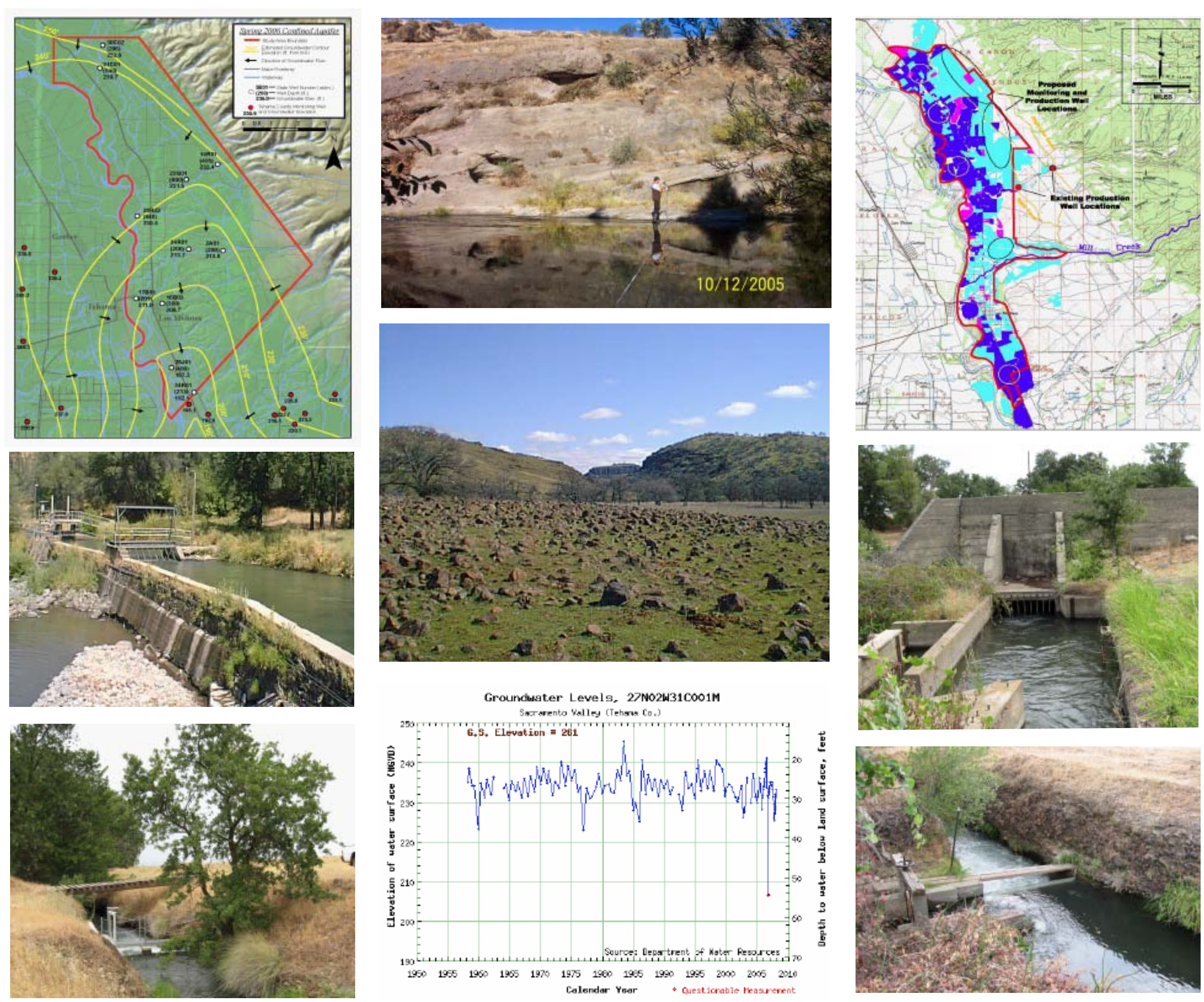
Lower Mill Creek Watershed Conjunctive Use Project

Tehama County, California



Prepared by the California Department of Water Resources
Northern District Groundwater Section
in Cooperation with
Mill Creek Conservancy and Los Molinos Mutual Water Company

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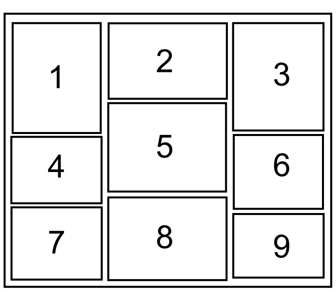

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Lower Mill Creek Watershed Project
Conjunctive Use Study
Tehama County, California

Division of Planning and Local Assistance
Northern District

November 2008

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Conjunctive Use Study

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This summary report was prepared by the Department of Water Resources (DWR), Northern District, Groundwater Section. The report fulfills the scope of work and services provided by the Groundwater Section under DWR Contract 288745, between the DWR and the Mill Creek Conservancy, to conduct a conjunctive use study in the Lower Mill Creek Watershed. The report was prepared under the direct supervision of Daniel McManus, Chief of the Northern District Groundwater Section, Professional Geologist No. 6261, and was written by William Ehorn, Professional Geologist No. 7005, in accordance with the provisions of the Geologist and Geophysicists Act of the State of California.

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Section 1. Background, Introduction, and Scope

Background

In 1920, the Tehama County Superior Court of the State of California adjudicated entitlements to all Mill Creek flow below 203 cubic feet per second (cfs). As such, water right holders on Mill Creek legally divert a significant portion of the surface water flow for agricultural beneficial use. During certain times of the year, especially during dry or critically dry years, the agricultural demand for surface water can reduce Mill Creek flow and expose in-stream barriers to fish migration. Fishery experts recognize Mill Creek as a high priority stream for the protection and enhancement of Chinook salmon spawning habitat. Mill Creek surface water diverters currently participate in a long-term cooperative management plan to help provide sufficient flow for fish migration while also maintaining irrigation supplies and the recognition of surface water rights. As part of these efforts, Mill Creek water users participate in water lease and groundwater exchange programs designed to increase in-stream flow during critical spring and fall fish migration periods. Along with other entities, the Department of Water Resources (DWR) plans to establish methods of monitoring and studying fish passage, assessing agricultural water use efficiency, and examining the potential for additional use of groundwater as opposed to use of surface water diversions in the Lower Mill Creek watershed.

This report provides a background of the geology and hydrogeology in the Lower Mill Creek watershed area, a detailed discussion of the groundwater resources, and an overview of the potential for conjunctive use of surface water and groundwater resources. It also provides recommendations for additional groundwater monitoring and potentially favorable locations for production well installation associated with possible future conjunctive use programs.

Data currently on file with DWR along with published and unpublished reports, contributed to the majority of information provided in this report. We also used data that DWR collected and analyzed as part of the 2003 Tehama County Water Inventory and Analysis, which was conducted in cooperation with Camp Dresser & McKee, Inc. under the direction of the Tehama County Flood Control and Water Conservation District.

Introduction and Scope

The headwaters of Mill Creek initiate at the base of Mount Lassen in the Cascade Mountain Range. Mill Creek maintains a perennial flow as it tracks its way through the mountains and meadows of the upper watershed, the steep-sided canyons of the Tuscan Formation foothills, the alluvial valley floor, and into the Sacramento River near the city of Tehama. The Los Molinos Mutual Water Company (LMMWC) serves as the Watermaster for Mill Creek and operates diversions for agricultural water from both the north and south banks. These diversions deliver water within the LMMWC service area which extends outside the natural hydrologic boundary of Mill Creek. In order to help evaluate the effects of LMMWC's diversions, the project boundary was extended outside the Mill Creek watershed and into the Antelope and Dye Creek watersheds to include the LMMWC's entire service area. Figure 1 shows the Mill Creek project study area and the LMMWC service area.

Regionally, the Lower Mill Creek project area is in the Sacramento Valley Groundwater Basin. At the subregional level, the project area is further divided into inventory and sub-inventory units, also known as groundwater subbasins. The breakdown of units at the regional level serves to group areas of similar hydrology and hydrogeology. At the local level, the sub-inventory units group areas of similar land use, water use, and local water purveyor areas. Figure 1 also shows the three groundwater subbasins (Antelope, Dye Creek, and Los Molinos) in the project study area.

This groundwater study is presented in four sections. Section 1, this section, provides an introduction to the study area and a discussion of the project scope. Section 2 presents a discussion of the regional and local geology and hydrogeology of the Sacramento Valley and the Lower Mill Creek watershed area. Section 3 provides a detailed characterization of well infrastructure and groundwater resources at the subbasin level within the Lower Mill Creek project area. Section 3 also includes the following subject areas:

- well distribution
- well depths
- sources of water – 2002
- groundwater monitoring wells
- groundwater levels
- groundwater movement
- groundwater extraction
- well yield
- well specific capacity
- groundwater storage
- surface water / groundwater interaction

Section 4 discusses conjunctive use and recommendations regarding the potential for groundwater substitution and future locations of monitoring and production wells in the Lower Mill Creek watershed.

Section 2. Geology and Hydrogeology

The following section provides an overview of the regional and project level geology for the Northern Sacramento Valley. The overview summarizes recent work along with previous information developed by DWR for the 2003 Tehama County Water Inventory and Analysis.

Regional Geology and Hydrogeology of the Sacramento Valley Groundwater Basin

The Lower Mill Creek Watershed project area is located in the Sacramento Valley Groundwater Basin portion of Tehama County. The regional geology of the Northern Sacramento Valley area is shown on Plates 1, 2, and 3. The plates include the geology of the Northern Sacramento Valley, the surrounding foothills, and a portion of the upper mountain areas. Plates 1 and 2 present the surface geology and associated legend. Plate 3 consists of two regional geologic cross sections and illustrates the subsurface geology, geologic stratigraphy, and hydrogeologic units.

The two regional cross sections presented in this report focus on the Sacramento Valley region near the Lower Mill Creek project area. The locations of the cross sections are shown on the geologic plan-view map on Plate 1. Cross section A-A' is oriented east to west and traverses through the city of Red Bluff. Cross section B-B' is also oriented east to west but is located in the southern portion of Tehama County and transverses from Vina on the east side of the valley, through the city of Corning, to Flournoy, which is on the west side of the valley. The cross sections show the regional geology of the Sacramento Valley just to the north and south of the Lower Mill Creek project area and are representative of the geology in that area. A vertical exaggeration of 1:1,000 feet and a horizontal exaggeration of 1:10,000 feet were used to portray the topographic surface and subsurface geologic units with greater detail.

The Sacramento Valley Groundwater Basin extends from just north of Red Bluff to the Sacramento-San Joaquin Delta and is bordered by the Coast Ranges on the west and the Cascade Range and Sierra Nevada Range on the east. It covers an approximate area of 4,900 square miles, which includes all of Sutter County and parts of Butte, Glenn, Tehama, Colusa, Yuba, Yolo, Solano, Placer, Sacramento, and Shasta counties.

The Sacramento Valley is a structural basin filled with up to 5 miles of sediment. These marine and continentally derived sediments have been deposited almost continuously from the Late Jurassic period to the present. Older sediments in the basin were emplaced in a marine environment and usually contain saline or brackish groundwater. Younger sediments were deposited under continental conditions and generally contain fresh groundwater. Sediment deposits are thinner near the margins of the basin and expose older metamorphic, granitic, and marine sedimentary rocks which underlie and bound the Sacramento Valley sediments.

Principal hydrogeologic units of the Sacramento Valley Groundwater Basin consist of Pliocene sedimentary deposits, such as the Tuscan Formation and Tehama Formation, and Quaternary terrace deposits, such as the Riverbank Formation and Modesto Formation. The Tuscan Formation and Tehama Formation are the source of water for deep irrigation, municipal, and domestic wells, while the Riverbank and Modesto Formations yield water to very shallow domestic wells.

Groundwater occurs under both unconfined and confined conditions in the Sacramento Valley region. Unconfined conditions are present in the surficial Quaternary deposits and in the Pliocene deposits that are exposed at the surface. Confined conditions usually exist at a depth of 200 feet or more where a confining layer rests above the underlying aquifer deposits. Although the Tuscan Formation is unconfined where it is exposed near the valley margin, at depth, the Tuscan Formation is confined and forms one of the major aquifer systems in the eastern portion of the valley. The Tehama Formation is also confined at depth, with coarse-grain, near-surface deposits contributing to the unconfined aquifer system.

Older granitic and metamorphic rocks underlie the valley and form the basement bedrock on which younger marine and continentally derived sediments and volcanic rock have been deposited. The basement rock is at considerable depth along the valley axis and west of the present-day Sacramento River where it ranges from 12,000 to 19,000 feet below ground surface. A thick sequence of sandstone, shale, and conglomerate rocks of marine origin immediately overlies the basement bedrock, which ranges from Jurassic to Eocene in age. Within the Tehama County portion of the Sacramento Valley, these sediments contain groundwater that is saline or brackish and serve as the base of fresh groundwater.

The oldest of the Jurassic to Eocene marine sediments is known as the Great Valley Sequence and is Jurassic to Cretaceous in age. Sediments of the Great Valley Sequence were originally deposited as horizontal layers, but because of compressive stress within the region, portions of the formation have been folded and faulted upward, especially at the margins of the Sacramento Valley.

Large-scale valleys were cut into the Great Valley Sequence by post-depositional erosion. Subsequent in-filling of the northernmost of these canyons created wide-scale deposition of the Lower Princeton Submarine Valley Fill. Cross sections A-A’ and B-B’ on Plate 3 demonstrate this unconformable relationship. Water contained within the Great Valley Sequence is primarily saline.

The Lower Princeton Submarine Valley Fill of the Eocene epoch consists of a mixture of marine sediments and continental materials. Those materials were derived from the walls of the eroded submarine canyon which had been carved into the Great Valley sediments (Redwine 1972). Groundwater contained within these sediments is almost exclusively saline. The Lower Princeton Submarine Valley Fill is one of several formations in the Sacramento Valley Region that exists in the subsurface but is not exposed at the surface (Plate 3). Information on the extent and position of this unit is limited because the majority of data concerning its existence and character is derived from oil and gas exploration well logs.

Other formations in the Sacramento Valley and Redding Regions of Tehama County that are encountered only in the subsurface are the Eocene Ione Formation, the Miocene Neroly Formation, and Upper Princeton Valley Fill (Plate 3). Surface exposures of the Ione Formation can be seen in the Sacramento Valley near Oroville at Table Mountain where it underlies the Lovejoy Basalt.

After the deposition of the Ione Formation and before the deposition of the Upper Princeton Valley Fill, several volcanic eruptions in the Cascade Range produced a series of basalt flows that spread across the valley sediments during the Miocene epoch. These flows compose the hard, black microcrystalline Lovejoy Basalt. Lovejoy Basalt exists intermittently throughout the Sacramento Valley. The only surficial exposure in Tehama County is at the Orland Buttes in southern part of the county. Groundwater, primarily saline or brackish, is transmitted and stored within the secondary porosity created by the fracturing and jointing of the basalt.

The Miocene Upper Princeton Valley Fill is widespread throughout the Sacramento Valley. Depending on its location, the fill may overlie portions of the Lower Princeton Submarine Valley Fill, the Ione Formation, or the Lovejoy Basalt. The Miocene Upper Princeton Valley Fill consists primarily of sandstone with interbedded layers of shale and conglomerate. In contrast to the submarine depositional environment of the Lower Princeton Submarine Valley Fill, the Upper Princeton Valley Fill was deposited by terrestrial rivers draining the valley after the regression of marine waters (Redwine 1972). Water contained within the Upper Princeton Valley Fill is primarily saline to brackish.

The Pliocene Tuscan Formation and Tehama Formation unconformably overlie the Upper Princeton Valley Fill and are the major fresh groundwater-bearing units in the Northern Sacramento Valley and in Tehama County. Surface exposures of the Tuscan Formation are generally seen on the east side of the Sacramento Valley whereas exposures of the Tehama Formation can be seen on the west side of the valley (Plate 1). The Sacramento River acts as a surficial divide in most places; however, exposures of the Tuscan Formation are also seen on the west side of the river north of Red Bluff near the Bend area. Evidence of subsurface interlayering of the two formations has been encountered in wells west of the Sacramento River on the west side of the El Camino Irrigation District.

The Pliocene Tuscan Formation is composed of a series of volcanic mudflows, tuff breccias, tuffaceous sandstone, and volcanic ash layers. Mudflows originated in the vicinity of present-day Lassen Peak and most likely filled ancient stream channels as they flowed toward the valley. Upon reaching the valley floor, the mudflows fanned out, depositing layers of sediment. The Tuscan Formation contains four separate but lithologically similar units (known as Units A, B, C, and D) that are separated by layers of thin tuff or ash units in some areas (Maps: California 1985).

The Plio-Pleistocene Tehama Formation consists of massive, pale green, grey, and tan sandstone and siltstone with lenses of pebble and cobble conglomerate (Harwood and Helley 1985). Tehama sediments were deposited under fluvial conditions with source areas of the Coast Ranges and Klamath Mountains. These sediments are low to moderately permeable, with some local areas of high permeability. Permeability is defined by the formation’s ability to move water and is typically measured in terms of distance over time.

In the subsurface, the Tuscan Formation and Tehama Formation are interlayered along the central north-south axis of the valley. The Nomlaki Tuff lies at the base of both units providing an important stratigraphic marker, which suggests that both of the formations are contemporaneous. The base of these Pliocene Formations is considered to be significant because it is generally accepted as the base of freshwater in the Northern Sacramento Valley.

The surface geology of the Sacramento Valley and Redding portions of Tehama County is primarily composed of alluvial deposits whose source is the eroded material derived from surrounding mountain ranges. These sediments were deposited as alluvial fan, terrace, and basin deposits by a network of streams and rivers flowing into the Sacramento Valley. Along the front of the foothills, alluvial fan and terrace deposits of the Riverbank Formation and Modesto Formation mark the edge of the valley sedimentary units.

The Pleistocene Riverbank Formation represents the oldest of the alluvial fan and terrace deposits. The Riverbank Formation was formed by streams carrying eroded material from the surrounding mountain ranges to the base of the foothills where it was deposited in wide alluvial fans. It is present primarily on the west side of Tehama County and in discontinuous surface exposures on the east side of the county along such streams as Acorn Hollow, Toomes Creek, and Mill Creek.

In many places, more recent alluvial fan development has covered the Riverbank Formation. The thickness of the formation varies from less than 1 foot to about 30 feet, depending on location (Maps: California 1985). The Riverbank Formation overlies the Tehama Formation in the western portion of Tehama County and the Tuscan Formation in the eastern portion. The Modesto Formation overlies the Riverbank Formation in many locations throughout the county.

The alluvial fans and terrace deposits of the Pleistocene Modesto Formation were deposited in a similar manner to those of the Riverbank Formation, but they mark a more recent period of erosion and deposition of 42,000 to 14,000 years ago (Marchandt and Allwardt 1981). The terrace deposits of the Modesto Formation are exposed in many of the presently active stream-cut canyons along the foothills. Extending into the valley, Modesto Formation deposits widen into broad alluvial fans.

As with the Riverbank Formation, the thickness of the Modesto Formation varies from less than 10 feet in many of the terraces to nearly 200 feet across the valley (Maps: California 1985). However, DWR geologists have observed a maximum thickness of these terraces to be about 30 feet. The Modesto Formation overlies the Riverbank Formation or Tehama Formation in the western portion of Tehama County and overlies the Riverbank Formation or Tuscan Formation in the eastern portion of the county.

The fine silts and clays of the Holocene basin deposits overlie the alluvial fans of the Riverbank Formation and Modesto Formation. Holocene basin deposits are the result of sediment-laden floodwater that rose above the natural levees of streams and rivers and spread out across vast low-lying areas. Holocene basin deposits in Tehama County exist in discontinuous exposures primarily east to southeast of Dairyville and in an isolated instance just southeast of Corning. Large exposures of basin deposits are seen in Butte, Glenn, Colusa, and Sutter counties, forming the highly productive agricultural soils characteristic of these areas.

Thickness of the Holocene basin deposits varies throughout the Sacramento Valley from less than 10 feet along the margins of the exposure to more than 100 feet in the center of the valley. However, in Tehama County, basin deposits tend to be shallower, generally from 1 to 20 feet thick. Basin deposits provide limited quantities of groundwater to shallow wells due to the fine-grained nature of the sediments. Alluvium overlies the basin deposits along presently active stream and river channels.

Holocene alluvium is the youngest of the geologic units present within the Sacramento Valley and Redding Regions. Alluvium consists of unweathered gravel, sand, and silt that has been transported and deposited by streams and rivers. Alluvium forms some of the natural levees found primarily along the Sacramento River, Dry Creek, Cottonwood Creek, Red Bank Creek, Thomes Creek, and Stony Creek (Maps: California 1985).

Alluvial deposits primarily overlie the basin deposits and the Modesto Formation and Riverbank Formation. Due to the limited extent and thickness of the alluvium, it is not considered a significant water-bearing unit.

