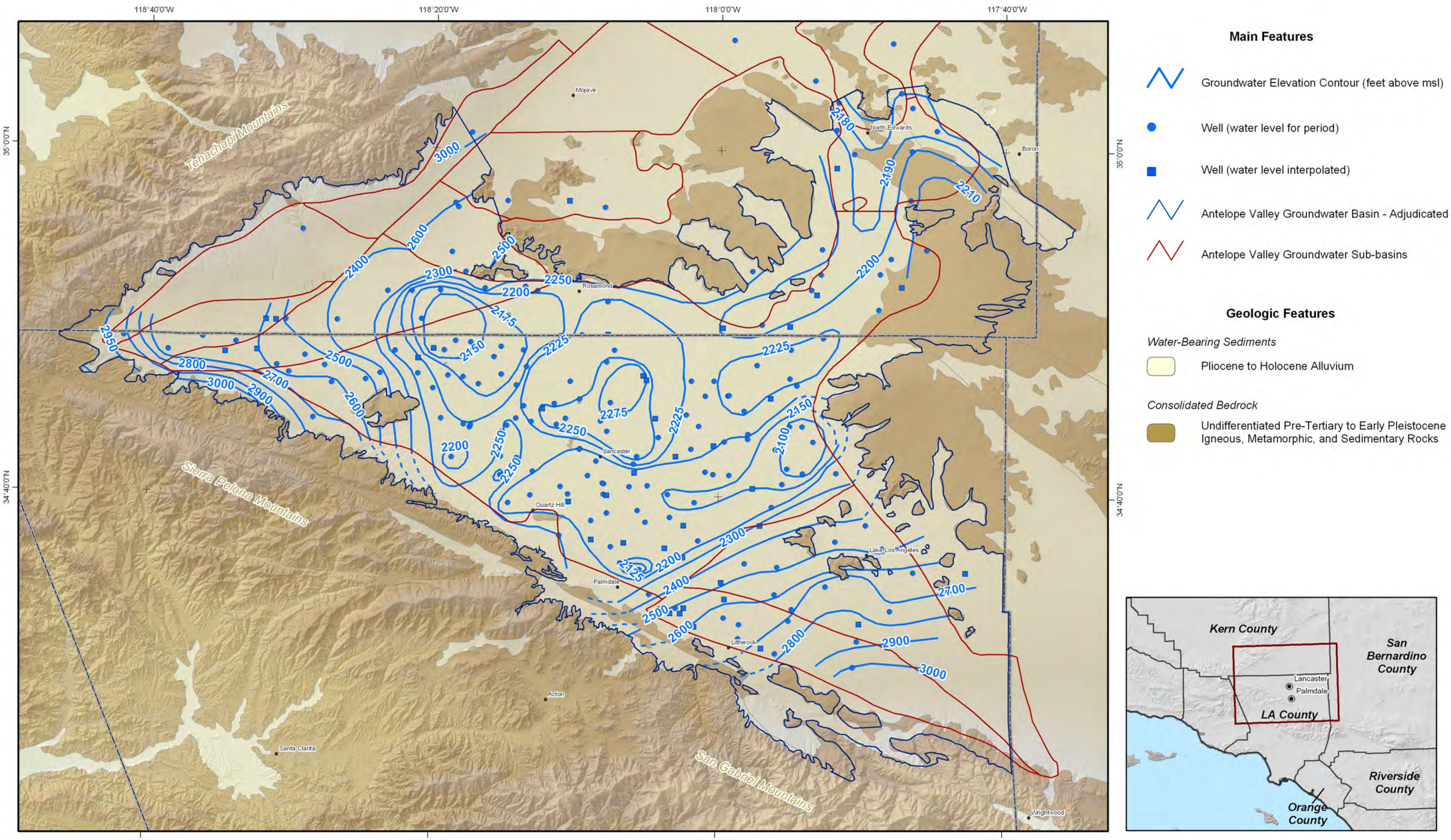
Groundwater Elevation Contours - 1971

Antelope Valley Groundwater Basin

Figure E2-7



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File: 1979_wl.mxd

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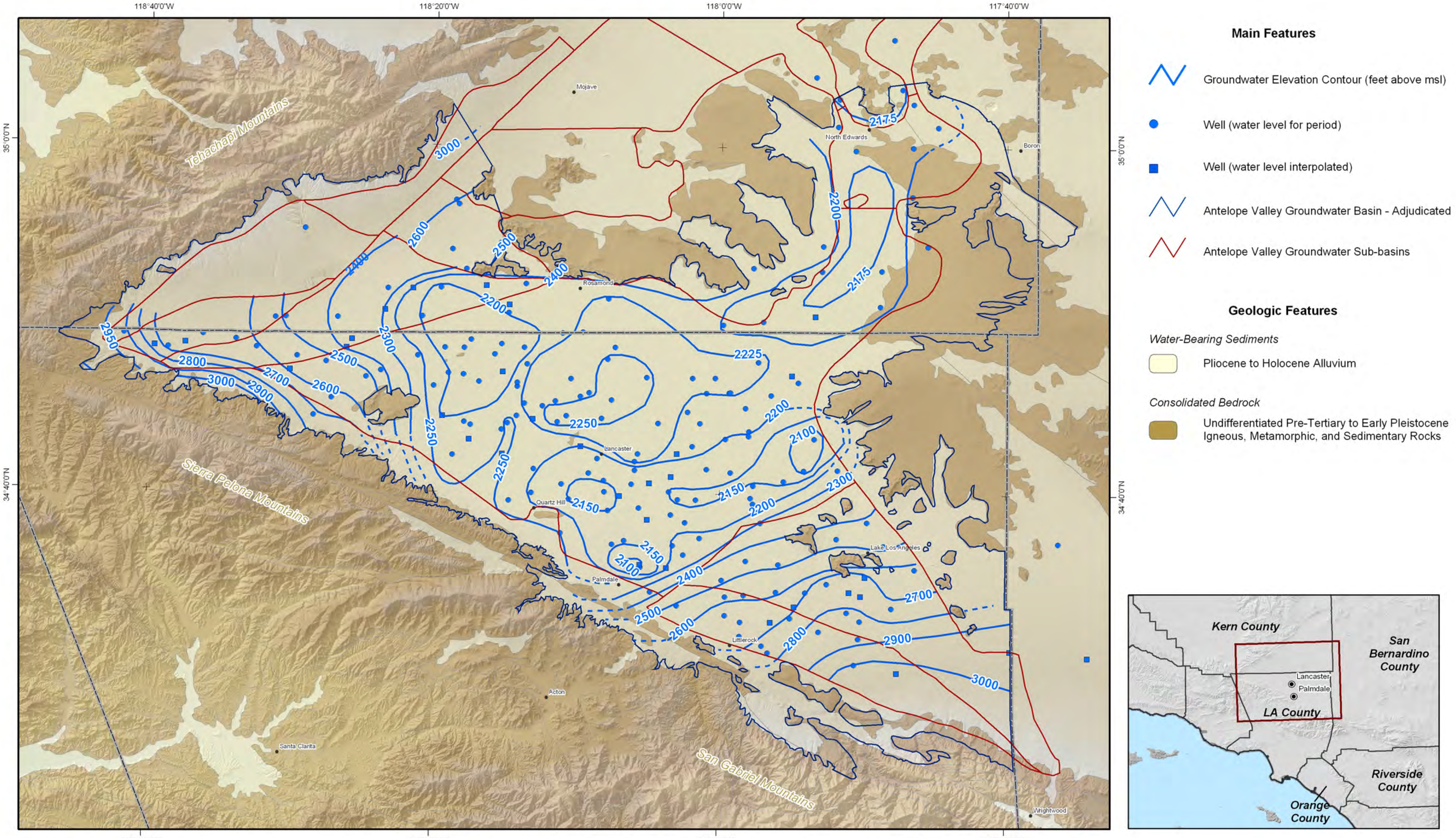
Groundwater Elevation Contours - 1979

Antelope Valley Groundwater Basin

Figure E2-8



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0 6 12 Miles
0 10 20 Kilometers