Structural Features

Deformational structures within the Sacramento Valley and Redding Groundwater Basin regions of Tehama County are related to regional stress patterns due to right-lateral transform tectonism in the San Andreas fault zone to the west, and major east-west crustal extension in the northern Basin and Range province to the east (Harwood and Helley 1987). These deformational structures manifest themselves in the form of folds and faults throughout the Northern Sacramento Valley. Two general trends are seen in the Tehama County area. One lies in an approximate north-northwest direction, and the other is oriented in an east-northeast direction.

North-northwest trending structures include the Willows-Corning fault, Black Butte Thrust fault, Chico Monocline, North Corning Dome, South Corning Dome, Los Molinos Syncline, an unnamed syncline located west of the Willows-Corning fault, and an unnamed anticline located east of the Willows-Corning fault. With the exception of the Chico Monocline, these structures trend in a more northerly direction and are thought to converge on the northwest trending Chico Monocline east of Red Bluff (Harwood and Helley 1987). The east-west trending Red Bluff fault acts as a terminus for the northerly trending structures.

East-northeast trending structures include the Red Bluff fault, which also marks the structural change from the north-northwest trending features in Tehama County. Other east-northeast trending structures included the Hooker Dome, Inks Creek Fold System, Battle Creek fault Zone, Seven Mile Dome, Tuscan Springs Dome, and Salt Creek Dome. The area encompassing these east-northeast trending structures is commonly referred to as the Red Bluff Arch and separates the Redding Groundwater Basin from the Sacramento Valley Groundwater Basin.

Local Geology and Hydrogeology of the Lower Mill Creek Watershed Project Area

The aquifer system in the study area is composed of continental deposits of late Quaternary to Tertiary age. The Quaternary deposits include Holocene basin deposits, Pleistocene deposits of the Modesto Formation and Riverbank Formation, and Pleistocene fanglomerate. The Tertiary deposits include Pliocene Tehama Formation and Tuscan Formation. The Tuscan Formation is the primary water-producing zone in the project area. Figures 2 and 3 show a geologic map and legend for the project area.

Stream Channel Deposits

Holocene stream channel deposits from the Sacramento River rest on the western edge of the project area. Stream channel deposits are also evident in the central portion of the Dye Creek subbasin near the town of Dairyville. They are associated with sediment-laden floodwaters that rose above the natural levees and deposited sediment across the low-lying areas. These deposits consist of moderately to highly permeable unconsolidated gravel, sand, silt, and clay. The thickness of the stream channel deposits varies from 1 to about 80 feet (Harwood and

Helley 1985). However, DWR geologists have observed a maximum thickness of approximately 30 feet. The deposits frequently represent the upper part of the unconfined portion of the aquifer; however, the thickness and areal extent of the deposits can limit the sustainable water-bearing capability.

Modesto Formation

The Pleistocene Modesto Formation was deposited between 14,000 and 42,000 years ago. It lies along the western extents of the project area and consists of undifferentiated terrace deposits of unconsolidated, weathered and unweathered gravel, sand, silt, and clay. DWR geologists have observed a thickness of 30 feet or less. Similar to the stream channel deposits, the thickness of the Modesto Formation tends to limit the water-bearing capacity. However, sand and gravel deposits of the Modesto Formation provide conditions for a reliable groundwater supply to many domestic wells in the area. In some areas, the Modesto Formation also provides a significant source of groundwater to shallow irrigation wells as well as to deeper irrigation wells having both shallow and deep perforation intervals. In locations where gravel and sand predominate, groundwater yields are moderate. Lesser yields occur in areas with high silt and clay content. Groundwater production from the Modesto Formation typically occurs under unconfined conditions.

Riverbank Formation

The Riverbank Formation was deposited between 450,000 and 130,000 years ago. It forms wide alluvial fans and terrace deposits consisting of weathered reddish gravel, sand, and silt. The formation's reddish color is attributed to post-depositional weathering. The topographic location and the weathered red color both distinguish the Riverbank Formation from the more recent alluvial fan and terrace deposits (Maps: California 1985). Exposures of the Riverbank Formation exist along Mill Creek and in smaller drainages in the project area. The thickness of the formation ranges from less than 1 foot to 200 feet depending on its location. Topographically, the stream terrace deposits of the Riverbank Formation appear above the younger Modesto Formation terrace deposits. Erosion of the Riverbank Formation terraces and deposition of the Modesto Formation and basin deposits have produced limited surface exposure of the Riverbank Formation. The thickness of the Riverbank Formation can be a limiting factor to its water-bearing capabilities. The Riverbank Formation is moderately to highly permeable and it yields moderate quantities of water to domestic and shallow irrigation wells. The formation also provides water to deeper irrigation wells that have multiple zones of perforation. Well yields are higher in areas where concentrations of gravel and sand are present. Groundwater generally occurs under unconfined conditions throughout the Riverbank Formation.

Fanglomerate

The Pleistocene fanglomerate is located along the eastern foothills of the study area. The formation is an alluvial fan deposit derived from erosion and deposition of volcanic mudflows that compose the Tuscan Formation. It consists of polylithic volcanic clasts set in weathered tuffaceous matrix. The fan deposits are poorly sorted and vary from being somewhat indurated to well cemented. The fan deposits range in thickness to depths of 150 feet (Ely 1994). The fanglomerate is not sufficiently thick to produce large quantities of groundwater (Olmsted and Davis 1961).

Tehama Formation

The Pliocene Tehama Formation consists of fluvial deposits predominantly composed of silt and clay with gravel and sand interbeds (DWR 1987). In the project area, the formation is situated within the western portions of the Antelope, Dye Creek, and Los Molinos subbasins at depths ranging from 100 to 150 feet (DWR 1987). Along the axis of the valley, the Tehama Formation deposits commonly lie just below the terrace deposits and can be seen in cut-bank exposures of the Sacramento River. At depth, the Tehama Formation interfingers with the Tuscan Formation along the axis of the valley. Because of the massive amounts of sandy-silt, silty-clay, and lenses of poorly-consolidated sand and gravel, the permeability of the Tehama Formation is low to moderate and has localized areas of high permeability. Specific capacities on most wells are less than about 35 gallons per minute per foot (gpm/ft) of drawdown.

Tuscan Formation

The Pliocene Tuscan Formation is one of the primary sources of groundwater in the study area. Its depth ranges from surface level on the eastern edge of the study area to about 100-150 feet deep as it draws nearer to the Sacramento River. The formation is composed of a series of volcanic mudflows, tuff breccia, tuffaceous sandstone, and volcanic ash layers. The formation is described as four separate but lithologically similar units known as Units A, B, C, and D, with Unit A being the oldest. In some areas, the units are separated by layers of thin tuff or ash units (Harwood and Helley 1985). Units A, B, and C are found within the subbasins and extend through the subsurface to west of the Sacramento River (DWR 2007). Unit A is the oldest water-bearing unit of the formation and is characterized by the presence of metamorphic clasts within interbedded lahars, volcanic conglomerate, volcanic sandstone, and siltstone. Unit B is composed of a fairly equal distribution of lahars, tuffaceous sandstone, and conglomerate. Unit C consists of massive mudflow or lahar deposits with some interbedded volcanic conglomerate and sandstone. In the subsurface, these low permeability lahars form thick confining layers for groundwater contained in the more permeable sediments of Unit B. The Tuscan Formation reaches a maximum thickness of 1,500 feet over older sedimentary deposits (DWR 2000). The formation flattens beneath valley sediments then dips an average of approximately 2.5 degrees east of the valley. At the Chico Monocline, it steepens sharply to 10 to 20 degrees southwestward toward the valley (Olmsted and Davis 1961).

Groundwater in the Tuscan Formation is contained primarily within the pore spaces of the reworked sand and gravel layers. Much of the groundwater is confined under pressure by layers of impermeable clays, lahars, or tuff breccia. Volcanic sands of the Tuscan Formation are known to yield high amounts of water to many wells on the east side of the Sacramento Valley. Groundwater encountered within Unit A is associated with primary porosity of the conglomerate and sandstone layers and with secondary porosity associated with the fractured tuff breccia. Within Unit B, the interbedded, permeable layers of reworked sand and gravel become a conduit for groundwater movement, transmitting water into the aquifer from recharge areas in the Cascade foothills. The permeable layers of the Unit B sediments compose the main aquifer material for groundwater storage in the valley and in the Lower Mill Creek Watershed project area. The fine-grained, consolidated lahars of Unit C form thick, low- permeable, confining layers for groundwater contained in the more permeable sediments of Unit B. Unit D consists mainly of the hard lahar layers that form the steep cliffs, which also confine the movement of Mill Creek through the lower foothill reach. Unit D has a very low permeability and any water associated with the unit is most likely due to secondary permeability from fractures and jointing.

Tuscan Aquifer Properties and Well Production Potential: Aquifer properties are typically determined by performing an aquifer performance test in which water is pumped at a specified rate while the changes in groundwater levels are monitored in the pumping well and nearby non-pumping wells. Aquifer properties are described in terms of transmissivity and storativity. Transmissivity is the rate at which water is transmitted through a unit width of an aquifer extending the entire saturated thickness of the aquifer. The units of Transmissivity are described in terms of the number of gallons per day per foot (gpd/ft) of aquifer. Dividing the transmissivity by the aquifer thickness provides an estimate of the hydraulic conductivity of the geologic material which composes the aquifer. Storativity is the volume of water an aquifer releases from storage per unit area of the aquifer, per unit change in groundwater level. Because the measurement of storativity results in a water volume over an aquifer volume, the units cancel, and storativity is reported as a dimensionless value with no units.

In cooperation with the United States Geological Survey (USGS), DWR compared transmissivity and specific capacity values to well production potential where data was available in the Sacramento Valley. Specific capacity is the rate of pumping-well production divided by the drawdown of the groundwater level. Specific capacity is reported in units of gpm/ft of drawdown. According to the study, irrigation wells with specific capacity values between 10 and 100 gpm/ft have a fair to good water producing potential. These wells are screened across aquifers with transmissivity values ranging between 10,000 and 100,000 gpd/ft. Irrigation wells with specific capacity values between 100 and 1,000 gpm/ft have a good to very good water producing potential and are screened across aquifers with transmissivities between 100,000 and 1,000,000 gpd/ft.

A constant-discharge aquifer performance test was conducted in November 1989 by DWR on the Tuscan aquifer in the Lower Mill Creek project area. Specifically, the production well was located in the Dye Creek Sub-Inventory Unit and was screened within the Tuscan aquifer system from 340 to 590 feet. The production well was pumped for 7 days at the rate of 2,000 gallons per minute (gpm) and then allowed to recover for 7 days while groundwater levels were monitored in the pumping well and several nearby nonpumping wells. The aquifer performance test results indicated that the transmissivity of the lower-confined portion of the aquifer to be approximately 126,000 gpd/ft. The transmissivity for the fully-penetrating portion of the aquifer was estimated to be 58,600 gpd/ft. The hydraulic conductivity (averaged over the full thickness of the aquifer) was calculated to be 319 gallons per day per square foot (gpd/ft^2), and falls within the range of values reported for an aquifer system composed of clean to silty-sand material. The storativity for the aquifer system was estimated at 0.0025 which is representative of a confined to semi-confined aquifer system. The specific capacity was calculated to be 18.38 gpm/ft. The average transmissivity of the Dye Creek well which was calculated to be 92,300 gpd/ft indicates that the Tuscan Formation aquifer in the project area has a fair to good water-producing potential.

In the spring of 2000, DWR conducted field studies to determine the hydrogeologic properties of the Tuscan Formation in the Vina Sub-Basin Unit adjacent to the south edge of the project area. Three separate constant discharge aquifer performance tests were conducted in the Deer Creek area using an idle agricultural production well and several surrounding monitoring wells. The pumping well was screened from 130 to 490 feet. The surrounding monitoring wells were screened in both the shallow (70 to 530 feet) and the deep (530 to 790 feet) portions of Tuscan aquifer system. The test results showed a wide range of estimated transmissivity values between the shallow and deep portions of the aquifer system. The shallow zone transmissivity ranged from about 103,900 to 418,700 gpd/ft, and the deep zone transmissivity ranged from about 60,500 to 373,900 gpd/ft. Using an average transmissivity value, the hydraulic conductivity of the upper Tuscan aquifer system is estimated to be about 700 gpd/ft^2, or the equivalent of clean sand. The storativity values from these tests characterize the Tuscan Formation as a confined or leaky aquifer system. The specific capacity of the production well was calculated to be 41.4 gpm/ft of drawdown.

In February 2003, DWR conducted another constant discharge aquifer performance test in the Deer Creek area of the Vina Subbasin Unit as part of the Deer Creek Water Exchange Program. The test production well was specifically constructed for pumping and testing the lower Tuscan aquifer system and has a screened interval from 620 to 920 feet. The test production well was pumped at a rate of 2,000 gpm over a period of 4 days and resulted in an estimated transmissivity of 40,505 gpd/ft. The hydraulic conductivity value, averaged over the full thickness of the lower aquifer system was calculated to be 135 gpd/ft^2, which is about half that of the upper Tuscan aquifer system. Even so, the hydraulic conductivity value for the lower Tuscan aquifer system still falls within the range of values reported for an aquifer system composed of clean to silty-sand material. The storativity values from this test were in the 10^{-4} to 10^{-5} range and characterize the lower portion of the Tuscan aquifer system as confined. The specific capacity of the pumping well was calculated at 16.6 gpm/ft of drawdown.

Section 3. Groundwater and Wells

The following section presents a summary of the existing well infrastructure, an overview of the estimated water supply and demand, and a description of the groundwater level monitoring grid, groundwater levels, and movement. It also provides an estimate of the groundwater extraction and well yield within the project area.

Well Distribution

Section 13751 of the California Water Code requires water well drillers to file a Well Completion Report (well log) with DWR for each well drilled. The well logs can provide a broad range of information regarding well location, use, construction, production, and a general description of the subsurface geology encountered while drilling.

An inventory of groundwater wells in the Lower Mill Creek Study area has been compiled from the well log data on file at DWR, Northern District in the Well Completion Report database as of June 2007. The well inventory was analyzed according to well location and the type of well use as provided on the well logs. Well locations derived from the well logs are recorded and plotted to the nearest township, range, and section (Figures 4 and 5). The type of well use is divided into the following four main categories: domestic, irrigation, municipal, and other. Well use identified as “municipal” also includes public and industrial wells. Well use identified as “other” includes stock, test, monitoring, abandoned, and unidentified wells.

Figure 4 shows the total number of wells per section. Figure 5 shows the number of domestic and irrigation wells per section. These figures demonstrate that most of the groundwater development is located along Highway 99. The Highway 99 corridor is characterized by a maze of agricultural development and low-medium density residential development. All of the residents in this area use groundwater as their primary source of domestic water supply, whether it comes directly from their own individual well or from a city supply.

Table 1 lists the number of wells in the project area by type of use. It also indicates the “Total Well Count” as 1,176 well logs for wells that are located in the project area and are on file at DWR, Northern District. Approximately 78 percent of these wells are for domestic use, while about 11 percent are for irrigation. Municipal wells account for only about 1 percent of the total number of wells in the project area. It should be noted that DWR does not receive well logs for all wells that are abandoned or destroyed. Table 1 also provides a statistical summary of well depth data.

Well Depth

By using well log data on file as of June 2007 for wells in the Lower Mill Creek project area, we analyzed and sorted the well depth data according to well use (domestic, irrigation, municipal, and other wells). Out of the 1,176 well logs on file, only 7 wells did not have a recorded depth. Table 1 shows that the average depth of domestic and irrigation wells is 90 and 163 feet, respectively. The average municipal well depth is based on a count of only 12 wells and is estimated at 205 feet.

Table 1. Well Count and Depth Data

Well Count Data	Domestic	Irrigation	Municipal	Other	Abandoned Destroyed	Total
Total Well Count	921	134	12	90	19	1,176
Wells w/o Depth Data	0	0	0	0	7	7
Wells w/ Depth Data	921	134	12	90	12	1,169
Well Depth Data						
Minimum Depth	19	35	40	8	18	8
Maximum Depth	315	597	556	897	535	897
Average Depth	90	163	205	134	88	103
Median	83	127	165	53	45	85
Standard Deviation	28	115	140	185	143	77

Notes: "Municipal" also includes public and industrial wells.
"Other" includes monitoring, stock, test, vapor extraction, and unknown wells.

The statistical distribution of the well depth data was also evaluated through a series of cumulative frequency distribution curves for domestic, irrigation, and municipal well depths. Figure 6 shows the cumulative frequency distribution curve for domestic well depths in the Lower Mill Creek project area. A total of 921 domestic wells were evaluated with respect to well depth. The depths of domestic wells range from 19 to 315 feet.

The cumulative frequency distribution of domestic well depth indicates that 70 percent of domestic wells are constructed to a depth of 100 feet or less. The high percentage of shallow domestic wells indicates that the shallow aquifer system provides apparent sufficient quantity for domestic use.

Figure 7 is a cumulative frequency distribution curve for irrigation well depth in the project area. We evaluated a total of 134 irrigation wells, ranging in depths from 35 to 597 feet.

The cumulative frequency distribution of irrigation well depth indicates that 50 percent of irrigation wells are constructed to a depth of 125 feet or less, and 75 percent of the irrigation wells are constructed to a depth of 175 feet or less. Only 15 percent of the irrigation wells are constructed deeper than 225 feet. The high percentage of relatively shallow irrigation wells further supports the domestic well evidence that the upper portion of the Tuscan aquifer system is of adequate supply.

Figure 8 shows the cumulative frequency depth distribution for public, municipal, and industrial wells in the Lower Mill Creek project area. We evaluated a total of 12 public, municipal, and industrial wells in terms of cumulative frequency distribution with respect to well depth. The depths of irrigation wells range from 40 to 556 feet. Figure 8 shows that 7 out of the 12 wells are constructed to depths ranging from 125 to 200 feet, with 50 percent of these wells are completed to a depth of less than 150 feet. Although the small number of wells in this data set somewhat restricts the statistical interpretation of these data, it appears that the majority of municipal wells are supplied from the aquifer systems that are less than 200 feet deep.

Water Source

DWR, Northern District, Land and Water Use Section conducts a land and water use survey for each county in the Sacramento Valley approximately every five years. In addition to the land use information, the surveys record the source of agricultural and domestic water supply as groundwater, surface water, or a mixed source. DWR conducted a Tehama County land and water use survey in 1999. Figure 9 is a map of the project study area which shows the water source distribution for the agricultural land use areas. Figure 9 shows that more than half of the project area is served by surface water diverted from Mill Creek through the LMMWC distribution system.

Groundwater Monitoring Wells

DWR, Northern District, Groundwater Section maintains a baseline regional groundwater level monitoring grid for the Sacramento Valley. Approximately 14 wells from the regional grid were monitored within the project area during the spring, summer, and fall seasons. As part of the Mill Creek project, the Groundwater Section reviewed the well log data base, canvassed the area, and obtained permission to add 12 additional wells to the existing regional monitoring grid.

Figure 10 shows the 27 wells in the monitoring grid that were established for the Mill Creek study. The monitoring wells are numbered using the State Well Numbering (SWN) system. The SWN system identifies each well by its location according to the township, range, section, tract, and number of wells within that tract. Figure 11 and the legend within Figure 10 illustrate an example of the SWN system. The monitoring wells in Figure 10 are labeled with an abbreviated SWN (last 5 characters), and the well depth shown in parenthesis. Table 2 lists the project monitoring wells by SWN, use, and qualification. The qualification is an interpretation on whether the well is in an aquifer that is unconfined, semi-confined, confined, or composite and is discussed in greater detail in the following section.

Groundwater Levels

Analysis of groundwater levels in the Lower Mill Creek project area is based on groundwater level data collected by DWR. Groundwater level data are collected from the network of wells shown in Figure 10 and listed in Table 2. The groundwater level monitoring grid consists primarily of active domestic and irrigation wells. To a lesser degree, the grid is also composed of municipal, idle and dedicated monitoring wells. Dedicated monitoring wells are designed and constructed for the sole purpose of groundwater monitoring and are strategically located to optimize data collection from a specific aquifer interval.

In order to fully characterize the seasonal groundwater level fluctuations in the project area, we measured the Mill Creek project monitoring grid monthly from the Fall of 2005 through December of 2007. We analyzed the groundwater level data to identify seasonal versus long-term changes in groundwater levels, the direction and rate of groundwater movement, and the estimated volume of groundwater in storage.

For each of the monitoring wells, we developed hydrographs (Appendix A). Groundwater hydrographs are a graphical plot of groundwater level depth over time. In addition to the hydrographs in Appendix A, a select number of representative hydrographs were chosen for discussion in the following paragraph and are again presented in Figures 12 through 15. Groundwater level data associated with all the monitoring wells have been entered into DWR's Water Data Library. They are available at the following Internet address: http://well.water.ca.gov/gw/. The groundwater level data may be accessed by SWN, map interface, groundwater basin, or by township location.

Table 2. Groundwater Level Monitoring Grid Well Information

State Well Number	Well Use	Qualification
25N02W-02A01M	Domestic	Unconfined
25N02W-04Q01M	Domestic	Unconfined
25N02W-09G01M	Domestic	Unconfined
25N02W-15N01M	Domestic	Unconfined
25N02W-16B03M	Domestic	Composite
25N02W-16L01M	Public	Confined
25N02W-17B01M	Irrigation	Unknown
25N02W-21B01M	Domestic	Unconfined
25N02W-28J01M	Irrigation	Composite
25N02W-34K01M	Irrigation	Unknown
26N02W-05A01M	Domestic	Unconfined
26N02W-05E01M	Domestic	Unconfined
26N02W-08D01M	Domestic	Unconfined
26N02W-09E01M	Irrigation	Unconfined
26N02W-14G01M	Irrigation	Semi-confined
26N02W-14R01M	Irrigation	Unknown
26N02W-15C01M	Domestic	Unconfined
26N02W-16C01M	Domestic	Unconfined
26N02W-17E01M	Irrigation	Unconfined
26N02W-21Q01M	Domestic	Unconfined
26N02W-22G01M	Irrigation	Confined
26N02W-29R01M	Monitoring	Semi-confined
26N02W-29R02M	Monitoring	Confined
26N02W-34R01M	Domestic	Semi-Confined
27N02W-30C02M	Irrigation	Unconfined
27N02W-31C01M	Irrigation	Composite
27N03W-25D01M	Domestic	Unconfined

Hydrographs presented in this report help us to estimate historic long-term groundwater level trends as well as seasonal fluctuations in groundwater levels. To help visualize changes in groundwater levels within the hydrograph, the individual measurement points are typically connected by a solid line. It is important to note, however, that the line connecting the actual measurement points does not represent a continuous recording of groundwater levels; rather, it serves as a visual aid and an approximation of levels between a series of known levels taken at individual points in time. Breaks or discontinuities in a hydrograph represents measurements that are missing from the regularly scheduled monitoring times. Missing measurements are typically the result of well access problems, such as locked gates or pump houses.

Seasonal groundwater level trends can vary by location, but throughout most of the Sacramento Valley agricultural areas, groundwater levels are typically the highest during the spring and lowest during the summer. Groundwater levels begin to slowly rebound after the agricultural season and continue to recharge throughout the winter months at a rate correlating to the location, duration, and timing of precipitation.

Because groundwater levels are typically most stable during the spring months, long-term trends or historic changes are typically analyzed by comparing spring-to-spring measurements. Because summer groundwater levels are typically the lowest of the year, they are useful for comparing to spring levels to determine the maximum seasonal fluctuation of groundwater levels within the aquifer. Fall groundwater levels are typically taken after the agricultural irrigation has ended but prior to the beginning of the rainy season. Comparison of summer versus fall groundwater levels can help provide an estimate of the rate and volume of groundwater that is recharged into the aquifer due to stream infiltration and groundwater underflow into the basin from adjacent areas.

In an effort to better interpret the groundwater level data, wells within the groundwater monitoring grid are qualified as unconfined, semi-confined, confined, or composite, depending upon which portion of the aquifer system the well is constructed (Table 2). An unconfined well is typically less than 150 feet and produces from the upper aquifer which has a greater interconnection with the overlying surface water systems. Confined wells are typically deeper than 300 feet and constructed to pull groundwater from deep production zones within the aquifer. Semi-confined wells are wells that are constructed somewhere between the unconfined and confined portions of the aquifer. A composite well is typically characterized by both shallow and deep aquifer production. A composite well is typically constructed with a long perforation interval, or with a shallow blank casing followed by open-hole construction.

Wells constructed in the unconfined portion of the aquifer system tend to show less seasonal fluctuation in groundwater levels than similarly located wells constructed in the lower, confined portion of the aquifer system. This is due to the fact that the shallow portions of the aquifer are largely open to the atmospheres which make the pressure exerted on the groundwater body equal to the surrounding atmospheric conditions. Thus, groundwater level changes in the unconfined aquifer reflect actual dewatering or filling of the aquifer. Confined aquifer systems, however, are typically separated from the upper aquifer by impervious material and subjected to the pressure from hundreds of feet of overlying sediments. Thus, groundwater level changes measured in the confined aquifer reflect a pressurized, or potentiometric, head. In a confined aquifer, only a small portion of the measured change in head (groundwater level) actually corresponds to dewatering of the aquifer. Similar amounts of seasonal dewatering from unconfined and confined aquifers will result in respectively small and large changes in groundwater levels.

The 4 hydrographs shown in figures 12 through 15 are representative of the Mill Creek project area. We selected these hydrographs based on length of record, well depth, geographic location, and representation of the shallow to deep aquifer systems.

Figure 12 is a hydrograph for monitoring well 27N02W31C001M. This composite-confined irrigation well has depth of 541 feet and is located near Antelope Creek in the northern portion of the study area. The hydrograph shows both seasonal and climatic groundwater level fluctuations. Seasonal fluctuations in this well vary about 5 to 8 feet, with groundwater level highs during the spring and lows during the fall. The climatic fluctuations are illustrated by the wet periods associated with 1983, 1997, 1998, and 2006, and dry periods associated with the drought conditions during 1960, 1977, 1986, 1992, 1993, and 1994. Spring-to-spring groundwater levels fluctuate about 14 feet due to climatic conditions. The overall long-term trend of spring-to-spring groundwater levels over the 49-year period of record appears stable.

Figure 13 is a hydrograph for monitoring well 26N02W16C001M. This unconfined domestic well has a depth of 50 feet and is located south of Dairyville. This well has shown seasonal groundwater level fluctuations of about 5 feet from the beginning of records in 1980 through

1995, about 10 feet from 1995 through 2003, and about 15 feet over the last several years. The increase in seasonal fluctuation is likely due to the increased residential development and irrigation pumping in the area. The groundwater level fluctuations associated with changing climatic conditions are visible but are less pronounced than in the hydrograph for well 27N02W31C001M in Figure 12. The spring-to-spring change between the wettest (1983) and driest (1991) water years over this well's period of record is about 10 feet. The overall long-term trend of spring-to-spring groundwater levels over the 27-year period of record appears relatively stable to slightly downward. However, the spring-to-summer fluctuation appears to be increasing as probably a result of less surface water use and more groundwater.

Figure 14 is a hydrograph for monitoring well 25N02W09G001M. This unconfined domestic well has a depth of 60 feet and is located between Mill Creek and the city of Los Molinos. Groundwater levels in this well show seasonal fluctuations of about 2 to 5 feet for the period of record from 1973 to 2007, with groundwater level highs during the spring and lows during the fall. The spring-to-spring fluctuation associated with climatic changes is about 10 feet. Groundwater levels in this well are relatively stable over the 34-year period of record.

Figure 15 is a hydrograph for monitoring well 25N02W34K001M. This composite-confined irrigation well has a depth of 235 feet and is located at the south end of the project study area with a period of record from 1963 to 2007. This well shows a seasonal fluctuation (spring high and fall low) of only 1 to 2 feet, with fluctuations increasing to about 5 feet after 1990. The increased fluctuation after 1990 is likely due to increased groundwater pumping in that area. The climatic signature in this well is very slight, with spring-to-spring groundwater level variations of only a few feet. Groundwater levels in this well appear to be relatively stable over the 45-year period of record. However, a slight downward trend of 3 to 5 feet is noticeable since 1990.

Groundwater Movement

We also used groundwater level data to develop groundwater elevation contour maps for the Lower Mill Creek project area. Similar to topographic ground surface elevation contours, the patterns and spacing of groundwater elevation contours can be used to help estimate the direction and gradient of groundwater movement. Groundwater contours are also used to help illustrate the spring-to-spring and spring-to-summer changes in groundwater elevations and the associated change in groundwater storage over a region. Contour maps provide a good graphical estimate of groundwater occurrence, movement, and changes in storage within the aquifer systems.

It is sometimes difficult for groundwater contours to accurately represent local conditions when the groundwater level data used for contour mapping is collected from wells constructed over varying depths of the aquifer system. In the Lower Mill Creek area, the groundwater-monitoring grid is primarily composed of active wells that vary in construction. Within the project area, the depth to groundwater in a shallow well constructed in the unconfined portion of the aquifer system can be significantly different from the groundwater level of a deep well constructed in the confined portion of the aquifer. Thus, groundwater contours developed using multiple well types would represent an average of mixed aquifer conditions (confined, unconfined, and composite).

To make the best use of the varying well data, the wells used to construct groundwater contour maps were divided into two groups based on depth and construction. We then created two separate sets of contour maps, one set representing the shallow unconfined aquifer zone the other set representing the deeper confined aquifer zone.

Figures 16 and 17 show the spring 2006 groundwater-elevation contours from the shallow and deep aquifer zones, respectively. The depths of the wells used in each contour map are displayed adjacent to the well label, along with the groundwater elevation. Additional wells from DWR's regional groundwater level monitoring grid were also used to assist in contouring the groundwater surface near the edges of the project area.

Figure 16 shows a west to southwest pattern of groundwater movement for the unconfined portion of the aquifer during the spring of 2006. The apex of flow in the unconfined aquifer appears to fall slightly east of the current Sacramento River location.

Figure 17 shows a similar pattern of groundwater movement in the confined portion of the aquifer during the spring 2006. The confined aquifer contours in Figure 17 show a slightly more pronounced eastern shift in the apex of groundwater flow, and a slight increase in the groundwater gradient adjacent to, and north of, the Los Molinos area. The eastern shift of the flow apex could be due to increased domestic and municipal groundwater demand in the Los Molinos area, or due to a geologic structural low in the Tuscan Formation that comprises the confined aquifer system. Both Figures 16 and 17 indicate that the Sacramento River is likely gaining in base flow due to subsurface discharge from the surrounding aquifer systems.

Figures 18 and 19 show the groundwater contours associated with the shallow unconfined and deep confined aquifer systems, respectively during the fall of 2006. Fall groundwater levels correspond to the approximate seasonal low for many wells in the project area. Both figures show little change of the general spring pattern groundwater movement in the project area. However, west of the project area, the groundwater elevation contours have shifted significantly to outline a depression starting near the city of Tehama, and continuing north and west past the city of Gerber. The lack of surface water supply and the high seasonal groundwater demand for agricultural beneficial use in these areas are likely the reasons for the noticeable drop in fall groundwater levels.

Figures 20 and 21 are 2006 spring-to-summer groundwater contour change maps. The contours in Figures 20 and 21 represent lines of equal change in the groundwater levels between the spring and summer 2006 monitoring periods. The groundwater level change contours for the unconfined aquifer represented in Figure 20 show a range of 0 to −6 feet decline in the Mill Creek project area between the spring and summer periods. West of the Sacramento River, the change in groundwater levels in the unconfined aquifer increases from −6 to −12 feet.

Figure 21 shows that the spring-to-summer change in groundwater levels for the confined portion of the aquifer system is about the same as the unconfined aquifer system within the Mill Creek project area. West of the Sacramento River, approximately 2 miles west of the city of Tehama, the spring-to-summer change in groundwater levels associated with the confined aquifer system increases to as much as −45 feet.

Groundwater Extraction

In order to manage groundwater resources, one of the components needed to know is the amount of groundwater being extracted from the basin. One method of determining groundwater extraction is by direct measurement, also referred to as metering, of individual production wells within the basin. However, in most areas of the Sacramento Valley, agricultural wells are not metered, consequently, not all groundwater extraction is monitored. This study uses the water balance approach to estimate groundwater extraction. The water balance approach uses land use surveys and municipal records to estimate groundwater extraction.

The results and methodology for determining groundwater extraction using the water balance approach were developed by DWR, Northern District, Land and Water Use Section for the 2003 Tehama County Water Inventory Analysis. The water balance data used in the 2003 study and in this report was collected in 1999. These results were modified to include the following Lower Mill Creek project area groundwater subbasins: Antelope, Dye Creek, and Los Molinos (Figure 1).

We determined the annual groundwater demand for normal water years and drought years by using the water balance approach, municipal records, and land use data developed by DWR and Tehama County Flood Control and Conservation District. In areas of the project having a mixed supply of surface water and groundwater, the difference between the agricultural demand and the surface water delivery is assumed to be equal to the amount of groundwater extraction.

Groundwater extraction estimates for a normal water year incorporate the 1999 land use and municipal extraction data projected for the 2000 population and cropping trends. The groundwater extraction estimates for a normal water year closely approximate the annual amount of groundwater extracted under the current level of development in the county. Groundwater extraction estimates for a drought water year represent the potential maximum amount of groundwater extraction that can be expected to take place under the current level of development and under a worst case scenario of precipitation, evapotranspiration, runoff, and reduction in surface water deliveries to the area.

Groundwater extraction data for the Lower Mill Creek project area portion of the Antelope, Dye Creek, and Los Molinos subbasin areas are presented in Figures 22 and 23. These figures represent the estimated groundwater extraction in acre-feet for normal and drought water years within the project area. The original data used in these figures was produced by DWR for the 2003 Tehama County Water Inventory Analysis. The results for of the Antelope and Los Molinos groundwater subbasins were modified from the 2003 report to estimate only the portion of the subbasin within the Lower Mill Creek project area. The modification was performed by multiplying the total groundwater extraction for the subbasin by the proportional agricultural area that is within the project area. This calculation is only an estimate and assumes that the proportion of groundwater extraction to surface water use is the same in the project area of the subbasin as in the entire subbasin. Figure 9 is a water-source map that shows both surface and groundwater use in the project area and should be used in conjunction with Figures 22 and 23 to interpret groundwater extraction for each subbasin. The entire Dye Creek subbasin is within the project area and the amount of extraction was not modified.

Figure 22 is a pie chart that illustrates the estimated volume of groundwater extraction during a normal water year for each of the three Lower Mill Creek project area subbasins. Figure 22 shows that the estimated volume of normal water year groundwater extraction in the Antelope, Los Molinos, and Dye Creek subbasins is about 6,130; 4,100; and 5,850 acre-feet respectively. The combined total normal water year groundwater extraction for the study area is estimated at 16,080 acre-feet.

Figure 23 is a pie chart that illustrates the estimated volume of groundwater extraction during a drought year (75 percent surface water cutback) for each of the three Lower Mill Creek project area subbasins. Figure 23 shows that the estimated volume of dry water year groundwater extraction in the Antelope, Los Molinos, and Dye Creek subbasins is about 6,020; 4,550; and 7,710 acre-feet respectively. The combined total dry water year groundwater extraction for the study area is estimated to be 18,280 acre-feet. When Figures 22 and 23 are compared, they indicate an increase in groundwater demand of about 2,100 acre-feet between normal water years and drought years. Most of the increase in groundwater extraction during a drought year occurs in the Dye Creek subbasin while the Antelope subbasin has a decrease in groundwater extraction. The reason for the difference is not obvious.

Well Yield

Well yield is the maximum amount of groundwater that can be continuously extracted from a well. Well yield values are largely a function of well size, well performance, and aquifer productivity. Sources of well yield data reviewed for this investigation include well logs filed with DWR, Northern District, along with data from published and unpublished investigations.

Well yield data from well logs in the Dye Creek subbasin and the project area portions of Antelope and Los Molinos subbasins are provided in the upper portion of Table 3. The well yield data provided from well logs are often derived by drillers who use a variety of pumping methods that can often produce variable results. Well yield data listed in those reports are often collected during well drilling or development and are commonly more a function of the particular pump test method rather than an accurate indication of maximum well yield for a given area. As such, well yield data shown in Table 3 should serve as a general approximation of actual well yield.

In 1961, Olmsted and Davis from the USGS compiled utility pump test records from the 1940s in a report entitled *Geologic Features and Ground-Water Storage Capacity of the Sacramento Valley, California*. In their report, Olmsted and Davis analyzed well yield data from large-capacity irrigation, industrial, and municipal wells in 21 study areas within the Sacramento Valley through 1948. Out of the 21 study areas, 2 are located in the valley portion of Tehama County within the Lower Mill Creek project area. The lower portion of Table 3 also shows a summary of well data from the report from wells on the east side of the Sacramento Valley from Red Bluff to Butte County. This area includes all three subbasins within the Lower Mill Creek project area.

Table 3. Well Yield Data from Well Completion Reports and 1961 USGS Study.

Subbasin	Well Yield Data from Well Completion Reports						
	Irrigation and Municipal Wells						
	Number Reports	Wells Tested	Average Depth	Average Diameter	Well Yield (gpm)		
					Max	Min	Average
Antelope (LMMWC Portion)	57	5	148	14	3,300	100	1,000
Dye Creek	52	4	109	8	300	75	206
Los Molinos (LMMWC Portion)	38	6	302	11	3,000	40	1,057

Study Area	Well Yield Data from 1961 USGS Study					
	Number Wells	Number Tests	Average Depth	Average Diameter	Average Specific Capacity	Average Well Yield
East-Side Valley (Red Bluff to Butte County)	42	46	268	--	70	770

Well yield data indicates that well yields increase as the axis of the Sacramento Valley (or the Sacramento River) is approached. Table 3 shows that the average yield for irrigation and municipal wells in the LMMWC portion of the Antelope and Los Molinos subbasins is about 3 to 4 times the yield than is in the Dye Creek subbasin. This drop in yield for the Dye Creek subbasin is likely a function of the shape of the basin and the limited data set, rather than a function of any major regional changes to the aquifer systems. The Dye Creek production well that was previously discussed on page 10 under the "Tuscan Aquifer Properties and Well Production Potential" heading, has a consistent yield of 2,800 to 3,300 gpm. However, the higher yields for the Dye Creek well could be attributed to the well design and its depth of 590 feet which allows for screening across several portions of the Tuscan Formation aquifer.

Data from the 1961 USGS study indicate that the average well yield for the general area on the east side of the valley near Red Bluff and Butte County is 770 gpm. These low yield estimates may be the result of older well drilling and construction methods which tend to limit the average casing diameter and well depth. DWR's Bulletin 118-6, *Evaluation of Groundwater Resources: Sacramento Valley*, averages well yields from PG&E (Pacific, Gas, and Electric Company) pump test data in the Sacramento Valley and characterizes the wells in the Los Molinos area as having yields of 1,000-2,000 gpm (DWR 1987).

Specific Capacity

The specific capacity of a well is the pumping rate divided by the total drawdown after a specified period of pumping. Similar to well yield, specific capacity is a method of measuring well productivity. Specific capacity is usually reported in gallons per minute per foot (gpm/ft) of drawdown along with the amount of elapsed pumping time prior to measurement. Sources of specific capacity data reviewed for this investigation include published and unpublished investigations and utility pump test records. Data from well logs were determined to be inadequate for an accurate evaluation of specific capacity on an inventory.

We also collected specific capacity data from work conducted by Olmsted and Davis and published in their 1961 USGS report. Specific capacity data from this study reported an average value of 70 gpm/ft for the east side of the Sacramento Valley from Red Bluff to northern Butte County (Table 3). We requested for access from PG&E to more recent pump test data that was collected through the PG&E agricultural water use efficiency testing program between 1989 and 1998, but they denied our requests.

Groundwater Storage

Groundwater storage in the Lower Mill Creek project study area was examined by analyzing the estimated existing amount of groundwater in storage, the available groundwater in storage, and the change in groundwater in storage.

Groundwater in Storage

Groundwater in storage is the volume of groundwater currently in storage within the saturated portion of the aquifer. Groundwater in storage values may be reported over a range of increasing depth intervals or over the entire aquifer (total groundwater in storage). Groundwater in storage is calculated by multiplying the specific yield of the aquifer by the saturated aquifer volume over a given depth.

Specific yield is a function of aquifer pore space and increases as the percentage of pore space to solid material increases within the aquifer. By definition, specific yield is the ratio of water volume that a rock will yield under gravity drainage to the volume of the entire rock. Values of specific yield can be derived directly from aquifer sampling or estimated from the description of aquifer units recorded in well logs. Estimates of specific yield used in this study were derived primarily from data developed by the USGS by utilizing aquifer descriptions listed in well logs (Olmsted and Davis 1961). We compiled additional specific yield data from unpublished field investigations conducted by DWR for areas where USGS specific yield estimates were not available.

Several methods exist for determining aquifer volume over a given saturated thickness. For our study, we used three-dimensional modeling to create an upper aquifer surface using spring 2006 groundwater level data. The difference in the area-volume between the spring 2006 surface and subsequent depths of 50, 100, and 200 feet below spring levels were then calculated. Using a similar approach, groundwater in storage over the entire freshwater portion of the aquifer (total groundwater in storage) was also calculated using the spring 2006 data for the upper surface and the base of freshwater data for the lower surface. Estimates of the base of fresh water were derived from C.F. Berkstresser, Jr. (Berkstresser 1973). We determined the average depth to groundwater by taking the difference between the upper aquifer surface and the topographic surface.

The average depth to groundwater appears high in the Los Molinos subbasin because the subbasin includes both the valley floor and foothill terrain (Tables 4 and 5). In contrast, the Antelope subbasin exists mostly on the valley floor resulting in less elevation change and a lower average depth to groundwater. Table 4 shows the estimated total groundwater in storage based on spring 2006 depth to groundwater measurements for each of the 3 subbasins within the Lower Mill Creek study area. Table 5 shows the change in the amount of groundwater in storage with hypothetical groundwater depths of 50, 100, and 200 feet below spring 2006 measurements for the Lower Mill Creek study area portion of each of the groundwater subbasins. Table 4 shows that the total estimated groundwater in storage within the Mill Creek project area is about 5,800 thousand acre-feet (TAF). Table 5 shows that if groundwater levels were to drop to 50, 100, and 200 feet below spring 2006 levels, the change in aquifer storage for the project area would be a reduction of about 170 TAF, 345 TAF, and 690 TAF respectively.