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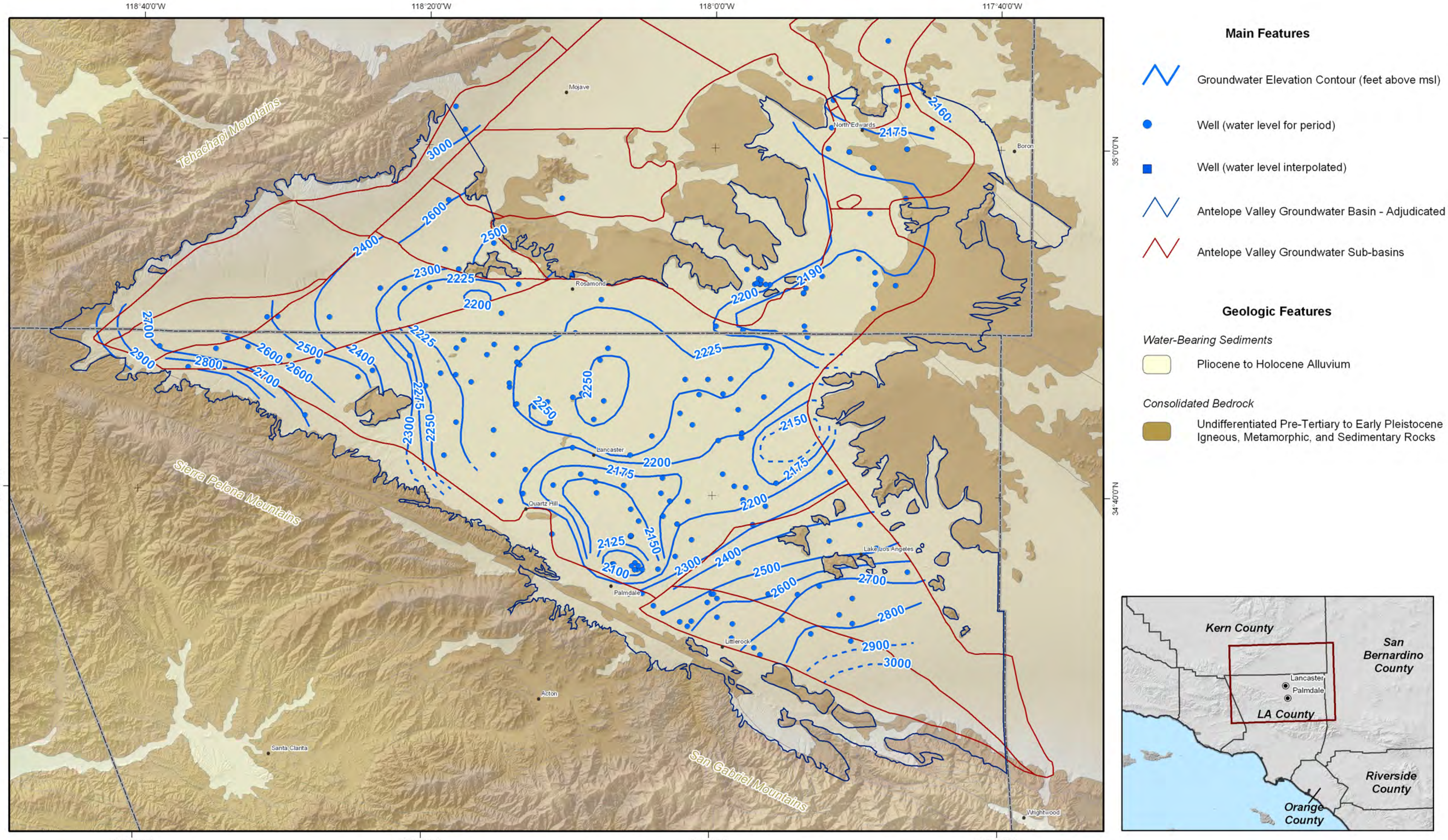
Groundwater Elevation Contours - 1985

Antelope Valley Groundwater Basin

Figure E2-9



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0 6 12 Miles
0 10 20 Kilometers

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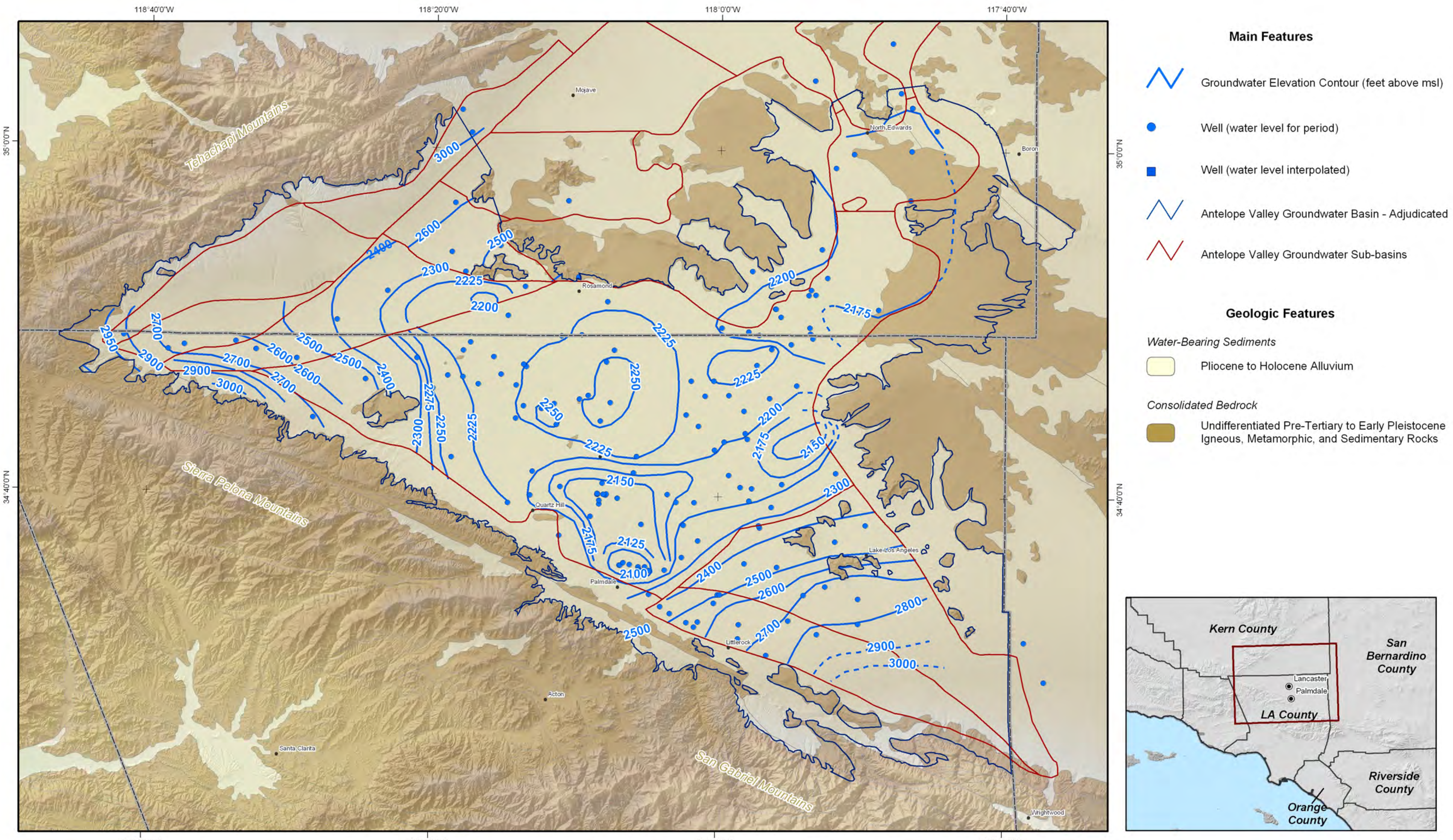
Groundwater Elevation Contours - 1992

Antelope Valley Groundwater Basin

Figure E2-10



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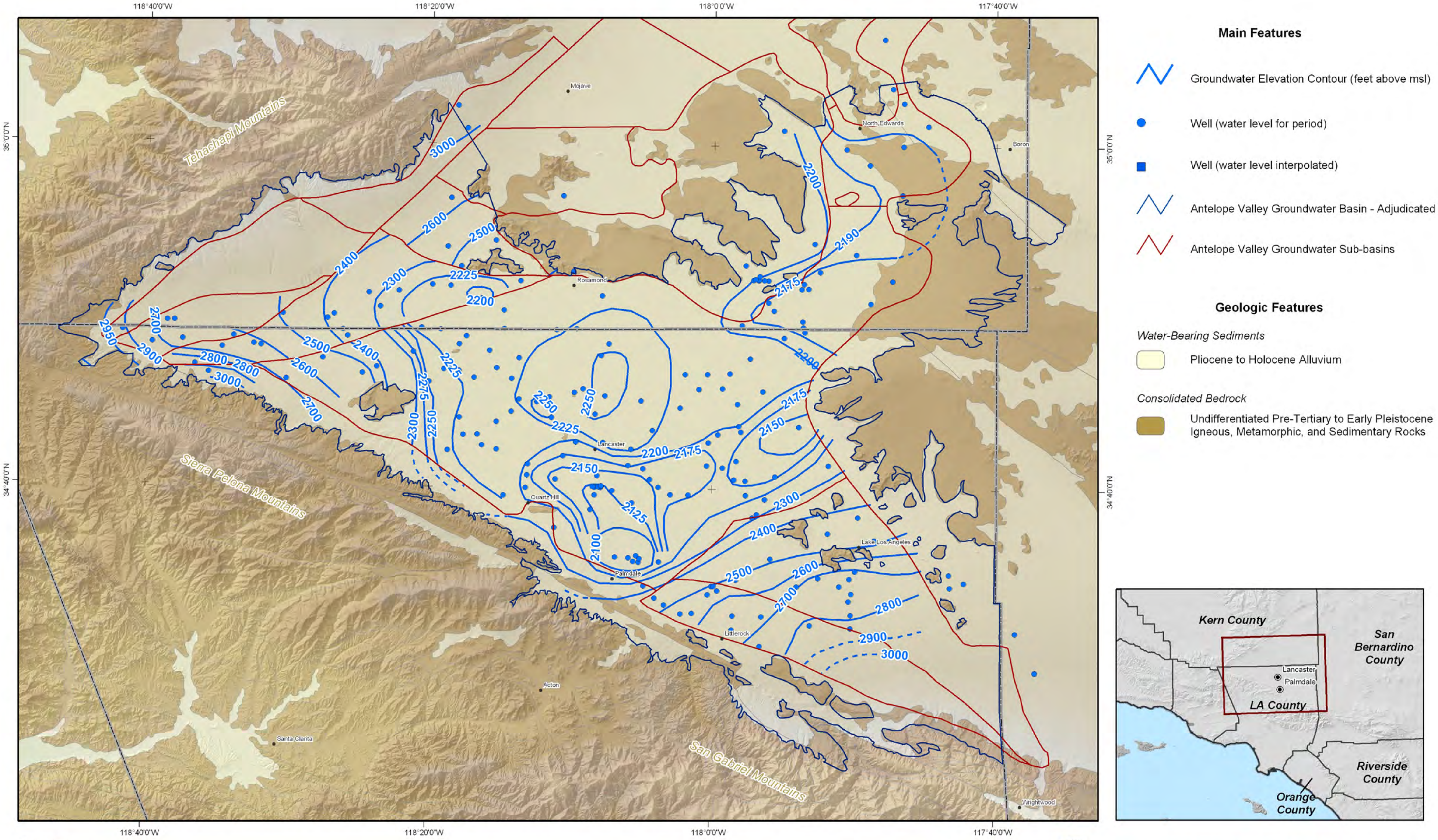
Groundwater Elevation Contours - 1998

Antelope Valley Groundwater Basin

Figure E2-11



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File: 2005_wl.mxd

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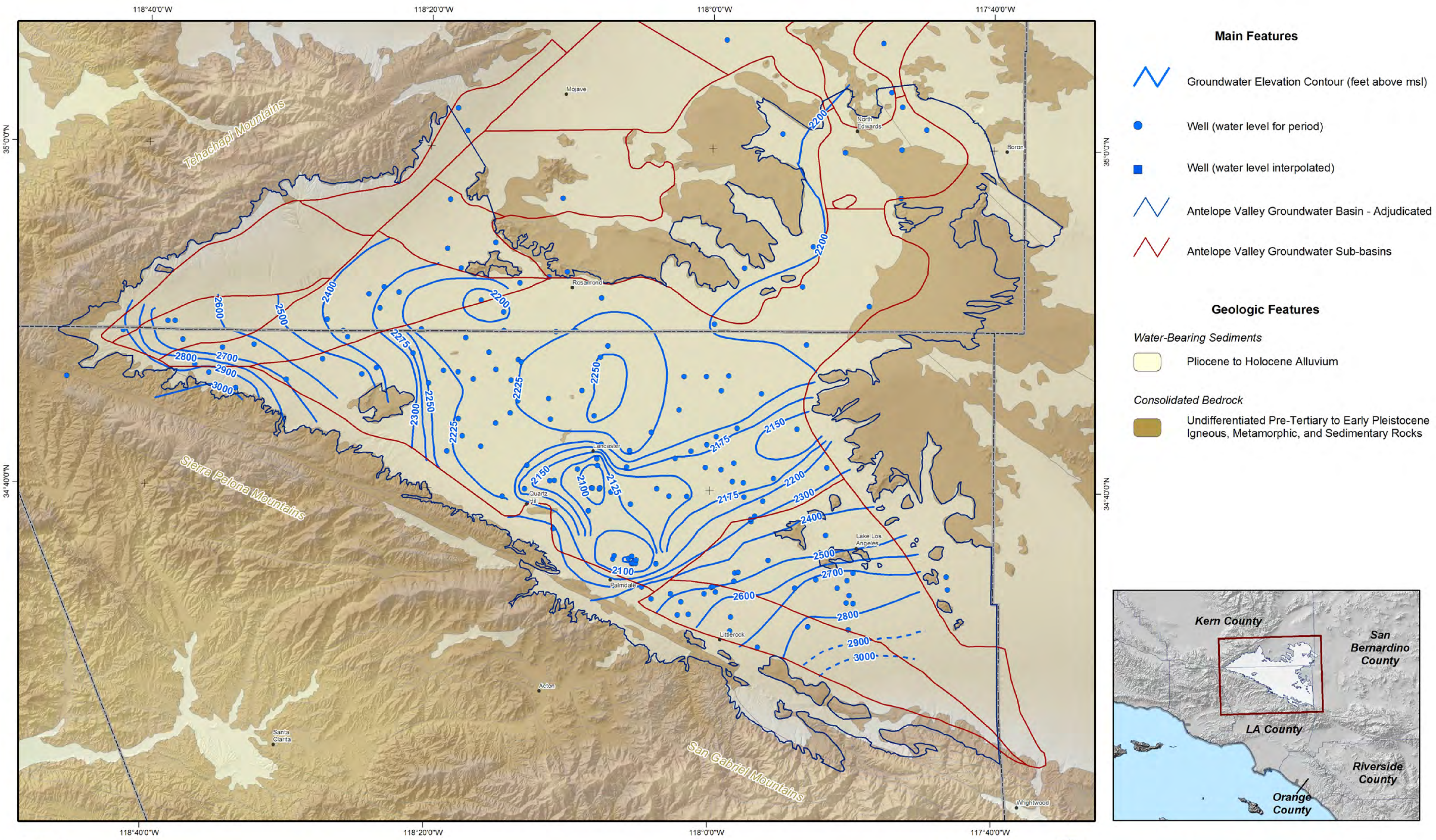
Groundwater Elevation Contours - 2005

Antelope Valley Groundwater Basin

Figure E2-12



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0 6 12 Miles
0 10 20 Kilometers

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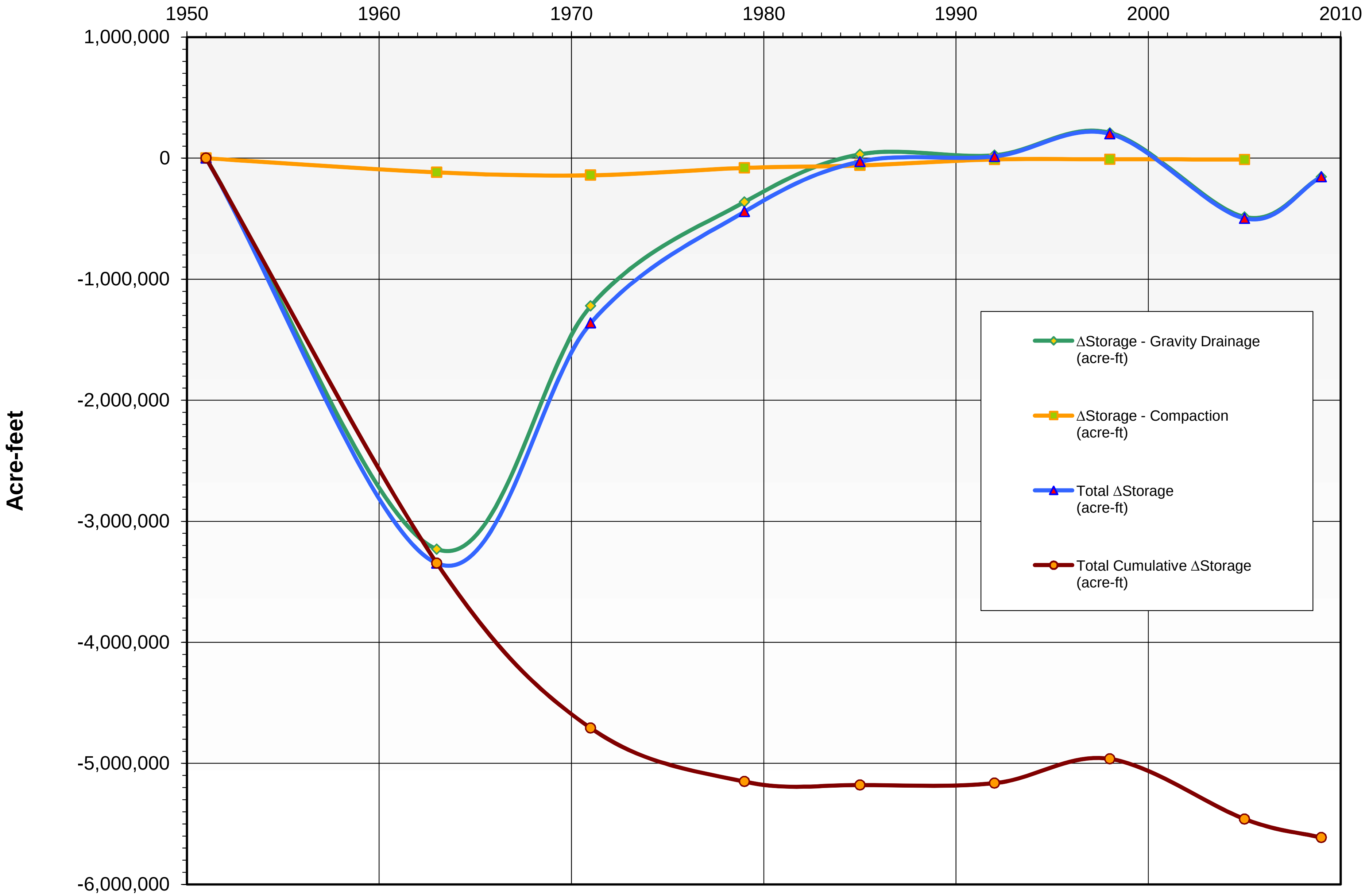
001