Table 4. Estimated Total Groundwater in Storage (Thousand Acre-Feet).

Subbasin Unit	Surface[1] Area (acres)	Specific Yield (%)	Average[2] DTGW Spring 2006 (feet)	Average[2] Depth to Base of FW (feet)	Calculated Average Aquifer Thickness (feet)	Estimated Total GW in Storage (TAF)[3]
Antelope	5,100	7.2	15	1,849	1,834	673
Dye Creek	28,100	7.3	73	1,881	1,808	3,709
Los Molinos	14,900	6.8	147	1,534	1,387	1,405
Totals:	**48,100**	**7.2**	**78**	**1,755**	**1,676**	**5,787**

Notes:
DTGW = Depth to Groundwater; FW = Freshwater; GW = Groundwater; TAF = Thousand Acre-Feet.
1. Surface area in Antelope and Los Molinos Subbasins only include the portion within the Mill Creek project area.
2. Average depth to groundwater and average depth to base of fresh water are based on weighted averages over a computer generated triangular surface within each subbasin.

Table 5. Estimated Groundwater in Storage at Depths to Groundwater of 50, 100, and 200 Feet Below Spring 2006 Measurements (Thousand Acre-Feet).

Subbasin Unit	Surface[1] Area (acres)	Specific Yield (%)	Average[2] GSE (feet)	Average[3] GWE Spring 2006 (feet)	Average DTGW Spring 2006 (feet)	Difference of Groundwater in Storage, Spring 2006					
						GWE -50 ft.		GWE -100 ft.		GWE -200 ft.	
						DTGW	TAF	DTGW	TAF	DTGW	TAF
Antelope	5,100	7.2	250	235	15	65	18	115	36	215	72
Dye Creek	28,100	7.3	301	228	73	123	103	173	206	273	412
Los Molinos	14,900	6.8	351	204	147	197	51	247	102	347	204
Totals:	**48,100**	**7.2**	**301**	**222**	**78**	**128**	**172**	**178**	**344**	**278**	**688**

Notes:
DTGW = Depth to Groundwater; FW = Freshwater; GSE = Ground Surface Elevation; GWE = Groundwater Elevation; TAF = Thousand Acre-Feet.
1. Surface area in Antelope and Los Molinos Subbasins only includes the portion within the Mill Creek project area.
2. Average ground surface elevations were calculated from a digital elevation map (DEM) with a 30-meter resolution for each subbasin.
3. Average groundwater elevations were calculated from weighted averages over a computer-generated triangular surface within each subbasin.

To further the general understanding of groundwater resources in the Lower Mill Creek area, we developed estimates of groundwater in storage. The estimates were not intended to use as a guideline for usable aquifer capacity. Because of the numerous shallow domestic wells within the Lower Mill Creek study area, with 70 percent being less than 100 feet deep, the actual amount of usable groundwater storage will be much less than the volumes estimated over the aquifer intervals listed above. Excessive extraction, or "mining" of groundwater, can lead to increased pumping costs, dewatering of wells, increased infiltration, reduced flow from surface water systems, and the potential degradation of the water quality within the aquifer. Ultimately, determination of the "useable" groundwater in storage should be locally defined and empirically determined through active management and adequate monitoring of the groundwater resource.

Available Groundwater Storage Capacity

Available groundwater storage capacity is the difference between the total existing amount of fresh groundwater in storage and the maximum amount of groundwater the aquifer is capable of storing. Calculation of available groundwater storage requires estimating how high groundwater levels could rise in the aquifer system before damage occurs to the existing agriculture, urban infrastructure, or before natural discharge into surface water systems prevents further storage. Available groundwater storage is typically calculated and recorded as a volume over a given aquifer surface area.

Table 6. Estimated Available Groundwater Storage Capacity Based on Spring 2006 Groundwater Measurements (Thousand Acre-Feet).

Subbasin Unit	Surface Area[1] (acres)	Specific Yield (%)	Average[2] DTGW Spring 2006 (feet)	Average[2] Depth to Base of FW	Estimated Total GW in Storage (TAF)[3]	Average Available GW Storage (feet)	Estimated Maximum GW Storage Capacity (TAF)	Available GW Storage Capacity (TAF)
Antelope	5,100	7.2	15	1,849	673	3	675	2
Dye Creek	28,100	7.3	73	1,881	3,709	1	3,711	2
Los Molinos	14,900	6.8	147	1,534	1,405	2	1,407	2
Totals:	48,100	7.2	78	1,755	5,787	2	5,793	6

Notes:
DTGW = Depth to Groundwater; FW = Freshwater; GW = Groundwater; TAF = Thousand Acre-Feet.
1. Surface area in Antelope and Los Molinos Subbasins only include the portion within the Mill Creek project area.
2. Average depth to groundwater, base of fresh water, and available aquifer storage in feet above spring 2006 levels is based on weighted averages over a computer generated triangular surface throughout each subbasin.
3. Average available groundwater storage is based on comparing historic hydrographs and calculating the weighted average in the difference between spring 2006 and the highest level on record.

We developed estimates of the available groundwater storage capacity by reviewing groundwater level data from long-term monitoring wells to determine the highest historical groundwater elevation for the wells in the project area. The historical high groundwater elevations, based on a weighted average, were then used to calculate the maximum groundwater in storage capacity. Similar to groundwater in storage calculations, the spring 2006 groundwater elevation was subtracted from the estimated maximum groundwater elevation and multiplied by the average specific yield of each area to obtain the available acre-feet of groundwater storage for each subbasin within the Lower Mill Creek project area. Table 6 shows the estimated groundwater in storage, the estimated maximum storage capacity, and the available groundwater storage capacity.

Table 6 also shows the groundwater subbasins within the Lower Mill Creek project area have a maximum groundwater storage capacity of about 5,793 TAF. When this is compared with the spring 2006 estimate of 5,787 TAF for the existing groundwater in storage, it appears the groundwater subbasins in the project area were over 99 percent full as of spring 2006.

Change in Groundwater in Storage

Change in groundwater in storage is dependent on many factors including climatic conditions, the annual rate of groundwater extraction, and the annual rate of groundwater recharge. Groundwater storage commonly fluctuates within a given year and from year to year. Groundwater in storage will typically decline during periods of drought and rebound during periods of above-normal precipitation. Within a given year, groundwater in storage will decline through the summer months with increased extraction from municipal and agricultural uses. It will then recover as extraction slows and seasonal precipitation increases recharge to the aquifer. In basins where the amount of annual groundwater extraction is at or below the amount of normal water-year recharge, the long-term change in groundwater in storage will remain the same. In basins where the annual amount of groundwater extraction exceeds the amount of normal water-year recharge, the long-term change in groundwater in storage will decline. Depletion of groundwater in storage is typically exhibited by a decline in groundwater levels during periods of normal precipitation.

Table 7. Change in Groundwater Storage, Spring-to-Summer 2006.

Subbasin Unit	Surface Area[1] (acres)	Specific Yield (%)	Average[2] DTGW Spring 2006 (feet)	Average[2] DTGW Summer 2006 (feet)	Average Change GWLs Spring-to-Summer 2006 (feet)	Estimated Spring-to-Summer GW Extraction (acre-feet)
Antelope	5,100	7.2	15	9	-6	-2,203
Dye Creek	28,100	7.3	73	71	-2	-4,103
Los Molinos	14,900	6.8	147	144	-3	-3,040
Totals:	**48,100**	**7.2**	**78**	**75**	**-4**	**-9,346**

Notes:
DTGW = Depth to groundwater; FW = Freshwater; GWLs = Groundwater Levels.
1. Surface area in Antelope and Los Molinos Subbasins only include the portion within the Mill Creek project area.
2. Average depths to groundwater are based on weighted averages over a computer-generated triangular surface throughout each subbasin.

Our calculations of the change in groundwater storage for the Mill Creek project area focused on the time period from spring to summer of 2006. The results are based on Figure 20 which represents the spring-to-summer change during 2006. We constructed digital three-dimensional groundwater elevation surfaces using the spring-to-summer groundwater level data, and the volume differences between the spring-to-summer groundwater elevation surfaces were calculated.

The results in Table 7 show an estimated 9,346 acre feet were removed from storage in the Mill Creek project area between spring and summer of 2006. When we compare estimates of the 2006 seasonal groundwater extraction based on groundwater level monitoring (Table 7) are compared with the normal water-year groundwater extraction estimates based on land and water use data (Figure 22), estimates of 9,346 versus 16,080 acre-feet are shown respectively. The seasonal groundwater extraction estimate based on land use data is about 60 percent greater than the 2006 estimate based on groundwater level monitoring data. Differences between the 2006 and 2000 water years could account for a significant portion of the difference. Due to extremely wet conditions during the spring months, groundwater levels measured during the spring of 2006 were the highest on record for many Sacramento Valley wells. Consequently, the agricultural need for groundwater was limited during the spring and early summer of 2006. The reduction in groundwater demand in 2006 could likely account for up to a 30 percent decrease in groundwater extraction. The remaining 30 percent difference is likely within the margin of error associated with using the land use water balance approach and the groundwater level contouring methods.

Surface Water – Groundwater Interaction

Between 2005 and 2007, DWR conducted flow measurements of Mill Creek to assess the interaction between surface water and groundwater. Changes in stream flow between measuring points would indicate gains or losses with the groundwater table. Stream flow measurement locations were selected based on the channel geology, channel geometry, vegetation, surface water diversions, and known gauging station locations.

As Mill Creek enters the eastern edge of the valley, it crosses a short surficial exposure of Unit B of the Tuscan Formation. Moving to the west, Unit B dips beneath the ground surface and continues into the valley where it comprises one of the major water bearing aquifer systems in the valley. At the surface, Mill Creek continues across Units C of the Tuscan Formation until it reaches the Sacramento River. The Riverbank Formation, Modesto

Formation, and younger stream channel deposits are locally traversed by Mill Creek in places where they have not been eroded away in the stream channel.

The upstream measuring site was located where the stream crosses Unit B of the Tuscan Formation. The downstream site was located just above the LMMWC main diversion, which serves as a year-around diversion and contains a "spill-back" structure that restricts monitoring of return flows to the creek. The total distance between the upper and lower stream-flow monitoring sites was about 2 miles.

We performed the stream-flow measurements in fall to minimize fluctuations associated with evapotranspiration of riparian vegetation, induced recharge from applied agricultural water, and precipitation. Abnormally dry weather during the winter of 2006-07 provided many opportunities for stream-flow monitoring because of low temperatures and the lack of rainfall.

Stream-flow measurements can be affected by monitoring equipment related issues such as operator experience, instrument errors, and adverse stream channel conditions. DWR personnel who are experienced in stream-flow gauging operated the monitoring equipment for these measurements. A Price AA current meter and wading rod were used, and the measurements were completed using USGS standards. Overall, errors associated with stream-flow measurements are ± 5 percent based on USGS guidelines.

The results of the measurements are summarized in Table 8. The measurements performed on October 12, 2005, indicate an increase in flow from the upstream measurement to the Main Diversion of 1.02 cubic feet per second (cfs), while the results from October 19, 2005; December 7, 2006; and January 24, 2007, all show a decrease in flow of 4 cfs to over 8 cfs from the upper most measurement to just above the LMMWC Main Diversion. Although the change in flows is within the 5 percent error of the measurements, the repeatability of the data suggests a loss of flow which could be the result of surface water infiltrating along surface exposures of the Tuscan Formation and providing recharge to the groundwater aquifer. Additional measurements are needed to further support this conclusion.

Table 8. Mill Creek Flow Measurements (cfs)

Flow Measurement Location	Monitoring Dates and Flow (cfs)			
	10/12/2005	10/19/2005	12/7/2006	1/24/2007
Upstream Site[1]	95.54	105.60	131.30	145.50*
Above Main Diversion	96.56	97.17	127.27	138.48*
Change in Flow:	**1.02**	**-8.43**	**-4.03**	**-7.02**

Notes:
* = Average of 2 measurements
1. The upstream measuring site was located where the stream crosses Unit B of the Tuscan Formation.

Section 4. Conjunctive Use and Recommendations

Conjunctive use is the coordinated and planned management of both surface and groundwater resources in order to maximize the efficient use of the resource. Groundwater substitution and in-lieu recharge are components of conjunctive use. Groundwater substitution is the use of groundwater in substitution of forgone surface water supplies. In-lieu recharge is utilization of surface water in place of groundwater in order for aquifers to naturally recharge and recover. In the case of the Lower Mill Creek project area, water is diverted primarily for irrigation purposes through open ditches as far north as 8 miles from the point of diversion. The irrigation efficiency, based on a 2005 water balance conducted by the California Polytechnic State University, Irrigation Training and Research Center (Cal Poly), is estimated to be between 50 and 65 percent (Cal Poly 2005). This results in diverting 35 to 50 percent more water than required for in-field crop demand. During certain times of the year, especially during dry or critically dry water years, the agricultural demand for surface water can reduce Mill Creek flow and expose in-stream barriers to fish migration. Providing groundwater, in substitution for surface water, to agricultural water users is one possible solution to help maintain in-stream flows and reduce water loss associated with lengthy deliveries through unlined distribution systems.

Based on the well inventory analysis and groundwater storage data in Section 3, the groundwater aquifer systems in the Lower Mill Creek project area are nearly full during any given year. Recharge from the east-side creeks along with over 90 years of applied surface water and limited groundwater extraction contribute to maintaining high groundwater levels within the project area aquifers. Groundwater level monitoring and land use estimates indicate that the current groundwater extraction in the project area during a normal water year ranges between 10,000 and 16,000 acre-feet per year (Table 7 and Figure 22). Similar analysis for areas just west of the Sacramento River estimate normal year groundwater extraction for the Red Bluff subbasin to be about 60,000 acre-feet. Groundwater level response associated with the increased pumping in the Red Bluff subbasin results in a seasonal decline of 20 to 45 feet over the area of concentrated pumping. However, annual recharge appears to maintain this level of groundwater extraction without long-term decline in spring-to-spring groundwater levels.

Based on the well log inventory, the well depth distribution curve in Figure 6 shows that 90 percent of the domestic wells within the project area are less than 125 feet deep. The well depth distribution for irrigation wells shows that 80 percent of those wells within the project area are less than 200 feet deep (Figure 7). Installation of new production wells for the purpose of conjunctive use or groundwater substitution programs should be designed to extract water from deeper portions of the aquifer system in order to minimize or eliminate potential impacts associated with increased seasonal fluctuation of groundwater levels in the shallower aquifer zones.

Although the inventory of well logs indicates average agricultural well yields to be in the 1,000 gpm range, much of these data are based on older wells with limited pumping data. In areas with deeper and more recently designed gravel pack wells, production in the 2,000 to 3,000 gpm range over much of the project area seems likely.

LMMWC has two existing wells that are suitable for groundwater substitution usage. One well is along the High Line Canal, and the other is along the Main Canal. Both wells were installed in order to supplement surface water supplies by pumping groundwater into the LMMWC distribution system. The well along the Main Canal is screened from 340 to 590 feet and is capable of pumping approximately 3,000 gpm (6.5 cfs). The well along the High Line Canal is 495 feet deep with an unknown screened interval and is capable of pumping approximately 800 gpm (1.8 cfs). Both of these wells discharge water into the distribution system canals near the top one-third of the LMMWC delivery system. Although locating these wells high in the distribution system provides flexibility for utilizing the additional supply, the location also results in potential inefficiencies due to increased water loss from the canal associated with increased delivery distances. Additional consideration should be given to locating new wells in areas that will maximize distribution flexibility along with delivery efficiency.

A potential problem with the two LMMWC wells, and the proposed new wells is groundwater quality. Recent water quality testing from the well along the Main Canal shows that boron levels in groundwater exceed the agricultural goal. Although we have no recent water quality data for the well along the High Line Canal, we believe it to be similar to the one along the Main Canal because they are relatively close together and have similar depths. Mixing the poor quality groundwater with surface water deliveries currently reduce the boron concentrations to manageable levels in the Main Canal, but expanded use of this technique is obviously limited. Drilling and installing monitoring wells in the area before constructing production wells will assist with screening for water quality, analyzing potential production zones, and providing program-related monitoring needed to evaluate the effects of increased pumping.

The Cal Poly study indicates that, if the irrigation system was 100 percent efficient, a reduction in the stream-flow diversion of 30 cfs in April and 10 cfs in May would be possible in order to benefit fish migration (Cal Poly 2005). Hypothetically, if a groundwater supply was used to make up the difference, it would take seven wells pumping 2,000 gpm each to provide 30 cfs. The costs associated with installation of 7 production wells, along with 5 to 7 dedicated monitoring wells needed for CEQA compliance, would likely cost approximately 3 million dollars. A less expensive alternative would be to install 2 or 3 production wells in strategic locations along with monitoring wells to provide an additional 10 to 15 cfs of Mill Creek water which could be allowed to bypass diversion if 1,500 to 2,500 gpm for 3 wells can be attained. Including the 2 existing wells along Main and High Line Canals, a total of approximately 18 to 24 cfs could be supplied through groundwater substitution. Figure 24 shows the location of the 2 existing wells along the Main and High Line Canals, the agricultural water source (based on the 1999 land and water use survey), and the proposed locations for future production and monitoring wells.

Grant funding through the AB303 Local Groundwater Management Assistances Grant is periodically available and could be used to significantly off-set the initial capital cost associated with well installations.

Production Well Recommendations

Our recommendation is for LMMWC to arrange installation of 2 to 3 production wells in the northern portion of their service area. Figure 24 shows the water source, the Main and High Line Canal wells, and the primary locations for the proposed production wells. The locations of the proposed production wells are in areas where surface water is currently used that also have conveyance facilities. Specifically, we recommend that LMMWC arrange for the two production wells to be located along the High Line and Main Canals toward the northern portion of the service area, so they are closer to the end-users to maximize delivery efficiency. We also propose a third production well to be located centrally in the LMMWC service area just north of Mill Creek. This area is currently served by surface water and is potentially suitable for groundwater substitution. In addition, this location is closer to the Sacramento River where well production and aquifer recharge is high.

Monitoring Well Recommendations

Prior to installing the recommended production wells, we recommend that LMMWC arrange for a small-diameter test hole to be drilled and for geophysical logs to be generated. Geophysical logs can be useful to identify potential aquifer zones, to determine well design options, to reveal possible water quality issues, and to estimate potential groundwater production. If the test hole location proves favorable, we recommend that LMMWC arrange for it to be used as a pilot hole for further drilling and installation of a dedicated, multi-completion monitoring well. Multi-completion monitoring wells make it possible to individually monitor multiple aquifer zones at a single site. After construction, we recommend that LMMWC arrange for installation of groundwater level data loggers and monitoring of water quality in order to collect the necessary data regarding the connectivity between aquifer systems and the overall viability of the site for production well installation.

In addition to the three primary locations for proposed monitoring and production wells, we recommend that LMMWC arrange for installation of additional dedicated monitoring wells at secondary sites to assist their future efforts in fulfilling the need for long-term monitoring of the local aquifer system. Figure 24 shows the locations of the proposed secondary monitoring wells sites. We selected these locations because they are in areas where groundwater is currently being used for agricultural supply, so they should be monitored on an on-going basis.

Summary

The potential for conjunctive use in the Lower Mill Creek watershed area is high. The Tuscan Formation has sufficient groundwater in storage in this area to allow for additional groundwater extraction while maintaining long-term sustainability. LMMWC should be able to use Groundwater substitution to supplement surface water supplies during dry or below normal water years, while in-lieu recharge should be used for aquifer recovery during normal, wet, or above normal water years.

Boron has been detected at levels above the agricultural goal in groundwater extracted near the base of the foothills adjacent to Dye Creek. Test holes and monitoring wells will need to be installed in strategic locations as an initial step to further assess groundwater quality concerns, as well as potential aquifer production, and to provide baseline groundwater level data over multiple aquifer intervals.

After the installation of two production wells in the northeastern third of the LMMWC service area, and one production well just north of Mill Creek near Los Molinos, an additional supply of approximately 10 to 15 cfs could be attained. Utilization of three new production wells, in addition to the two existing wells, could provide an additional instantaneous supply of approximately 18 to 24 cfs. The newly developed groundwater supply could be used in substitution of Mill Creek diversions for times when additional flows are needed for fish migration.

The Cal Poly report indicates that if the irrigation ditches were lined, or if the water was piped, the increase in efficiency would result in a reduction in diversions of about 30 cfs during April and about 10 cfs during May which are critical periods for spring-run salmon migration (Cal Poly 2005). Distribution efficiency improvement, along with the application of a groundwater substitution program, could result in the ability to reduce diversions by approximately 45 to 55 cfs during April, and 25 to 35 cfs during May.