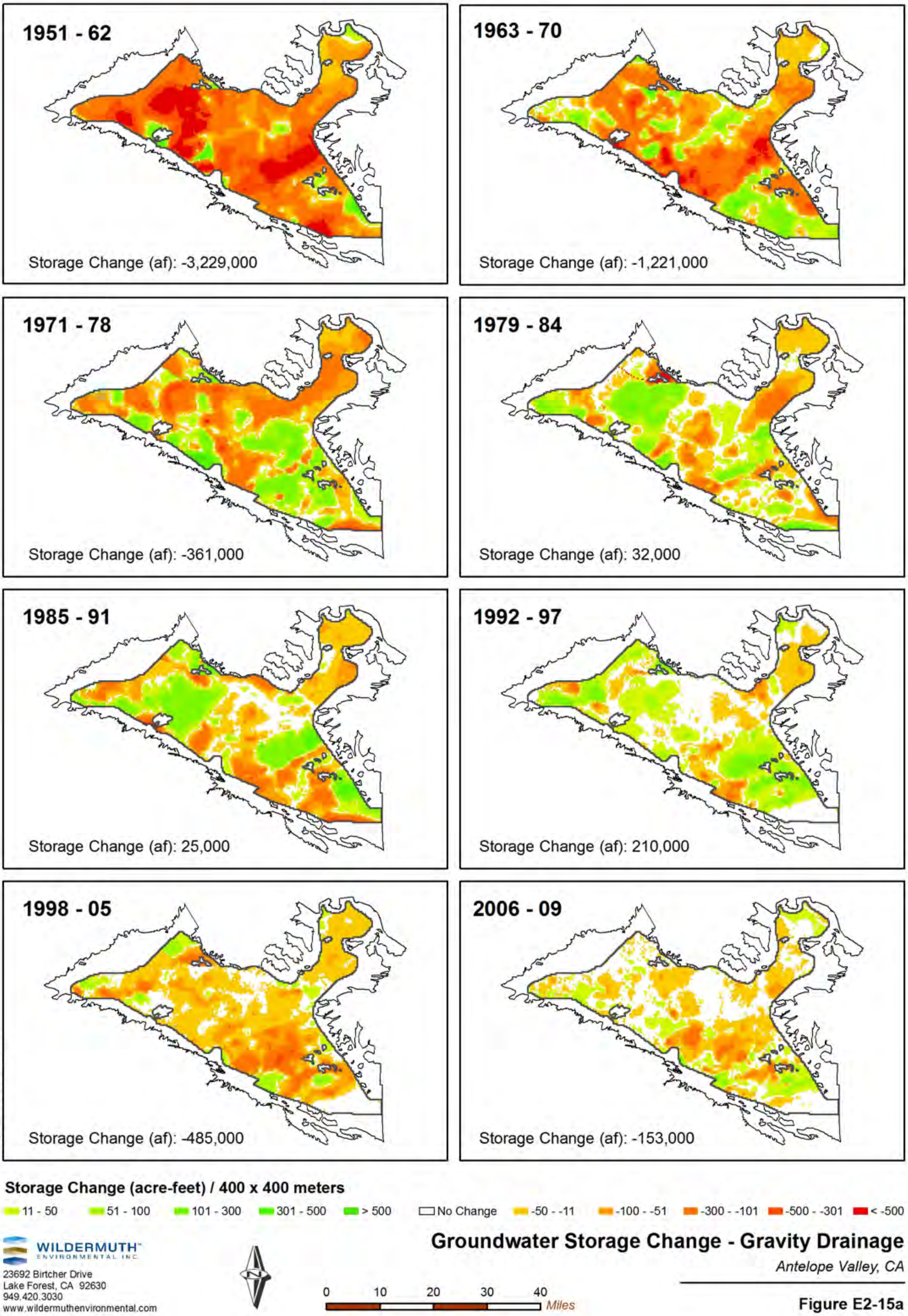
Groundwater Elevation Contours - 2009

Antelope Valley Groundwater Basin

Figure E2-13

Figure E2-14: Storage Change and Storage Change Components 1951 - 2009





Groundwater Storage Change - Gravity Drainage

Antelope Valley, CA

Figure E2-15a

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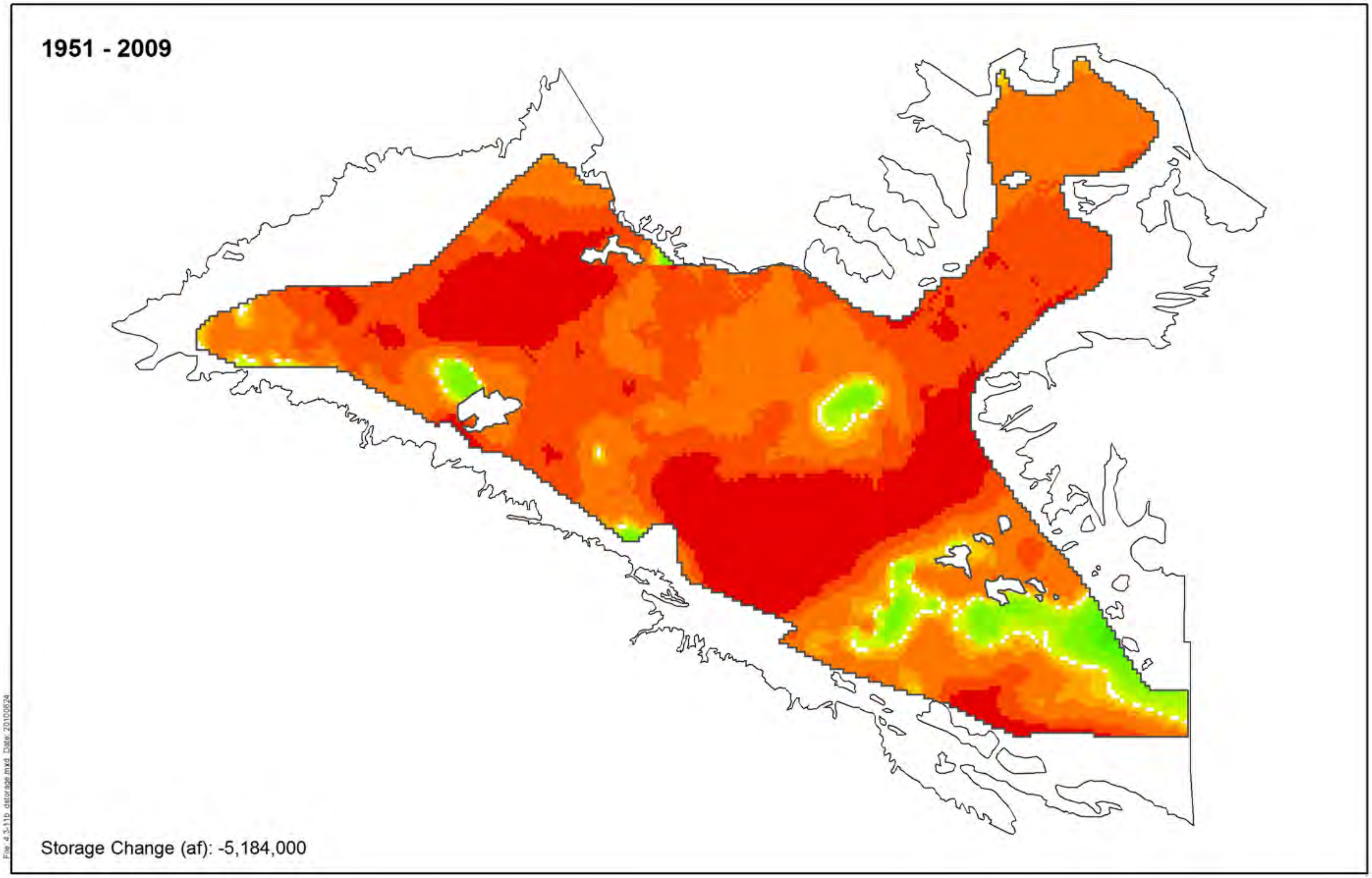

Storage Change (acre-feet) / 400 x 400 meters

🟩 11 - 50 🟩 51 - 100 🟩 101 - 300 🟩 301 - 500 🟩 > 500 ☐ No Change 🟨 -50 - -11 🟧 -100 - -51 🟧 -300 - -101 🟥 -500 - -301 🟥 < -500

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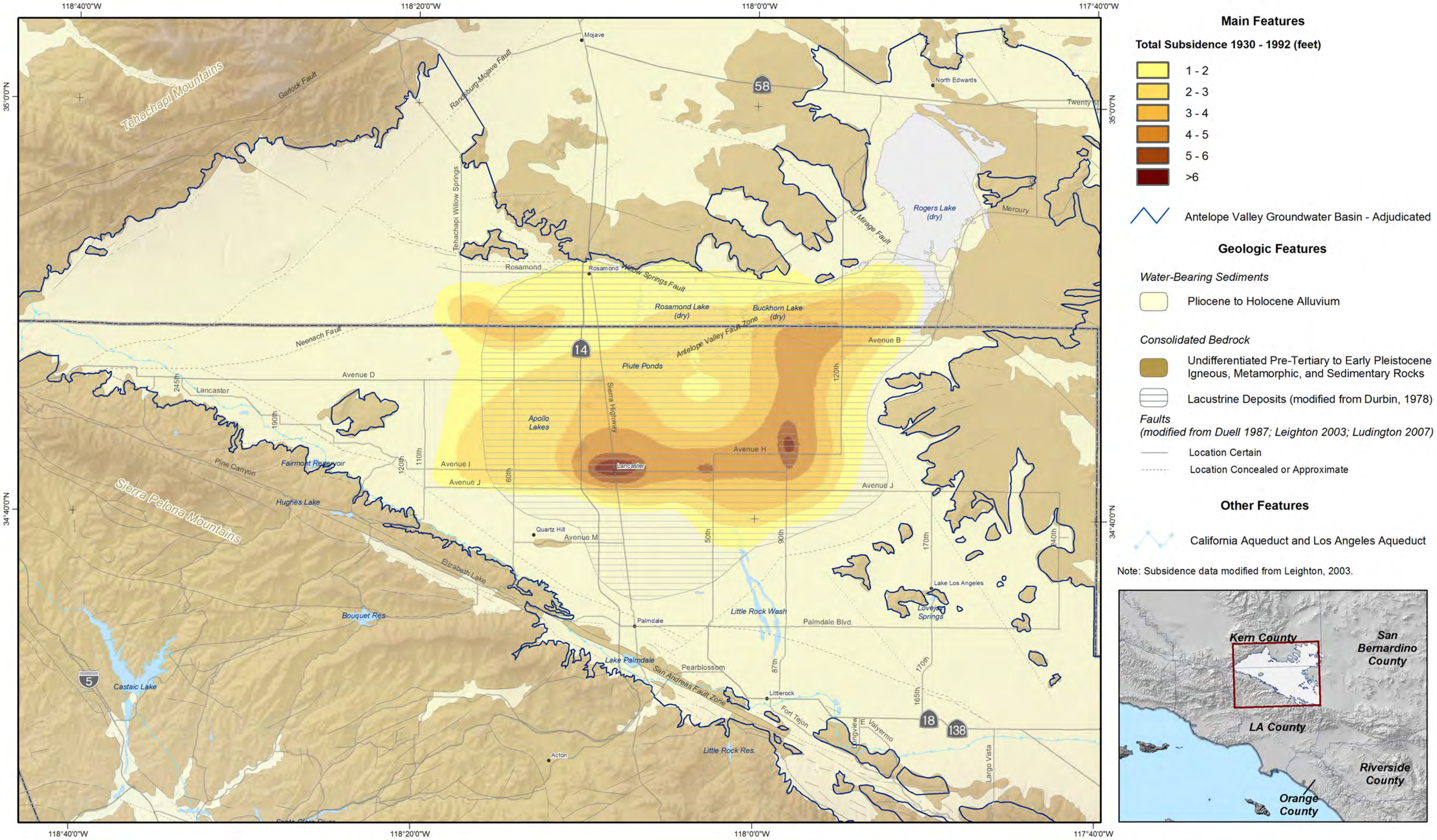
0 10 20 Miles
0 10 20 Kilometers

Groundwater Storage Change - Gravity Drainage

Antelope Valley, CA

Figure E2-15b



Main Features

Total Subsidence 1930 - 1992 (feet)

🟨	1 - 2
🟨	2 - 3
🟧	3 - 4
🟧	4 - 5
🟫	5 - 6
🟥	>6

Antelope Valley Groundwater Basin - Adjudicated

Geologic Features

Water-Bearing Sediments

Pliocene to Holocene Alluvium

Consolidated Bedrock

Undifferentiated Pre-Tertiary to Early Pleistocene Igneous, Metamorphic, and Sedimentary Rocks

Lacustrine Deposits (modified from Durbin, 1978)

Faults
(modified from Duell 1987; Leighton 2003; Ludington 2007)

Location Certain

Location Concealed or Approximate

Other Features

California Aqueduct and Los Angeles Aqueduct

Note: Subsidence data modified from Leighton, 2003.

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0 5 10 Miles

0 10 20 Kilometers

Total Subsidence 1930 to 1992

Antelope Valley Groundwater Basin

Figure E2-16

Table E3-1

Estimated Inflow, Outflow and Change in Storage for the Antelope Valley Adjudication Area, 1951 through 2005

(acre-ft)

Period	Year	Inflow											Outflow[3]				Change in Storage		
		Natural Recharge		Return Flow					Artificial Recharge[7]		Compaction	Total Inflow	Agricultural Pumping	Urban Pumping	Other Outflow	Total Outflow	Computed	Measured	Difference
		Runoff	Mountain Front	Agriculture[1]		Urban/M&I[2]													
				Gross[4]	Net[5]	Irrigation	Septics	Recycled Water[6]	Spreading	Injection									
1951-1962	1951	6,300		108,765	43,383	544	1,205	0	0	0	-9,750	41,683	362,549	6,039	300	368,889	-327,206	-278,874	-48,332
	1952	88,000		107,357	47,713	571	1,122	0	0	0	-9,750	127,656	357,856	5,550	300	363,706	-236,050	-278,874	42,824
	1953	24,100		105,949	52,044	597	1,853	116	0	0	-9,750	68,960	353,162	9,821	300	363,283	-294,324	-278,874	-15,449
	1954	35,300		104,540	56,374	623	1,886	109	0	0	-9,750	84,542	348,468	10,013	300	358,781	-274,239	-278,874	4,635
	1955	30,200		103,132	60,704	650	1,974	142	0	0	-9,750	83,920	343,774	10,529	300	354,603	-270,683	-278,874	8,191
	1956	21,978		101,724	63,882	676	2,656	185	0	0	-9,750	79,627	339,081	13,088	300	352,469	-272,842	-278,874	6,032
	1957	21,048		100,316	67,060	702	2,450	171	0	0	-9,750	81,681	334,387	12,553	300	347,240	-265,559	-278,874	13,315
	1958	117,066		102,039	70,238	729	2,542	70	0	0	-9,750	180,894	340,131	12,409	300	352,840	-171,946	-278,874	106,928
	1959	25,789		103,762	73,416	755	3,092	42	0	0	-9,750	93,343	345,792	16,745	300	362,836	-269,493	-278,874	9,381
	1960	10,815		105,485	76,593	781	2,589	26	0	0	-9,750	81,055	351,535	14,736	300	366,571	-285,516	-278,874	-6,642
	1961	9,200		107,209	82,188	808	3,874	23	0	0	-9,750	86,343	357,279	22,625	300	380,204	-293,861	-278,874	-14,987
	1962	61,866		102,946	89,027	775	5,341	41	0	0	-9,750	147,301	351,143	25,658	300	377,101	-229,801	-278,874	49,073
1963-1970	1963	17,564		98,684	96,749	852	3,581	37	0	0	-17,625	101,158	345,022	20,776	300	366,098	-264,940	-170,219	-94,722
	1964	14,938		94,421	98,305	1,023	3,900	56	0	0	-17,625	100,597	338,862	22,514	300	361,677	-261,080	-170,219	-90,861
	1965	19,582		90,159	104,303	818	3,903	92	0	0	-17,625	111,072	332,652	21,475	300	354,427	-243,355	-170,219	-73,136
	1966	106,700		85,896	108,765	774	4,134	103	0	0	-17,625	202,851	326,530	24,141	300	350,972	-148,121	-170,219	22,098
	1967	98,100		81,634	107,357	721	3,917	124	0	0	-17,625	192,593	320,209	22,873	300	343,382	-150,789	-170,219	19,429
	1968	39,850		77,371	105,949	1,190	5,058	145	0	0	-17,625	134,567	314,087	26,387	300	340,775	-206,208	-170,219	-35,989
	1969	187,995		73,109	104,540	1,211	5,313	154	0	0	-17,625	281,589	307,878	28,920	300	337,098	-55,509	-170,219	114,709
	1970	37,255		68,846	103,132	1,268	4,707	152	0	0	-17,625	128,890	300,142	25,863	300	326,305	-197,415	-170,219	-27,196
1971-1978	1971	33,648		72,429	101,724	1,706	5,040	150	0	0	-10,000	132,269	308,917	27,896	300	337,113	-204,845	-55,179	-149,666
	1972	24,153		59,466	100,316	1,574	5,600	148	0	0	-10,000	121,791	255,911	31,196	300	287,408	-165,617	-55,179	-110,438
	1973	54,805		58,653	102,039	1,633	5,358	145	0	0	-10,000	153,980	250,227	29,582	300	280,109	-126,128	-55,179	-70,949
	1974	36,711		61,327	103,762	1,986	5,184	143	0	0	-10,000	137,786	257,480	29,130	300	286,911	-149,124	-55,179	-93,945
	1975	23,301		64,039	105,485	1,663	5,085	287	0	0	-10,000	125,822	266,373	27,891	300	294,563	-168,741	-55,179	-113,562
	1976	25,949		52,115	107,209	2,489	5,046	285	0	0	-10,000	130,977	197,077	28,100	300	225,477	-94,500	-55,179	-39,321
	1977	28,932		70,023	102,946	3,431	4,505	283	0	0	-10,000	130,097	266,118	25,743	300	292,160	-162,063	-55,179	-106,884
	1978	229,688		63,991	98,684	2,300	4,959	281	0	0	-10,000	325,911	236,472	21,452	300	258,224	67,688	-55,179	122,867
1979-1984	1979	96,337		55,533	94,421	2,505	5,293	279	0	0	-10,000	188,835	190,180	22,525	300	213,005	-24,170	-4,708	-19,462
	1980	157,937		58,345	90,159	2,507	5,166	890	0	0	-10,000	246,659	193,315	22,147	300	215,762	30,896	-4,708	35,605
	1981	22,822		52,196	85,896	2,656	5,521	1,303	0	0	-10,000	108,198	160,637	20,889	300	181,825	-73,628	-4,708	-68,920
	1982	47,916		44,705	81,634	2,516	5,697	2,418	0	0	-10,000	130,181	152,229	24,408	300	176,938	-46,757	-4,708	-42,049
	1983	174,587		42,747	77,371	3,249	4,665	1,929	0	0	-10,000	251,800	157,425	19,711	300	177,436	74,364	-4,708	79,072
	1984	35,909		37,326	73,109	3,413	6,513	2,046	0	0	-10,000	110,989	139,104	26,308	300	165,712	-54,723	-4,708	-50,015
1985-1991	1985	24,465		33,374	68,846	3,024	7,125	2,239	0	0	-1,498	104,201	118,844	25,343	300	144,487	-40,286	2,139	-42,424
	1986	63,218		27,371	72,429	3,238	8,244	2,474	0	0	-1,498	148,104	100,691	29,936	300	130,927	17,177	2,139	15,039
	1987	18,900		21,197	59,466	3,597	9,103	3,241	0	0	-1,498	92,809	78,727	31,652	300	110,679	-17,870	2,139	-20,009
	1988	59,070		24,950	58,653	3,442	9,730	3,349	0	0	-1,498	132,747	89,925	34,607	300	124,832	7,915	2,139	5,776
	1989	27,000		15,488	61,327	3,330	11,840	6,437	0	0	-1,498	108,436	49,673	36,944	300	86,918	21,518	2,139	19,380
	1990	12,590		15,843	64,039	3,267	11,917	6,878	0	0	-1,498	97,193	51,052	34,205	300	85,557	11,636	2,139	9,497
	1991	34,264		15,125	52,115	3,241	9,948	6,657	0	0	-1,498	104,727	62,146	36,695	300	99,141	5,586	2,139	3,447
1992-1997	1992	78,135		19,606	70,023	2,894	11,021	6,308	0	0	-1,498	166,883	77,510	33,108	300	110,918	55,964	33,467	22,498
	1993	215,536		16,610	63,991	3,185	13,664	6,433	0	0	-1,498	301,311	61,654	38,366	300	100,319	200,992	33,467	167,525
	1994	27,533		17,198	55,533	3,400	14,919	6,429	0	0	-1,498	106,316	59,395	44,233	300	103,928	2,388	33,467	-31,079
	1995	115,729		19,800	58,345	3,318	15,037	6,877	0	0	-1,498	197,809	68,879	47,976	300	117,155	80,654	33,467	47,187
	1996	31,157		22,717	52,196	3,547	16,725	6,879	0	238	-1,498	109,243	74,152	49,134	300	123,585	-14,342	33,467	-47,809
	1997	23,237		25,419	44,705	3,660	16,843	7,163	0	656	-1,498	94,767	79,095	49,240	300	128,636	-33,869	33,467	-67,336
1998-2005	1998	118,860		27,019	42,747	2,996	15,105	7,729	0	0	-1,498	185,940	91,622	42,626	300	134,547	51,393	-62,145	113,538
	1999	20,850		28,216	37,326	4,184	17,630	7,357	0	0	-1,498	85,849	89,929	47,318	300	137,547	-51,698	-62,145	10,448
	2000	17,700		33,363	33,374	4,577	18,441	7,417	5,001	0	-1,498	85,012	106,667	47,703	300	154,670	-69,658	-62,145	-7,513
	2001	35,349		30,032	27,371	5,296	18,999	7,824	0	0	-1,498	93,340	101,109	56,278	300	157,687	-64,346	-62,145	-2,201
	2002	11,800		33,634	21,197	5,848	19,073	5,723	0	0	-1,498	62,143	120,376	52,005	300	172,680	-110,537	-62,145	-48,392
	2003	34,201		31,698	24,950	6,250	18,589	5,033	0	0	-1,498	87,526	116,302	46,682	300	163,284	-75,758	-62,145	-13,613
	2004	19,841		30,855	15,488	7,606	19,606	5,011	0	0	-1,498	66,054	111,690	52,602	300	164,591	-98,537	-62,145	-36,392
	2005	226,500		29,474	15,843	7,655	19,395	3,070	11	558	-1,498	271,535	102,054	49,341	300	151,695	119,840	-62,145	181,985