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Figure 1. Project Location Map

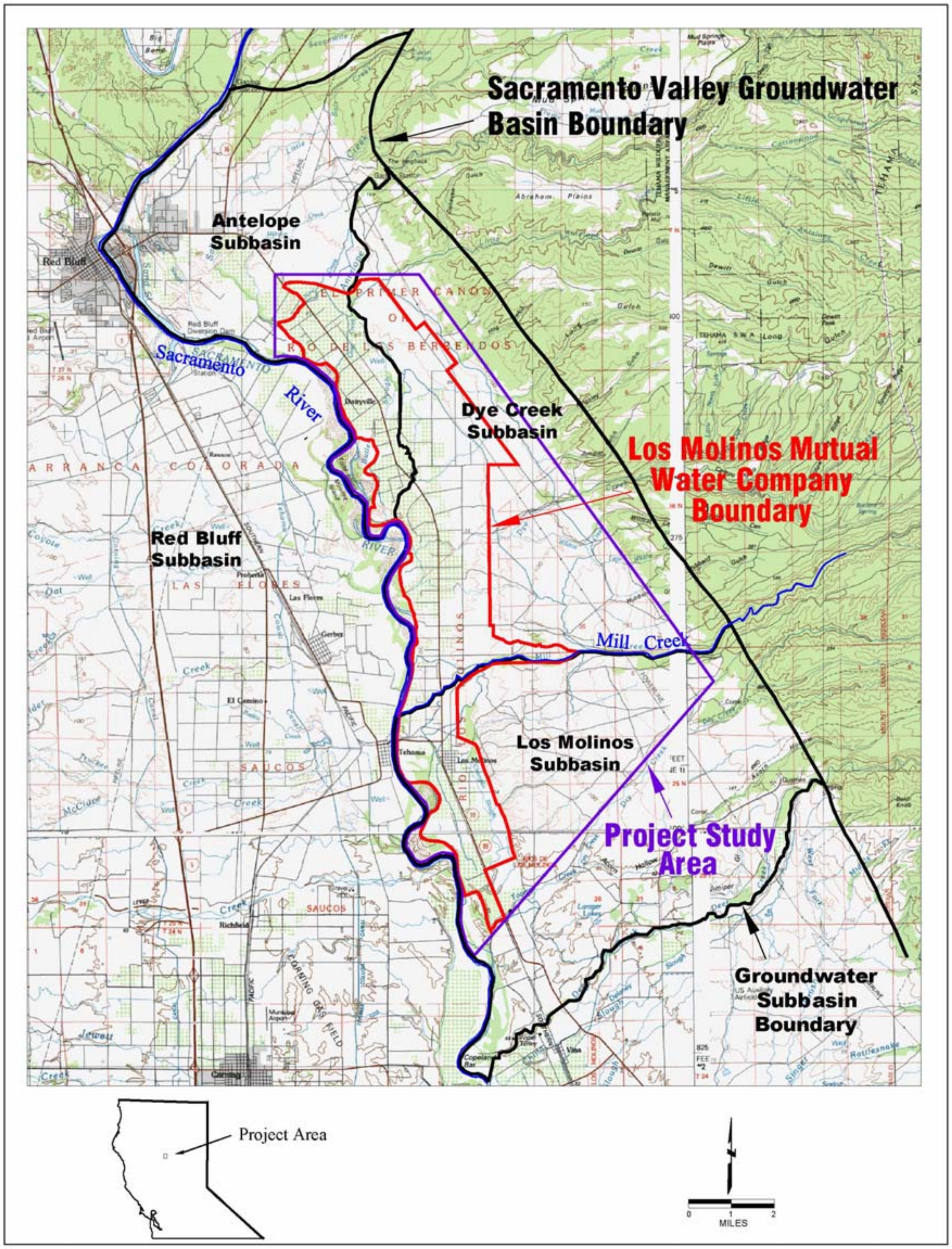


Figure 2. Project Geology Map

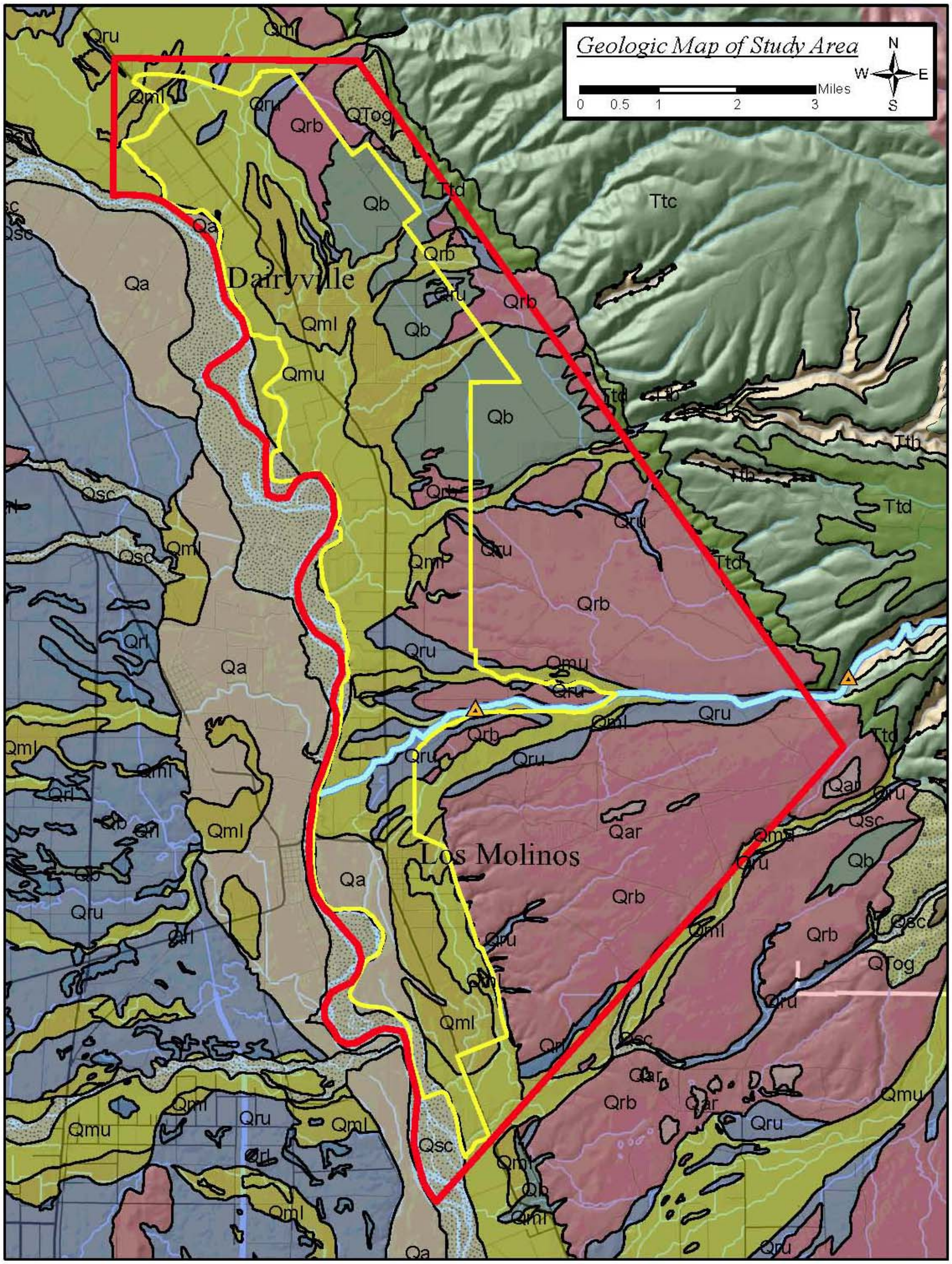


Figure 3. Project Geology Map Legend

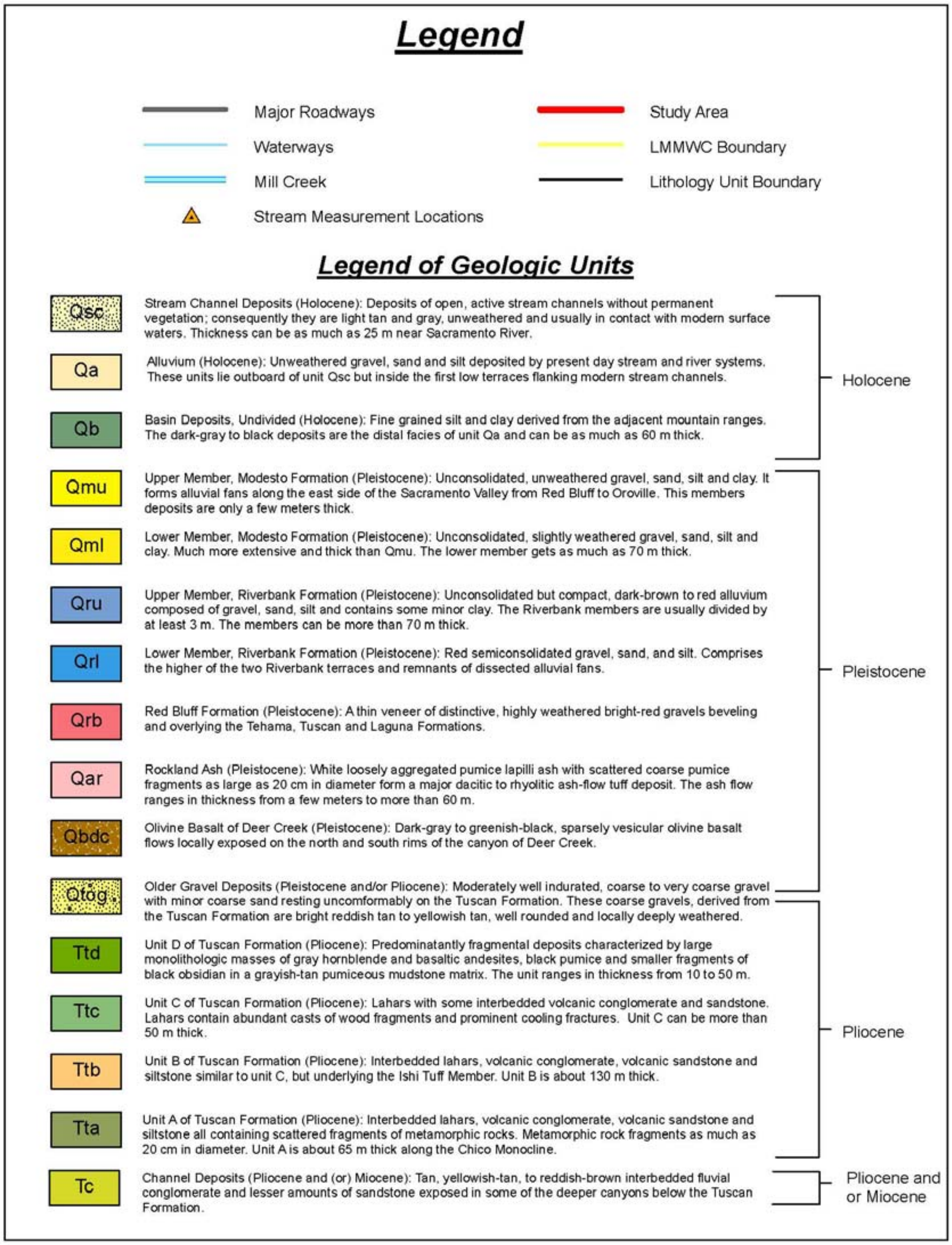


Figure 4. Well Inventory Map, Number of Wells Per Section

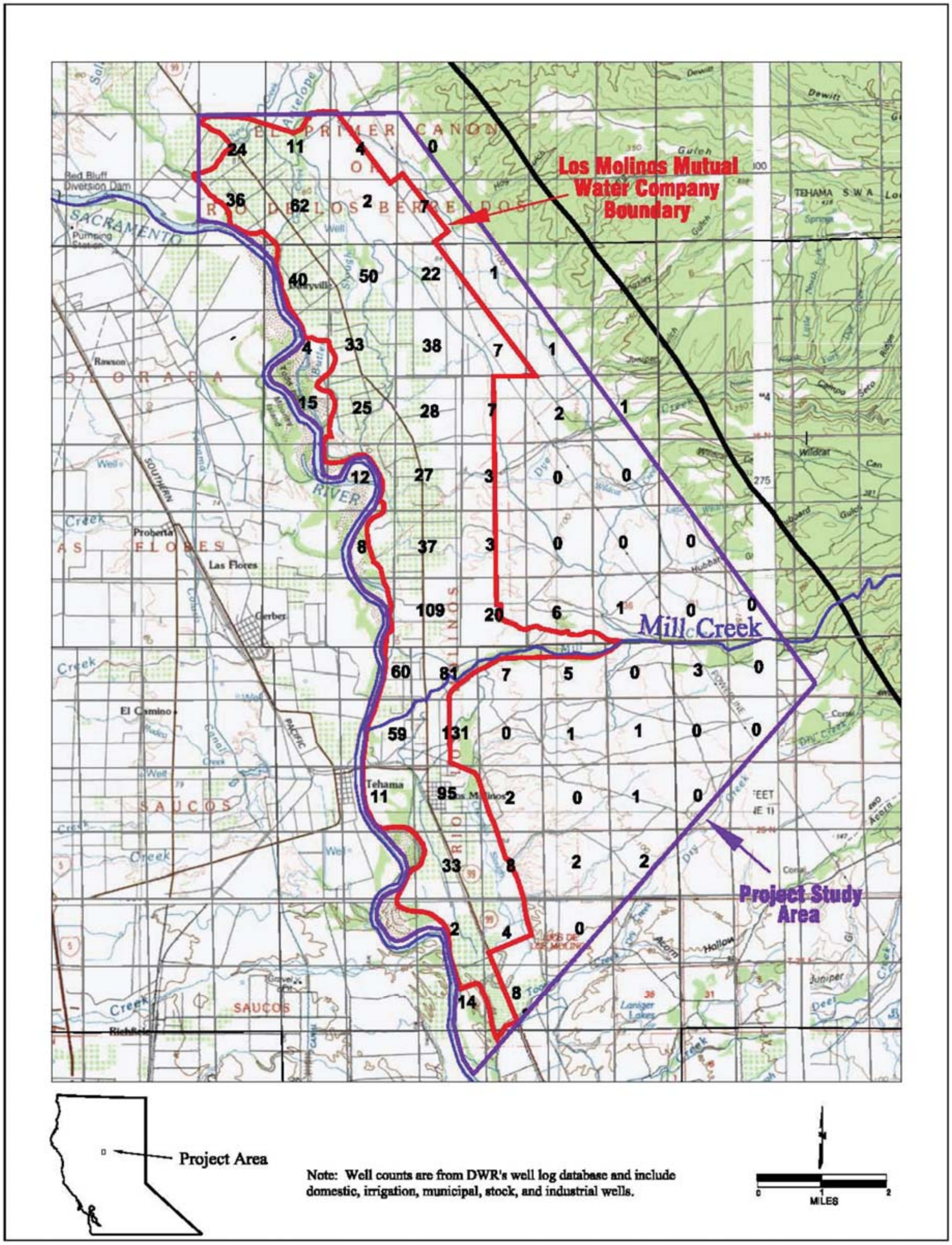


Figure 5. Number of Domestic Wells/Number of Irrigation Wells (Per Section)

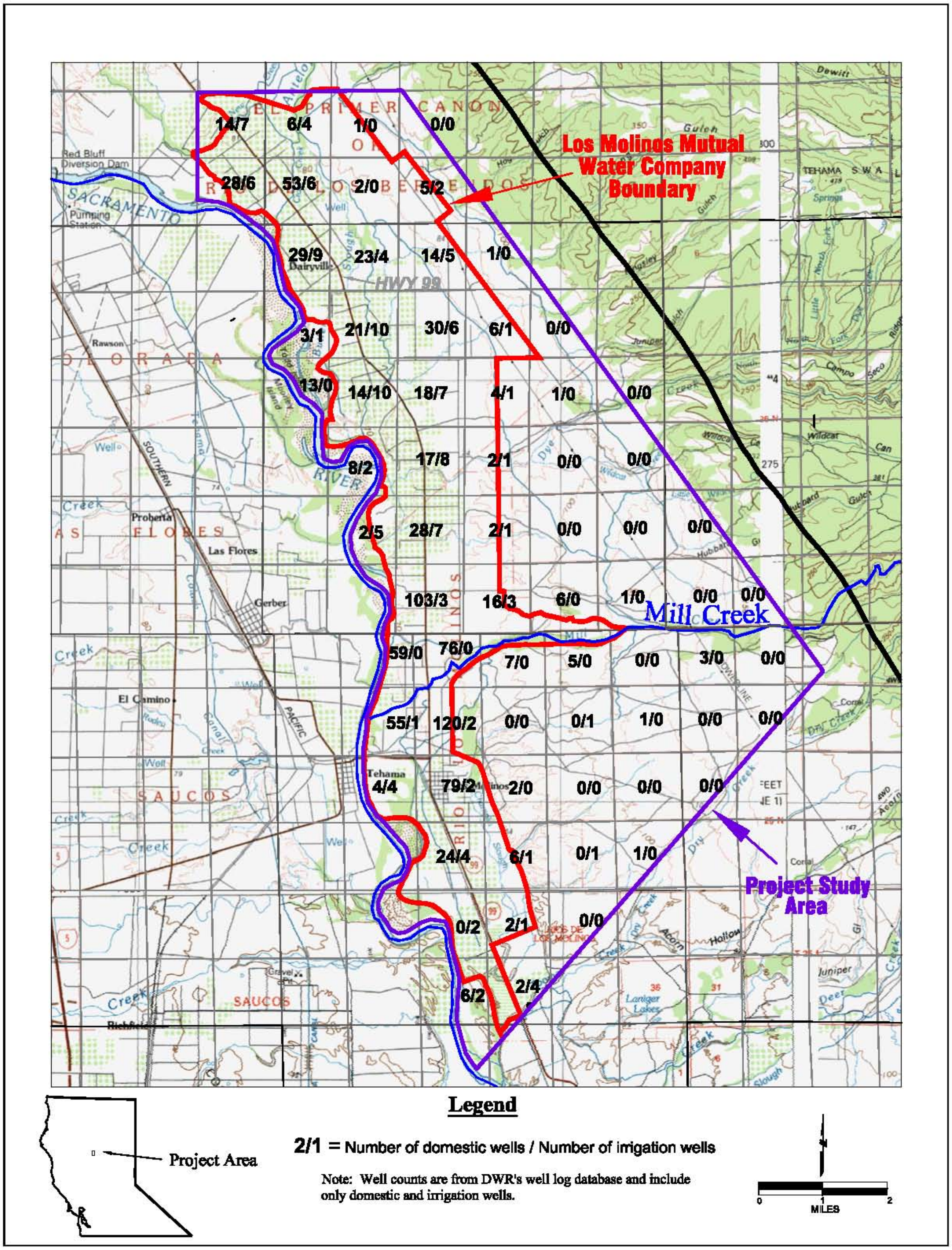


Figure 6. Well Depth Distribution of Domestic Wells

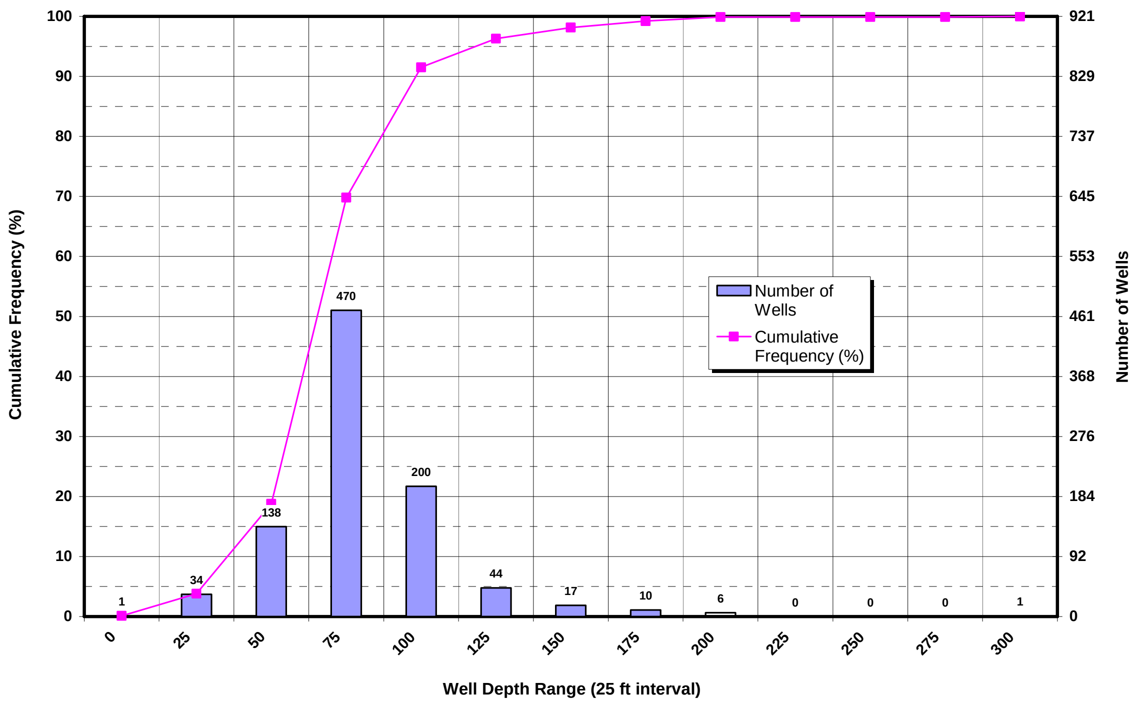


Figure 7. Well Depth Distribution of Irrigation Wells

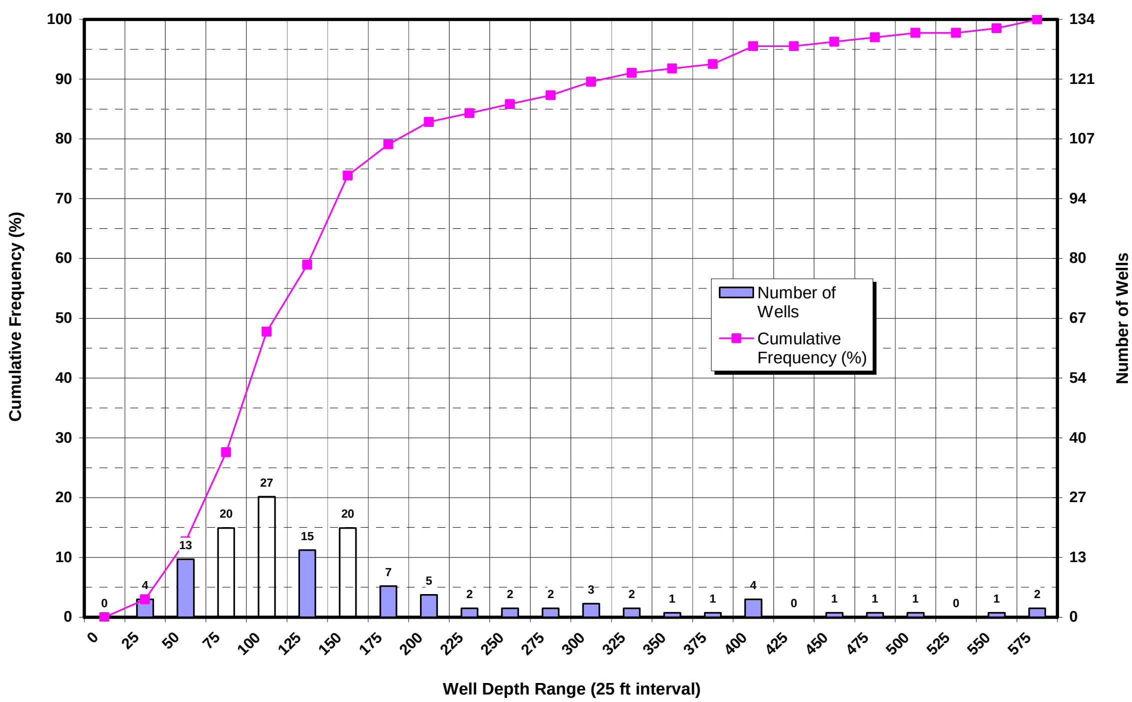


Figure 8. Well Depth Distribution of Public/Municipal Wells

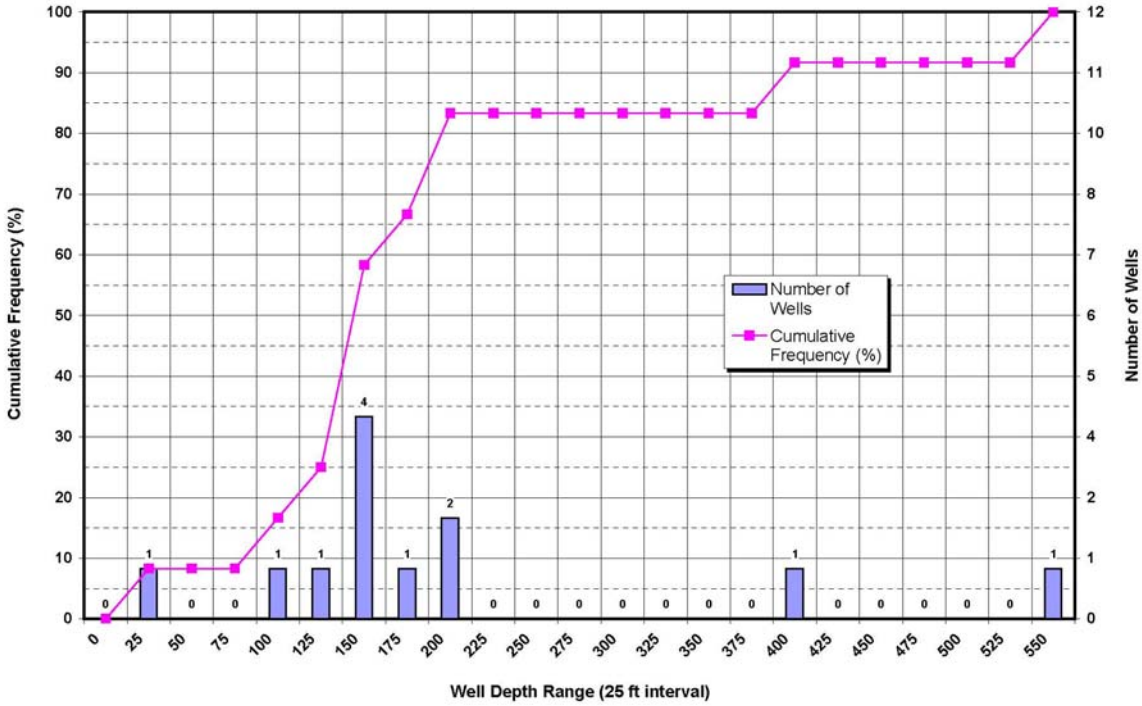
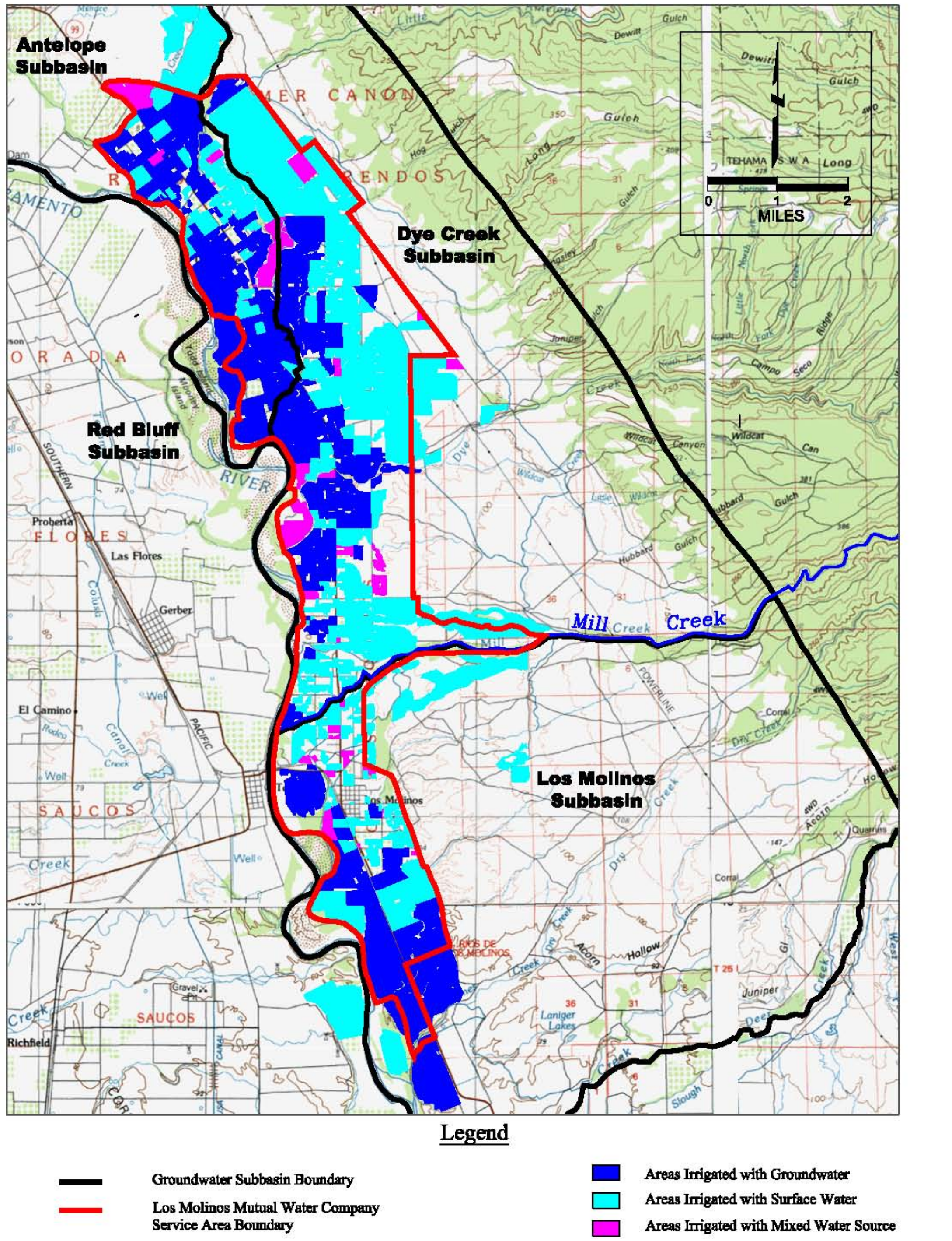


Figure 9. Water Source Map



NOTE:
Water source data is based on 1999 DWR land & water use survey. Water source areas represent potential water source, rather than actual water type used during any given year.

Figure 10. Lower Mill Creek Watershed Monitoring Well Grid

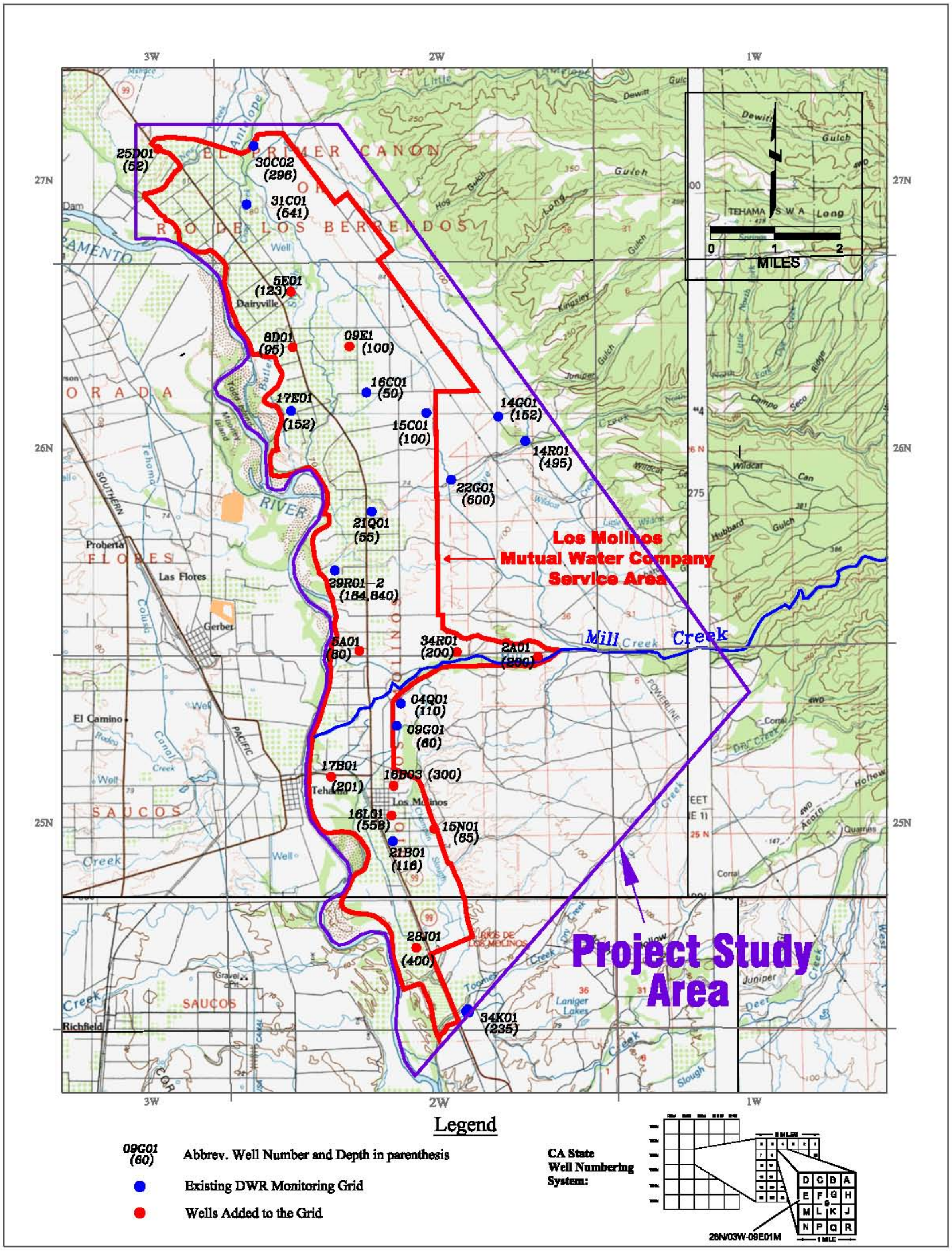
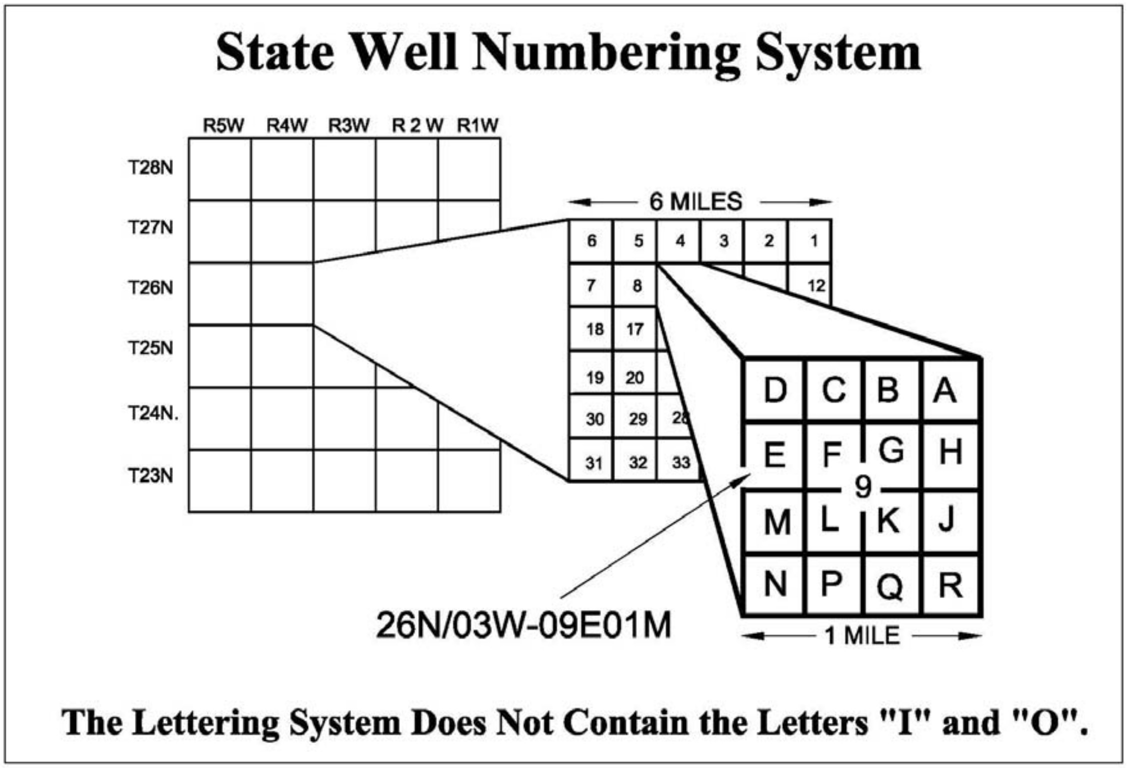


Figure 11. State Well Numbering System



For more information about this system, see "Water Fact #7: Numbering Water Wells in California." It is available online at http://www.dpla2.water.ca.gov/publications/waterfacts/water_facts_7.pdf .