[1] Includes deep percolation of all applied water (from groundwater, local and imported surface water and recycled water).

[2] Urban/M&I return flows derive from municipal, industrial, mutual water company, water reclamation and rural residential uses. Returns derived from septic systems and reclamation are applied in the year of application. Returns derived from outside irrigation are lagged 15 years.

[3] Assumes no rising groundwater or outflow to phreatophtytes.

[4] "Gross" = deep percolation past root zone in year of water application/spreading.

[5] "Net" = arrival of previously applied/spread water at water table.

[6] From discharge, and inadvertant recharge, of treated municipal waste water for environmental and disposal purposes.

[7] Purposeful recharge of imported water to the groundwater system.

Table E3-2: Historical Water Requirements and Return Flows

(acre-feet)

Year	Agricultural		Municipal / Industrial and Domestic						Total
			Main M&I		Mutual Water Companies and Rural Residential				Ag, M&I and Domestic Return Flows
	Water Requirements	Return Flows	Water Requirements	Efficiency	MWC Water Requirements	Rural Res Water Requirements	Efficiency	Return Flows	
1919	77,565	23,269	776	0.755	39	62	0.439	247	23,516
1920	80,606	24,182	988	0.755	49	79	0.439	314	24,496
1921	88,834	26,650	1,199	0.755	60	96	0.439	381	27,031
1922	97,062	29,118	1,411	0.755	71	113	0.439	449	29,567
1923	105,290	31,587	1,623	0.755	81	130	0.439	516	32,103
1924	113,518	34,055	1,835	0.755	92	147	0.439	583	34,638
1925	121,746	36,524	2,047	0.755	102	164	0.439	651	37,175
1926	144,656	43,397	2,259	0.755	113	181	0.439	718	44,115
1927	167,566	50,270	2,471	0.755	124	198	0.439	785	51,055
1928	186,145	55,843	2,683	0.755	134	215	0.439	853	56,696
1929	204,724	61,417	2,895	0.755	145	232	0.439	920	62,337
1930	180,112	54,034	3,107	0.755	155	249	0.439	987	55,021
1931	170,125	51,037	3,318	0.755	166	265	0.439	1,055	52,092
1932	160,138	48,041	3,530	0.755	177	282	0.439	1,122	49,163
1933	150,150	45,045	3,742	0.755	187	299	0.439	1,189	46,234
1934	140,163	42,049	3,954	0.755	198	316	0.439	1,257	43,306
1935	130,176	39,053	4,166	0.755	208	333	0.439	1,324	40,377
1936	144,611	43,383	4,378	0.755	219	350	0.439	1,391	44,774
1937	159,045	47,713	4,590	0.755	229	367	0.439	1,459	49,172
1938	173,479	52,044	4,802	0.755	240	384	0.439	1,526	53,570
1939	187,914	56,374	5,014	0.755	251	401	0.439	1,593	57,967
1940	202,348	60,704	5,225	0.755	261	418	0.439	1,661	62,365
1941	212,941	63,882	5,437	0.755	272	435	0.439	1,728	65,610
1942	223,533	67,060	5,649	0.755	282	452	0.439	1,795	68,855
1943	234,126	70,238	5,861	0.755	293	469	0.439	1,863	72,100
1944	244,719	73,416	6,073	0.755	304	486	0.439	1,930	75,346
1945	255,311	76,593	6,285	0.755	314	503	0.439	1,997	78,591
1946	273,960	82,188	6,497	0.755	325	520	0.439	2,065	84,253
1947	296,757	89,027	6,238	0.755	312	499	0.439	1,983	91,010
1948	322,497	96,749	6,856	0.755	343	548	0.439	2,179	98,928
1949	327,685	98,305	8,226	0.755	411	658	0.439	2,614	100,920
1950	347,676	104,303	6,577	0.755	329	526	0.439	2,090	106,393
1951	362,549	108,765	6,229	0.755	311	498	0.439	1,980	110,745
1952	357,856	107,357	5,797	0.755	290	464	0.439	1,842	109,199
1953	353,162	105,949	9,576	0.755	479	766	0.439	3,043	108,992
1954	348,468	104,540	9,746	0.755	487	780	0.439	3,097	107,638
1955	343,774	103,132	10,202	0.755	510	816	0.439	3,242	106,375
1956	339,081	101,724	13,726	0.755	686	1,098	0.439	4,362	106,086
1957	334,387	100,316	12,659	0.755	633	1,013	0.439	4,023	104,339
1958	340,131	102,039	13,136	0.755	657	1,051	0.439	4,174	106,214
1959	345,875	103,762	15,978	0.755	799	1,278	0.439	5,078	108,840
1960	351,618	105,485	13,381	0.755	669	1,070	0.439	4,252	109,738
1961	357,362	107,209	20,023	0.755	1,001	1,602	0.439	6,363	113,572
1962	351,240	102,946	27,604	0.755	1,380	2,208	0.439	8,772	111,718
1963	345,119	98,684	18,507	0.755	925	1,481	0.439	5,881	104,565
1964	338,997	94,421	20,156	0.755	1,008	1,612	0.439	6,406	100,827
1965	332,876	90,159	20,171	0.755	1,009	1,614	0.439	6,410	96,569
1966	326,754	85,896	21,364	0.755	1,068	1,709	0.439	6,789	92,685
1967	320,633	81,634	20,242	0.755	1,012	1,619	0.439	6,433	88,066
1968	314,511	77,371	26,139	0.755	1,307	2,091	0.439	8,307	85,678
1969	308,390	73,109	27,456	0.755	1,373	2,196	0.439	8,725	81,834
1970	302,268	68,846	24,328	0.755	1,216	1,946	0.439	7,731	76,577
1971	311,131	72,429	26,048	0.755	1,302	2,084	0.439	8,278	80,707
1972	258,393	59,466	28,941	0.755	1,447	2,315	0.439	9,197	68,663
1973	252,893	58,653	27,692	0.755	1,385	2,215	0.439	8,801	67,454
1974	260,133	61,327	26,790	0.755	1,339	2,143	0.439	8,514	69,841
1975	269,078	64,039	26,279	0.755	1,314	2,102	0.439	8,352	72,391
1976	227,036	52,115	26,077	0.755	1,304	2,086	0.439	8,287	60,402
1977	299,706	70,023	23,281	0.755	1,164	1,862	0.439	7,399	77,422
1978	276,582	63,991	25,625	0.755	1,281	2,050	0.439	8,144	72,135
1979	244,010	55,533	27,354	0.755	1,368	2,188	0.439	8,693	64,226
1980	254,239	58,345	26,697	0.755	1,335	2,136	0.439	8,484	66,829
1981	227,045	52,196	28,534	0.755	1,427	2,283	0.439	9,068	61,264
1982	192,624	44,705	29,444	0.755	1,472	2,356	0.439	9,357	54,063
1983	181,978	42,747	24,106	0.755	1,205	1,928	0.439	7,661	50,408
1984	158,865	37,326	33,660	0.755	1,683	2,693	0.439	10,697	48,023
1985	141,879	33,374	36,822	0.755	1,841	2,946	0.439	11,702	45,076
1986	116,210	27,371	42,604	0.755	2,130	3,408	0.439	13,540	40,910
1987	94,306	21,197	47,044	0.755	2,352	3,763	0.439	14,950	36,148
1988	106,671	24,950	50,283	0.755	2,514	4,023	0.439	15,980	40,930
1989	69,683	15,488	61,190	0.755	3,059	4,895	0.439	19,446	34,934
1990	71,125	15,843	61,585	0.755	3,079	4,927	0.439	19,572	35,415
1991	67,961	15,125	51,410	0.755	2,571	4,113	0.439	16,338	31,463
1992	84,158	19,606	56,954	0.755	2,848	4,556	0.439	18,100	37,706
1993	73,820	16,610	70,616	0.755	3,531	5,649	0.439	22,442	39,052
1994	75,937	17,198	77,101	0.755	3,855	6,168	0.439	24,503	41,701
1995	85,438	19,800	77,713	0.755	3,886	6,217	0.439	24,697	44,497
1996	96,411	22,717	86,433	0.755	4,322	6,915	0.439	27,468	50,185
1997	106,937	25,419	87,046	0.755	4,352	6,964	0.439	27,663	53,083
1998	113,062	27,019	78,063	0.755	3,903	6,245	0.439	24,808	51,828
1999	119,125	28,216	91,114	0.755	4,556	7,289	0.439	28,956	57,172
2000	139,348	33,363	95,301	0.755	4,765	7,624	0.439	30,287	63,649
2001	125,649	30,032	98,186	0.755	4,909	7,855	0.439	31,203	61,236
2002	137,468	33,634	98,569	0.755	4,928	7,886	0.439	31,325	64,960
2003	130,350	31,698	96,067	0.755	4,803	7,685	0.439	30,530	62,228
2004	127,701	30,855	101,324	0.755	5,066	8,106	0.439	32,201	63,056
2005	121,576	29,474	100,234	0.755	5,012	8,019	0.439	31,854	61,328
2006	114,012	27,398	103,171	0.755	5,159	8,254	0.439	32,788	60,186

Note: Data from Scalmanini, 2010

Table E3-3
Total Agricultural Acreage, Water Requirements and Gross Return Flows to the Vadose Zone

Year	Agricultural Acreage Used in Calculating Associated Water Requirements and Return Flows (acres)	Water Requirements (acre-ft)	Effective Application Rate (acre-ft)	Return Flows (acre-ft)	Return Flow Rate (ft/yr)
1919	11,807	77,565	6.57	23,269	1.97
1920	12,284	80,606	6.56	24,182	1.97
1921	13,375	88,834	6.64	26,650	1.99
1922	14,466	97,062	6.71	29,118	2.01
1923	15,557	105,290	6.77	31,587	2.03
1924	16,648	113,518	6.82	34,055	2.05
1925	17,738	121,746	6.86	36,524	2.06
1926	20,935	144,656	6.91	43,397	2.07
1927	24,132	167,566	6.94	50,270	2.08
1928	26,774	186,145	6.95	55,843	2.09
1929	29,415	204,724	6.96	61,417	2.09
1930	26,160	180,112	6.88	54,034	2.07
1931	24,693	170,125	6.89	51,037	2.07
1932	23,226	160,138	6.89	48,041	2.07
1933	21,759	150,150	6.90	45,045	2.07
1934	20,292	140,163	6.91	42,049	2.07
1935	18,825	130,176	6.92	39,053	2.07
1936	20,932	144,611	6.91	43,383	2.07
1937	23,040	159,045	6.90	47,713	2.07
1938	25,148	173,479	6.90	52,044	2.07
1939	27,255	187,914	6.89	56,374	2.07
1940	29,363	202,348	6.89	60,704	2.07
1941	31,229	212,941	6.82	63,882	2.05
1942	33,094	223,533	6.75	67,060	2.03
1943	34,959	234,126	6.70	70,238	2.01
1944	36,825	244,719	6.65	73,416	1.99
1945	38,690	255,311	6.60	76,593	1.98
1946	41,977	273,960	6.53	82,188	1.96
1947	45,626	296,757	6.50	89,027	1.95
1948	49,169	322,497	6.56	96,749	1.97
1949	49,816	327,685	6.58	98,305	1.97
1950	55,856	347,676	6.22	104,303	1.87
1951	55,871	362,549	6.49	108,765	1.95
1952	56,082	357,856	6.38	107,357	1.91
1953	56,294	353,162	6.27	105,949	1.88
1954	56,505	348,468	6.17	104,540	1.85
1955	56,717	343,774	6.06	103,132	1.82
1956	56,928	339,081	5.96	101,724	1.79
1957	57,140	334,387	5.85	100,316	1.76
1958	56,533	340,131	6.02	102,039	1.80
1959	55,925	345,875	6.18	103,762	1.86
1960	55,318	351,618	6.36	105,485	1.91
1961	54,710	357,362	6.53	107,209	1.96
1962	55,241	351,240	6.36	102,946	1.86
1963	55,772	345,119	6.19	98,684	1.77
1964	56,304	338,997	6.02	94,421	1.68
1965	56,835	332,876	5.86	90,159	1.59
1966	57,366	326,754	5.70	85,896	1.50
1967	57,897	320,633	5.54	81,634	1.41
1968	58,428	314,511	5.38	77,371	1.32
1969	58,959	308,390	5.23	73,109	1.24
1970	59,491	302,268	5.08	68,846	1.16
1971	66,431	311,131	4.68	72,429	1.09
1972	52,851	258,393	4.89	59,466	1.13
1973	53,302	252,893	4.74	58,653	1.10
1974	58,128	260,133	4.48	61,327	1.06

Table E3-3
Total Agricultural Acreage, Water Requirements and Gross Return Flows to the Vadose Zone

Year	Agricultural Acreage Used in Calculating Associated Water Requirements and Return Flows (acres)	Water Requirements (acre-ft)	Effective Application Rate (acre-ft)	Return Flows (acre-ft)	Return Flow Rate (ft/yr)
1975	62,003	269,078	4.34	64,039	1.03
1976	45,701	227,036	4.97	52,115	1.14
1977	63,483	299,706	4.72	70,023	1.10
1978	57,045	276,582	4.85	63,991	1.12
1979	47,439	244,010	5.14	55,533	1.17
1980	50,792	254,239	5.01	58,345	1.15
1981	45,678	227,045	4.97	52,196	1.14
1982	40,607	192,624	4.74	44,705	1.10
1983	40,131	181,978	4.53	42,747	1.07
1984	35,124	158,865	4.52	37,326	1.06
1985	31,562	141,879	4.50	33,374	1.06
1986	25,979	116,210	4.47	27,371	1.05
1987	17,803	94,306	5.30	21,197	1.19
1988	23,337	106,671	4.57	24,950	1.07
1989	12,708	69,683	5.48	15,488	1.22
1990	13,098	71,125	5.43	15,843	1.21
1991	12,491	67,961	5.44	15,125	1.21
1992	18,297	84,158	4.60	19,606	1.07
1993	14,284	73,820	5.17	16,610	1.16
1994	15,145	75,937	5.01	17,198	1.14
1995	17,995	85,438	4.75	19,800	1.10
1996	20,573	96,411	4.69	22,717	1.10
1997	22,856	106,937	4.68	25,419	1.11
1998	23,811	113,062	4.75	27,019	1.13
1999	24,441	119,125	4.87	28,216	1.15
2000	29,262	139,348	4.76	33,363	1.14
2001	26,460	125,649	4.75	30,032	1.13
2002	29,752	137,468	4.62	33,634	1.13
2003	28,141	130,350	4.63	31,698	1.13
2004	27,242	127,701	4.69	30,855	1.13
2005	26,437	121,576	4.60	29,474	1.11
2006	26,790	123,280	4.60	29,788	1.11
Statistics 1949 to 1980					
Average	56,161	315,738	--	85,684	--
Standard Deviation	4,043	39,454	--	19,465	--
Max	66,431	362,549	--	108,765	--
Min	45,701	227,036	--	52,115	--
Coefficient of Variation	7%	12%	--	23%	--
Skew	-0.27	-0.83	--	-0.36	--

Table E3-4a
Natural Recharge 1951 to 2005 With 15-Year Lag

Period	Period Length	Total Outflow[1]	Storage Change[2] ΔS			Return Flows[3]	Artificial Recharge[4]	Natural Recharge[5]
	(yr)	$O_p + O_{ss}$ (acre-ft)	Gravity Drainage (acre-ft)	Compaction (acre-ft)	Total ΔS (acre-ft)	I_{rf} (acre-ft)	I_{ar} (acre-ft)	I_{nr} (acre-ft)
1951-1962	12	4,348,524	-3,229,489	-117,000	-3,346,489	822,342	0	179,693
1963-1970	8	2,780,733	-1,220,748	-141,000	-1,361,748	872,333	0	546,652
1971-1978	8	2,261,964	-361,432	-80,000	-441,432	881,447	0	939,086
1979-1984	6	1,130,679	31,751	-60,000	-28,249	561,154	0	541,276
1985-1991	7	798,198	24,971	-10,000	14,971	559,196	0	253,973
1992-1997	6	684,542	209,801	-9,000	200,801	493,096	894	391,353
1998-2005	8	1,236,702	-485,163	-12,000	-497,163	458,713	5,570	275,256
1951-2005	55	13,241,343	-5,030,309	-429,000	-5,459,309	4,648,280	6,464	3,127,290
1951-2005	Annual Mean	240,752	-91,460	-7,800	-99,260	84,514	118	56,860

Notes:

1) Sum of all groundwater pumping [O_p (ag, M&I, and rural residential)] and subsurface flow out of the basin (O_{ss}).

2) Sum of gravity drainage and water from compaction of sediments (subsidence).

3) Sum of return flows from agriculture, urban/M&I, and recycled water.

4) Sum of artificial recharge of imported water via spreading and injection.