Figure 12. Hydrograph, Well 27N/02W-31C001M

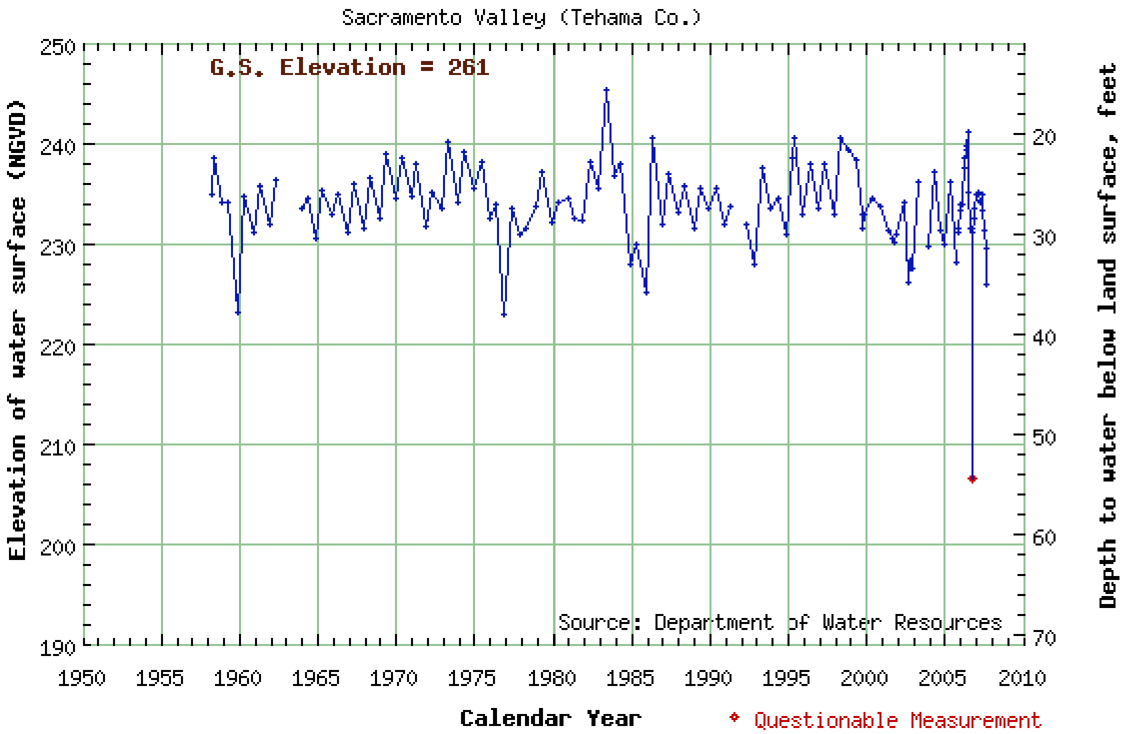


Figure 13. Hydrograph, Well 26N/02W-16C001M

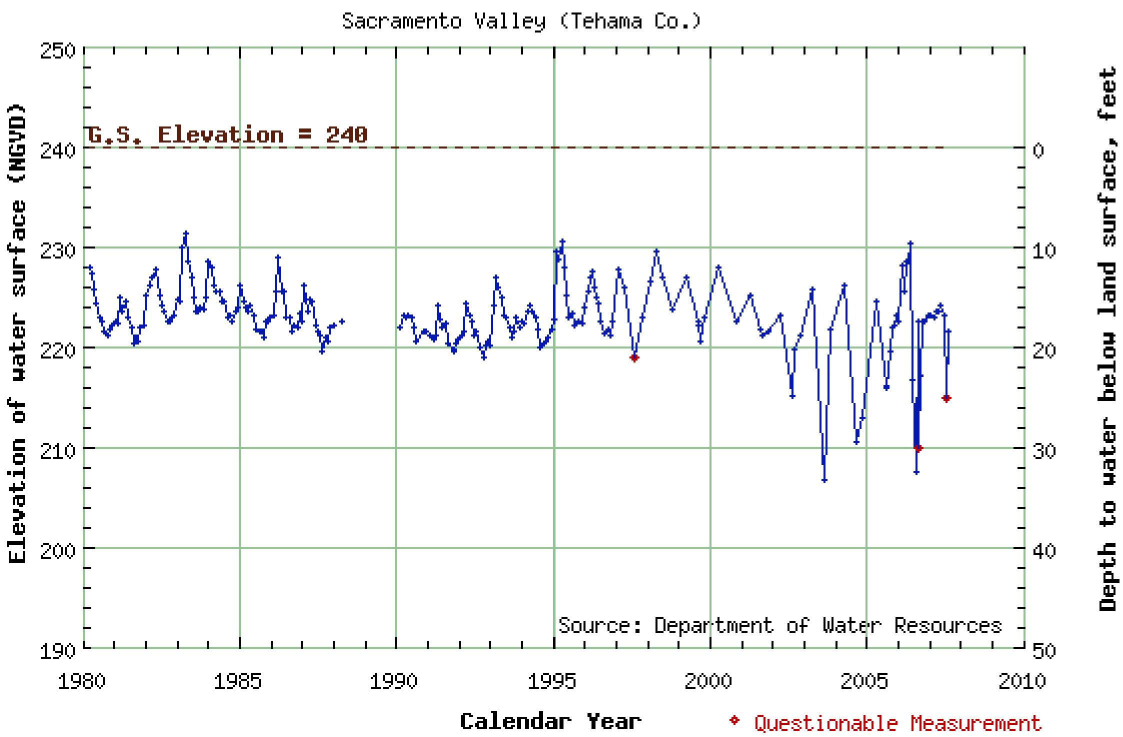


Figure 14. Hydrograph, Well 25N/02W-09G001M

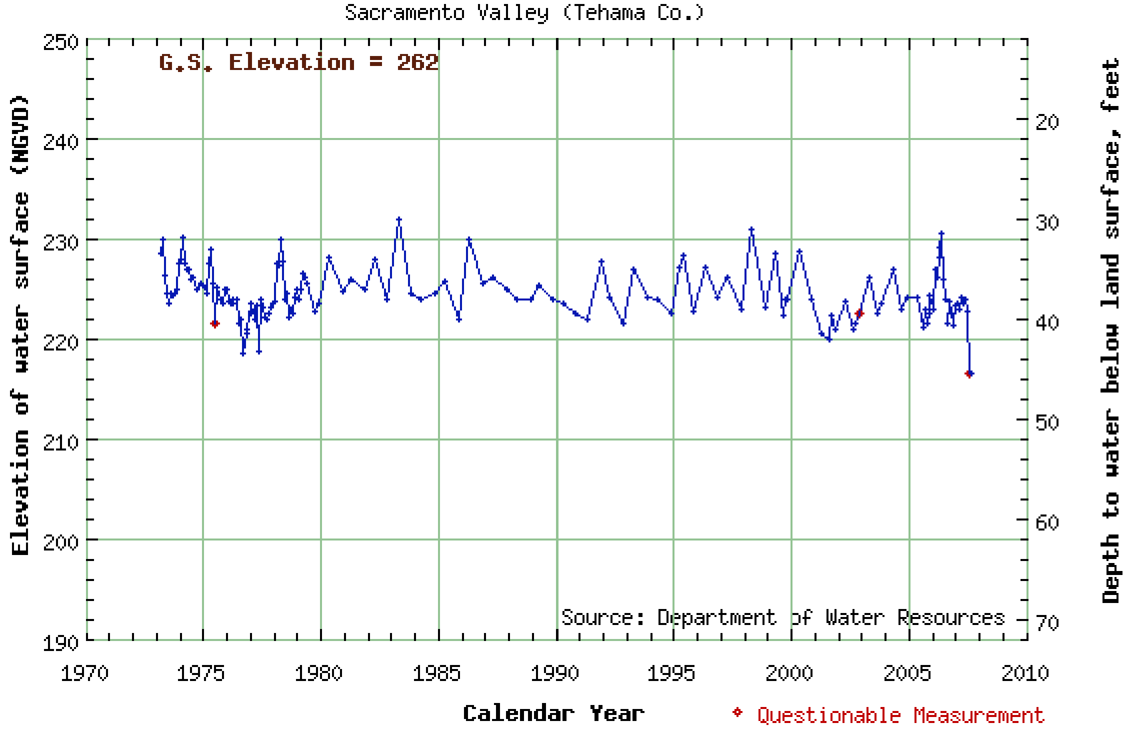


Figure 15. Hydrograph, Well 25N/02W-34K001M

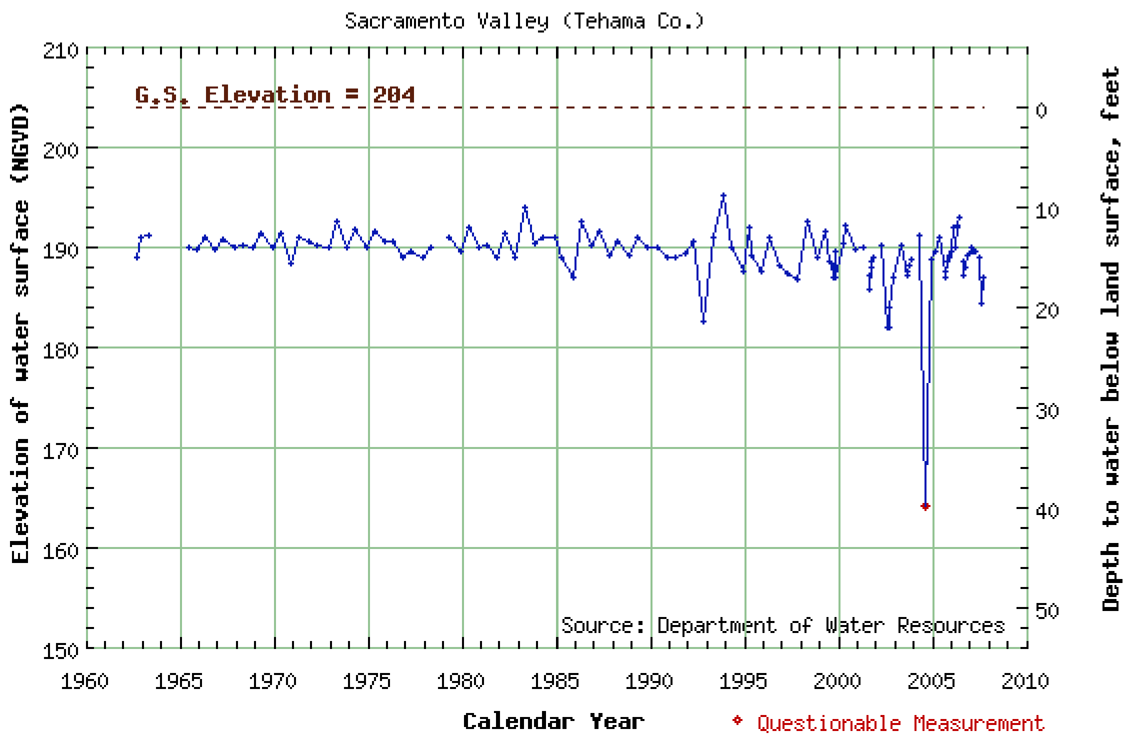


Figure 16. Spring 2006, Groundwater Contour Map: Unconfined Aquifer

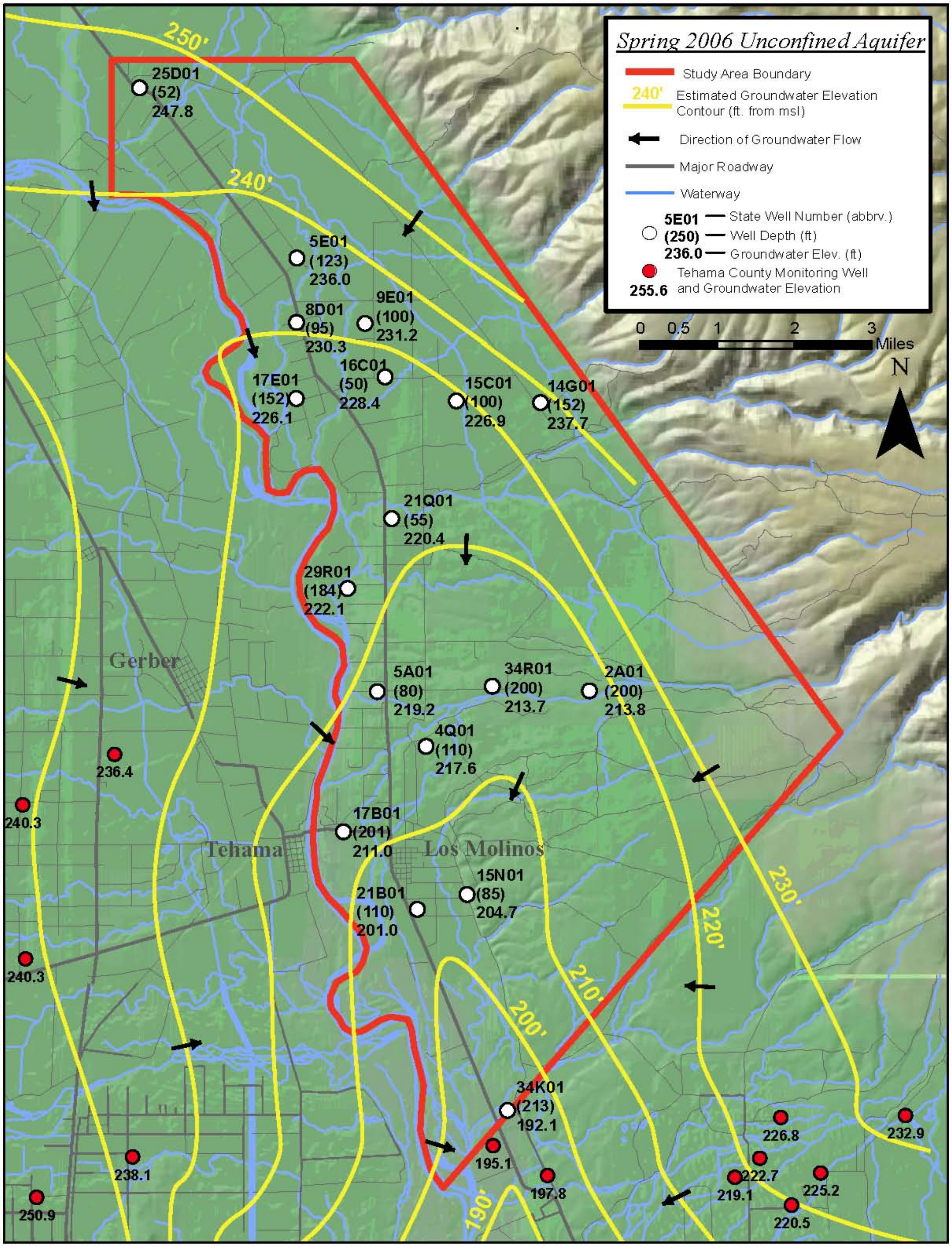


Figure 17. Spring 2006, Groundwater Contour Map: Confined Aquifer

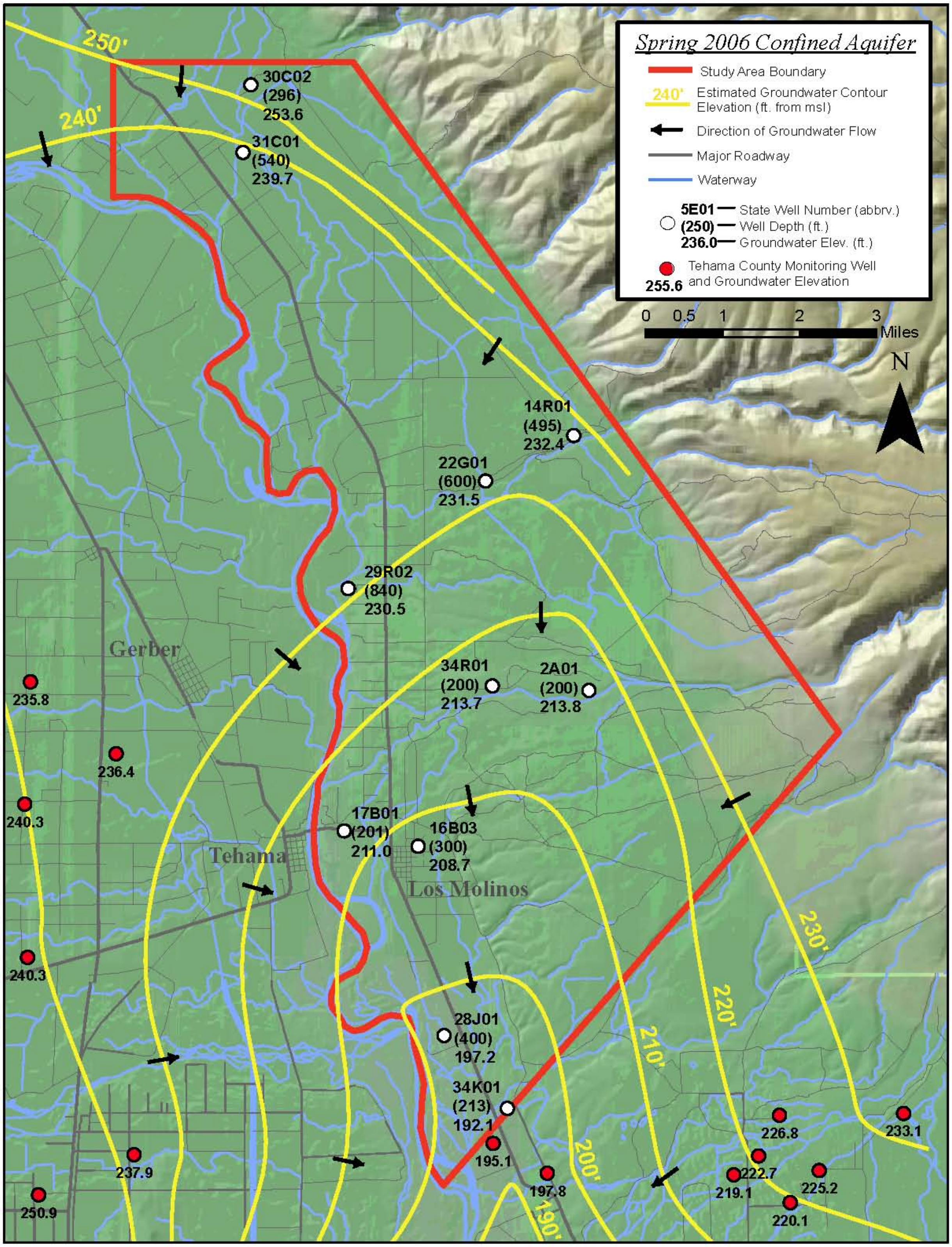


Figure 18. Fall 2006, Groundwater Contour Map: Unconfined Aquifer

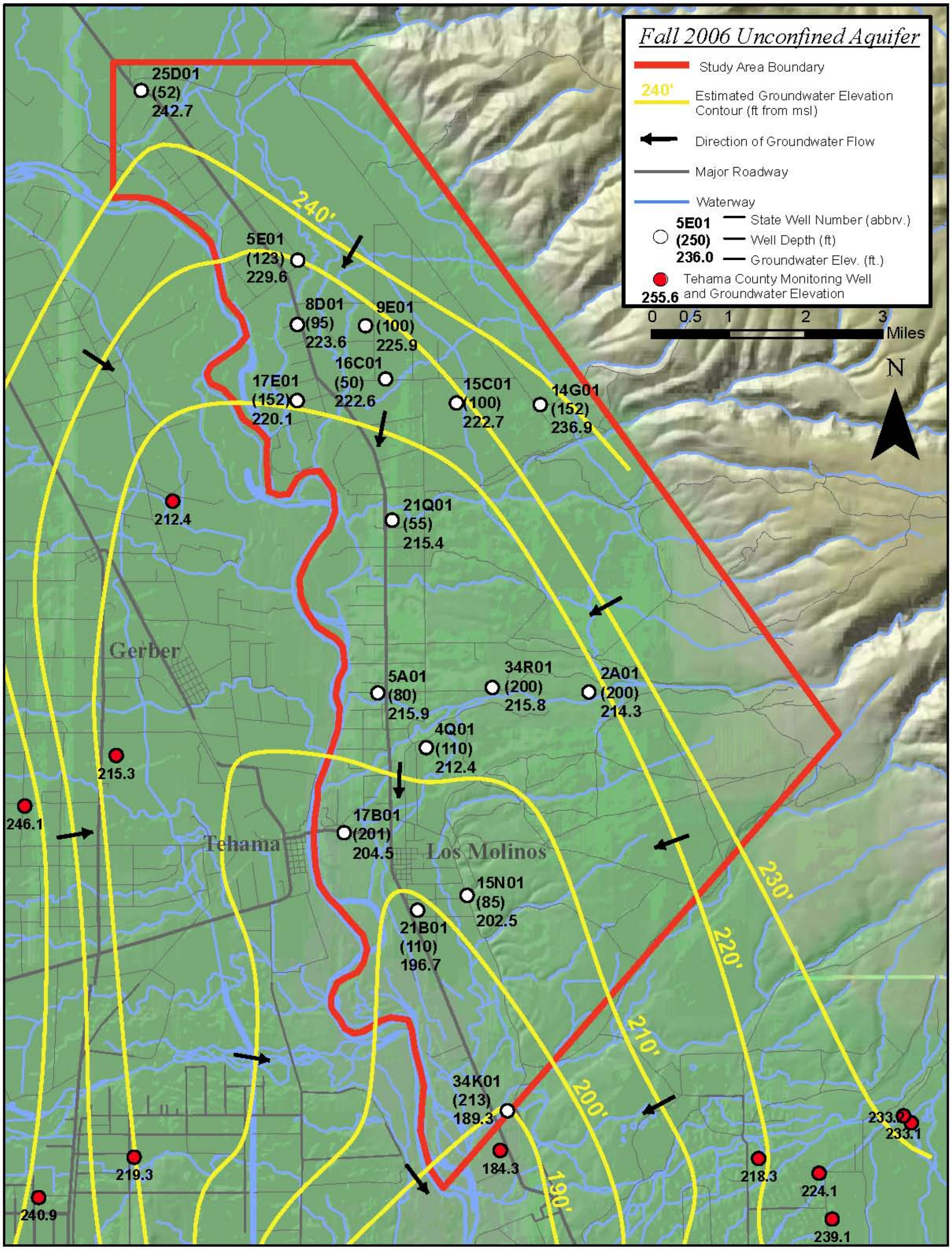


Figure 19. Fall 2006, Groundwater Contour Map: Confined Aquifer

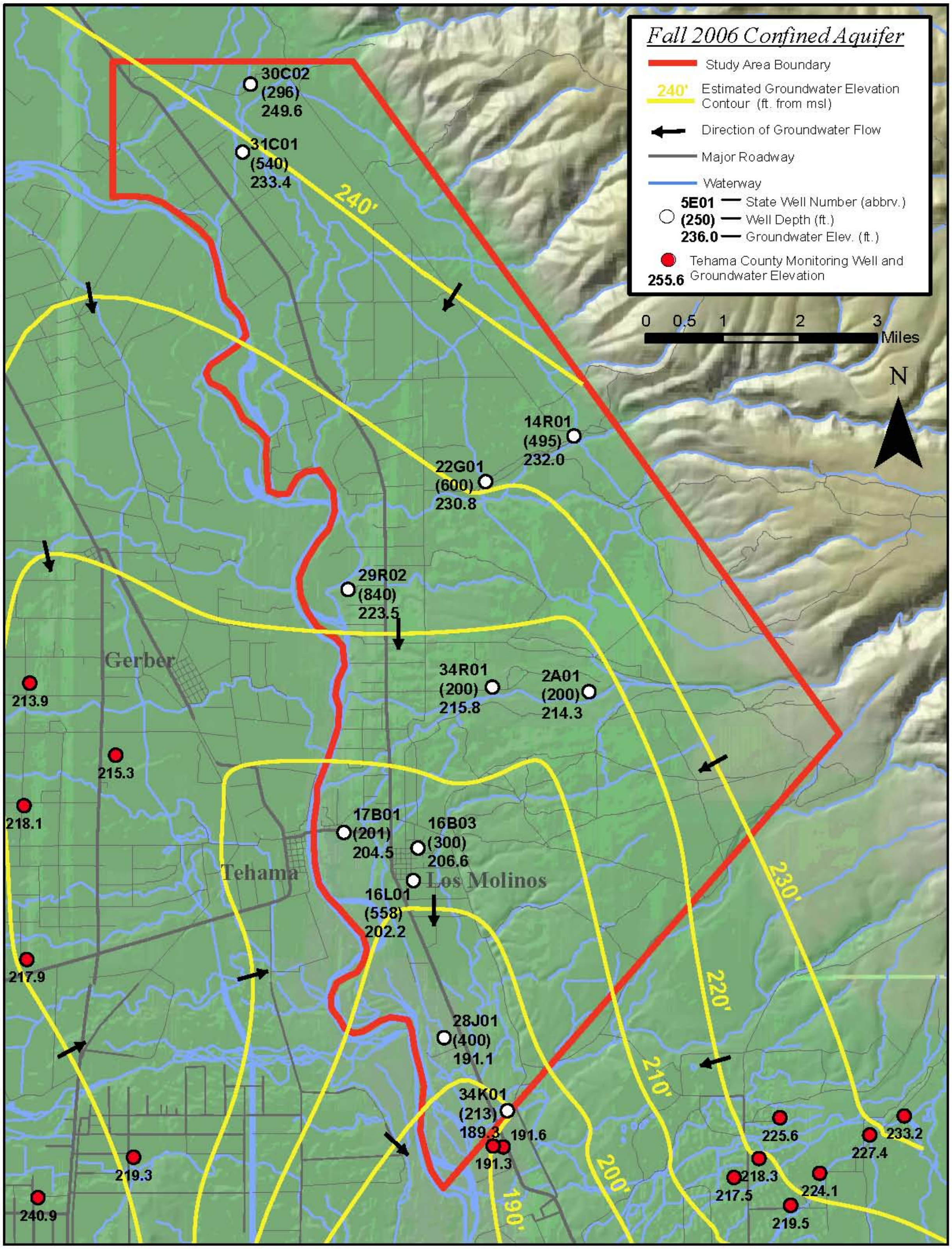


Figure 20. 2006 Spring-to-Summer Change, Groundwater Contour Map: Unconfined Aquifer