5) $= \Delta S + O_p + O_{ss} - I_{ar} - I_{rf}$

Table E3-4b
Natural Recharge 1951 to 2005 With 20-Year Lag

Period	Period Length	Total Outflow[1]	Storage Change[2] ΔS			Return Flows	Artificial Recharge	Natural Recharge
	(yr)	$O_p + O_{ss}$ (acre-ft)	Gravity Drainage (acre-ft)	Compaction (acre-ft)	Total ΔS (acre-ft)	I_{rf} (acre-ft)	I_{ar} (acre-ft)	I_{nr} (acre-ft)
1951-1962	12	4,348,524	-3,229,489	-117,000	-3,346,489	654,584	0	347,451
1963-1970	8	2,780,733	-1,220,748	-141,000	-1,361,748	732,735	0	686,250
1971-1978	8	2,261,964	-361,432	-80,000	-441,432	886,399	0	934,134
1979-1984	6	1,130,679	31,751	-60,000	-28,249	668,601	0	433,829
1985-1991	7	798,198	24,971	-10,000	14,971	669,227	0	143,942
1992-1997	6	684,542	209,801	-9,000	200,801	513,692	894	370,757
1998-2005	8	1,236,702	-485,163	-12,000	-497,163	613,090	5,570	120,879
1951-2005	55	13,241,343	-5,030,309	-429,000	-5,459,309	4,738,328	6,464	3,037,242
1951-2005	Annual Mean	240,752	-91,460	-7,800	-99,260	86,151	118	55,223

Notes:

1) Sum of all groundwater pumping [O_p (ag, M&I, and rural residential)] and subsurface flow out of the basin (O_{ss}).

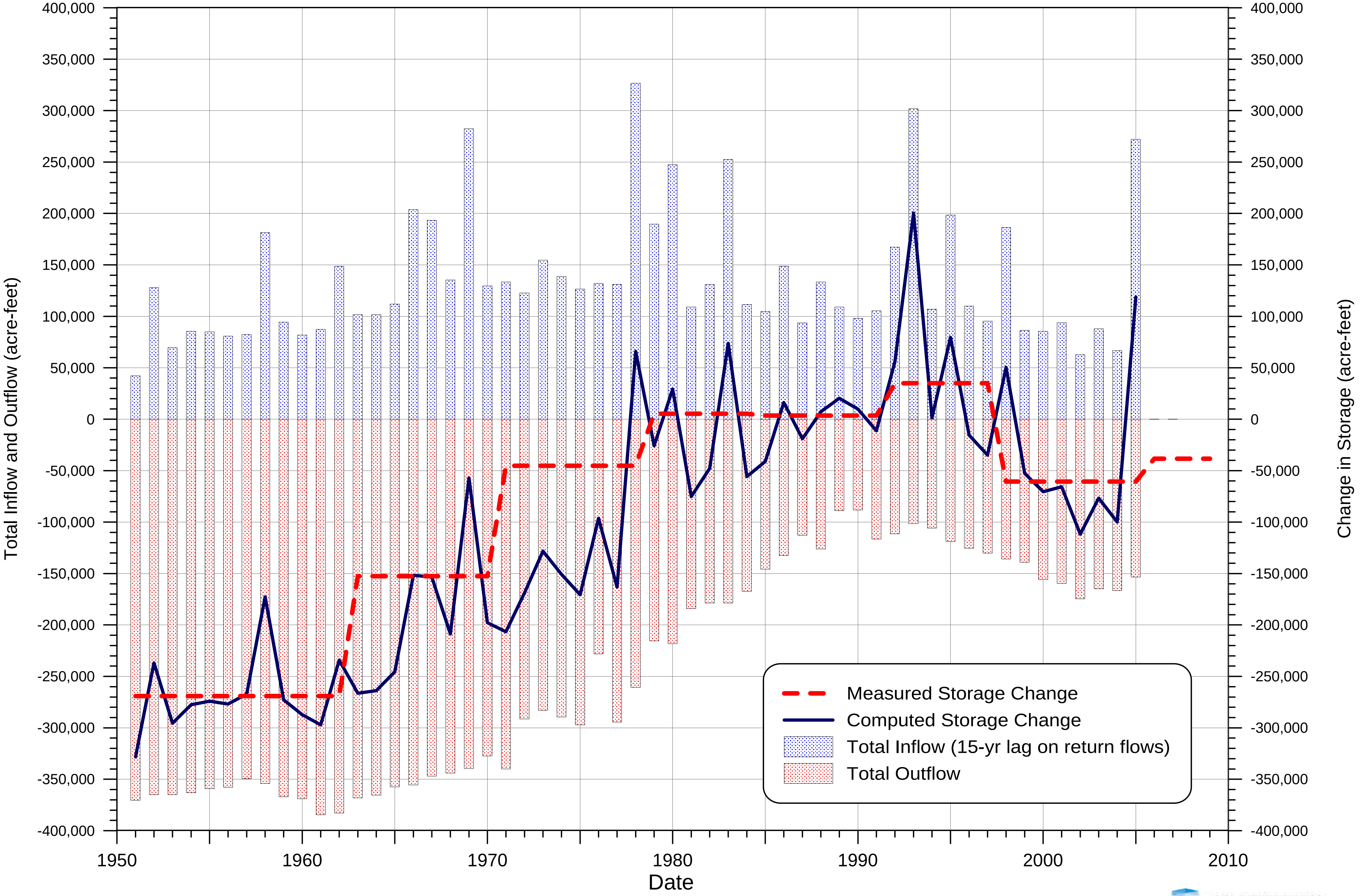
2) Sum of gravity drainage and water from compaction of sediments (subsidence).

3) Sum of return flows from agriculture, urban/M&I, and recycled water.

4) Sum of artificial recharge of imported water via spreading and injection.

5) = $\Delta S + O_p + O_{ss} - I_{ar} - I_{rf}$

Figure E3-1: Computed and Measured Storage Change 1951 - 2009



WILDERMUTH
ENVIRONMENTAL INC.

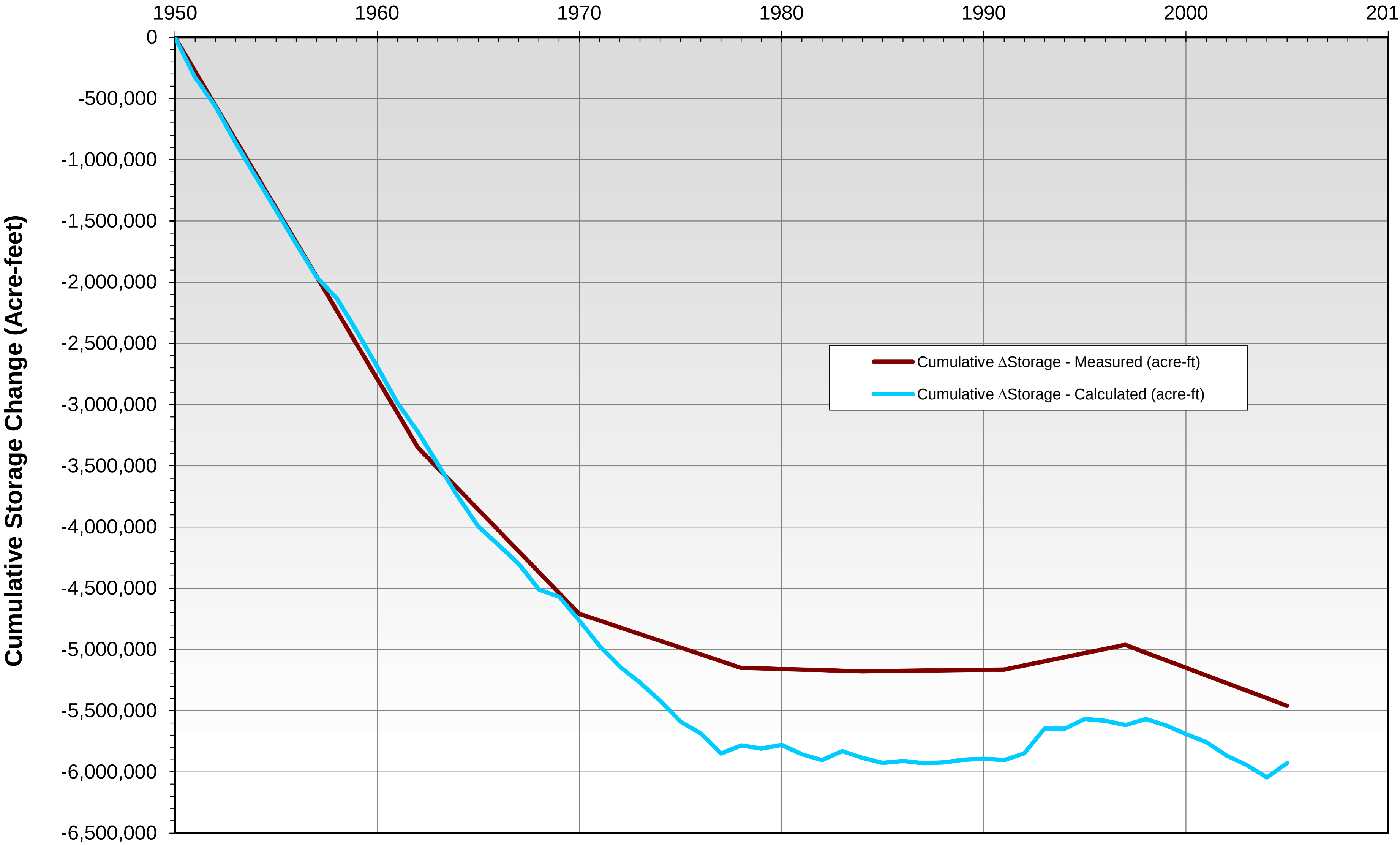


Figure E3- 2: Cumulative Calculated and Measured Storage Change 1951 - 2005

Figure E3-3
Comparison of Natural Recharge from Durbin and WEI Estimates for Various Lag Assumptions