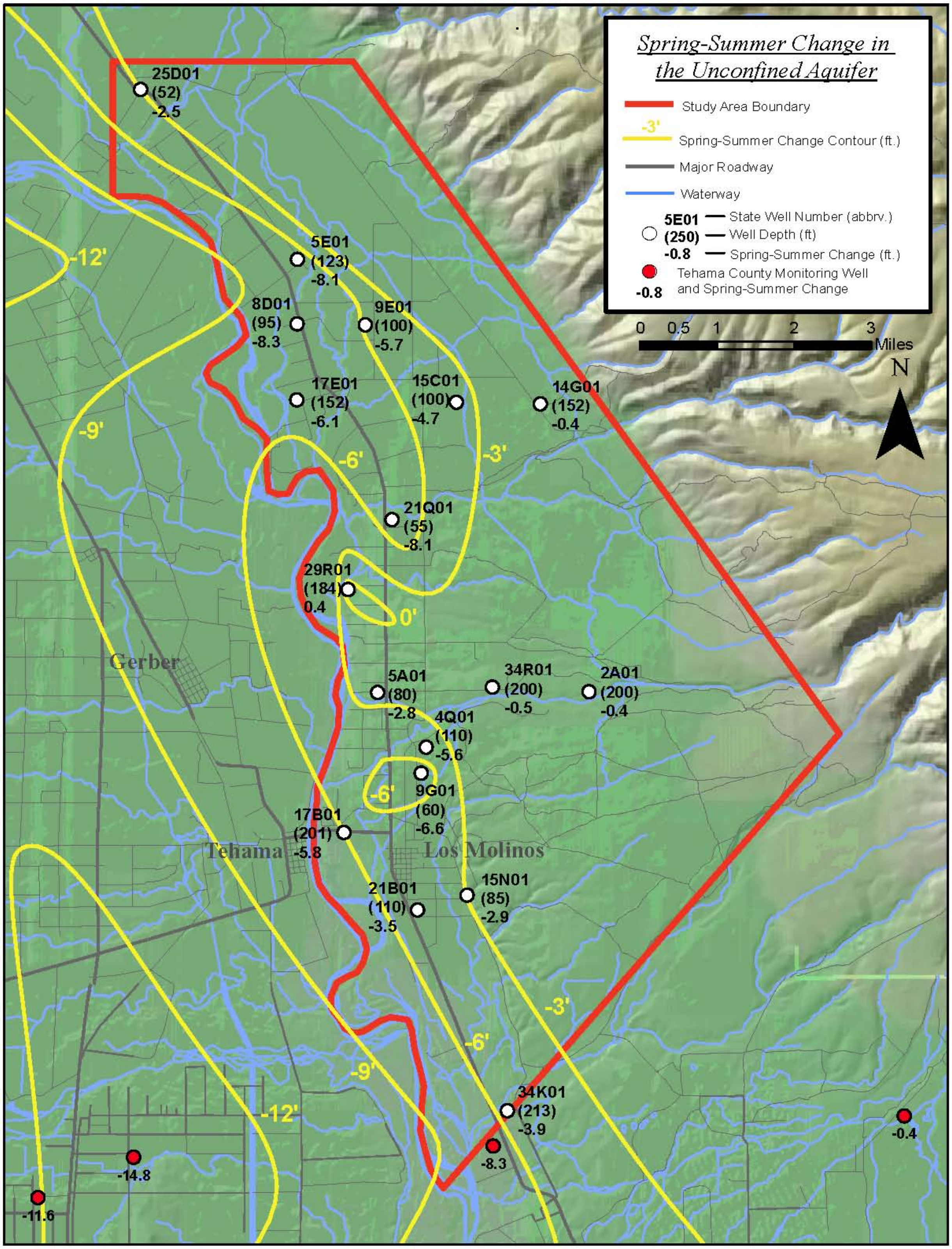


Figure 21. 2006 Spring-to-Summer Change, Groundwater Contour Map: Confined Aquifer

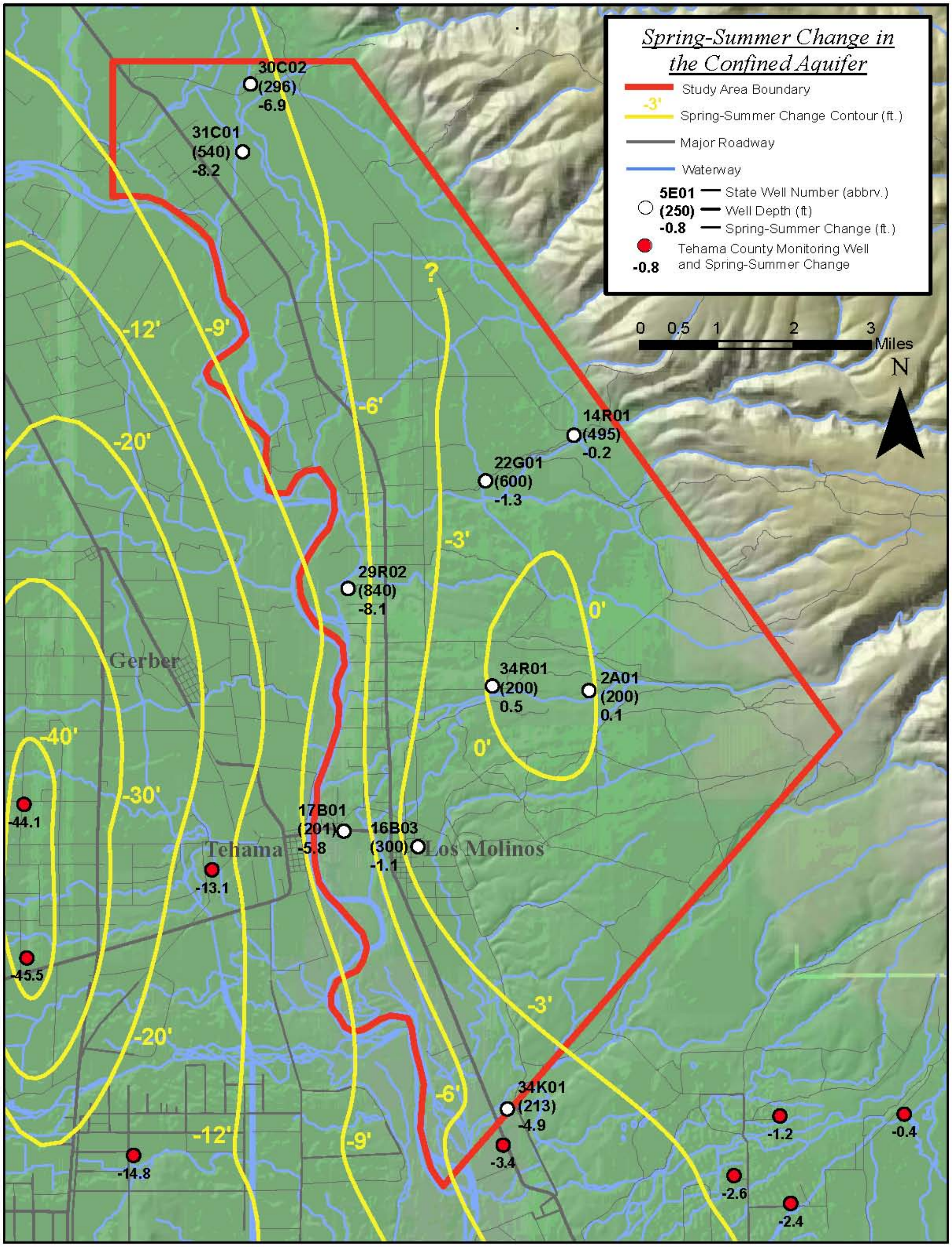
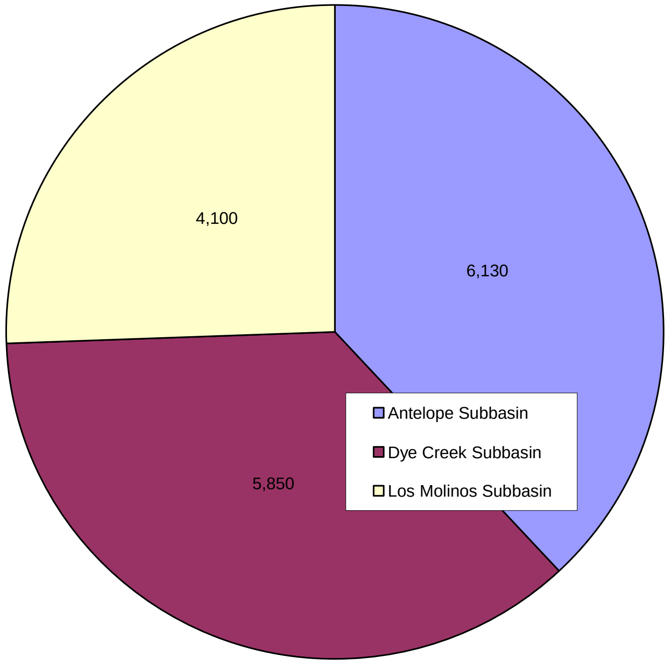
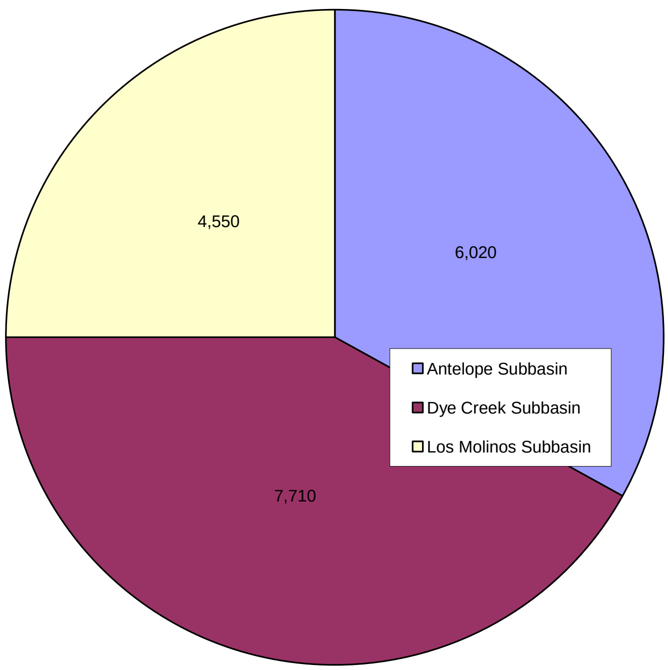


Figure 22. Normal Water Year Groundwater Extraction by Subbasin in Acre-Feet



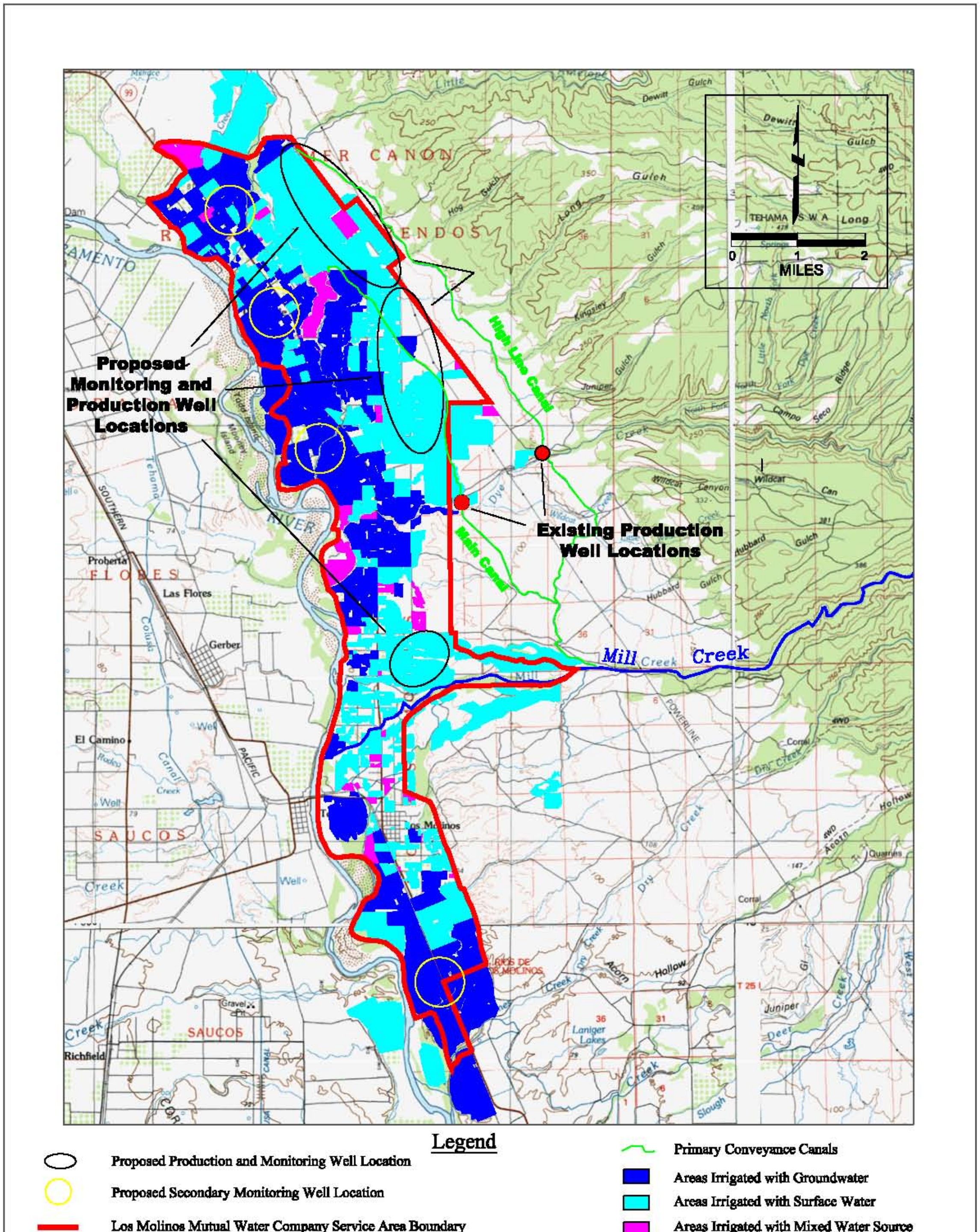
Total = 16,080 Acre-Feet

Figure 23. Drought Year Groundwater Extraction by Subbasin in Acre-Feet



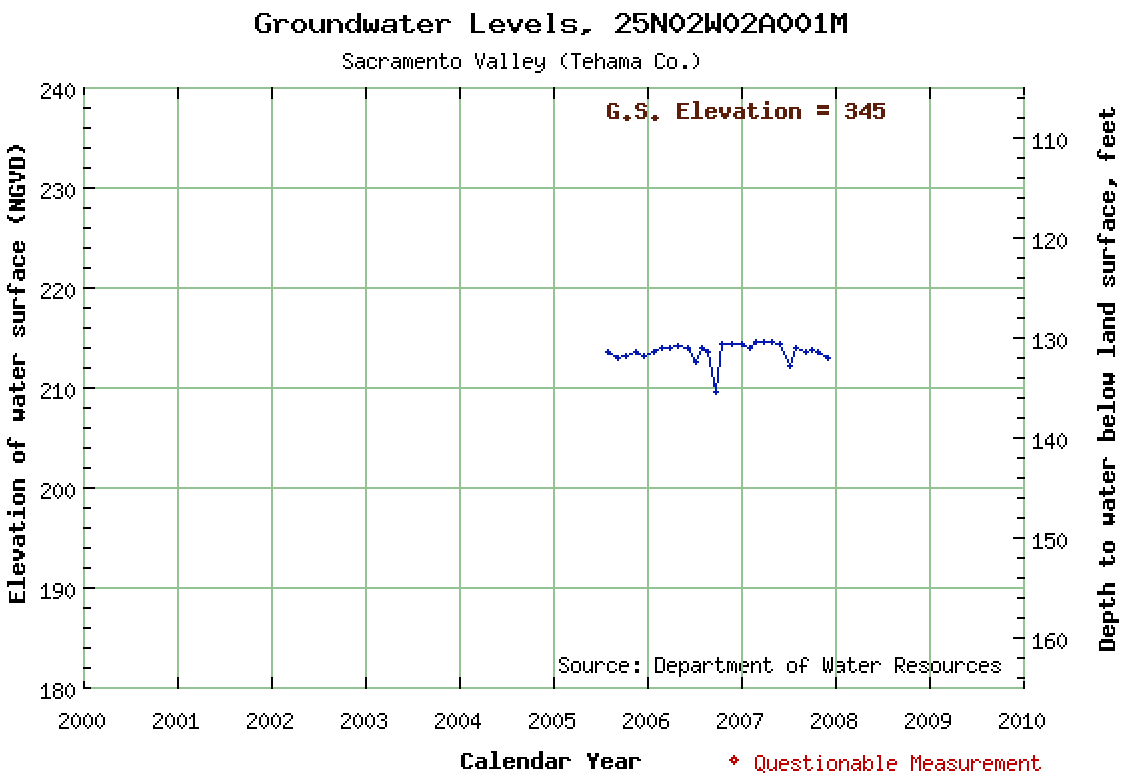
Total = 18,280 Acre-Feet

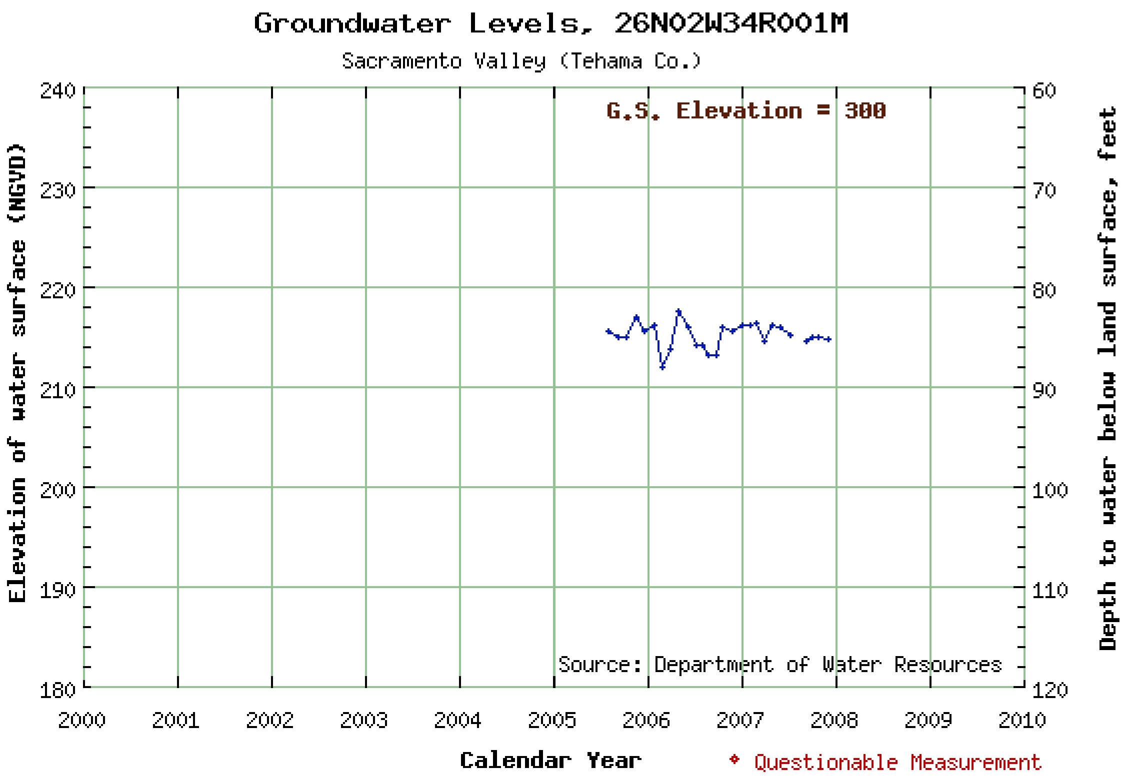
Figure 24. Proposed Production and Monitoring Well Locations

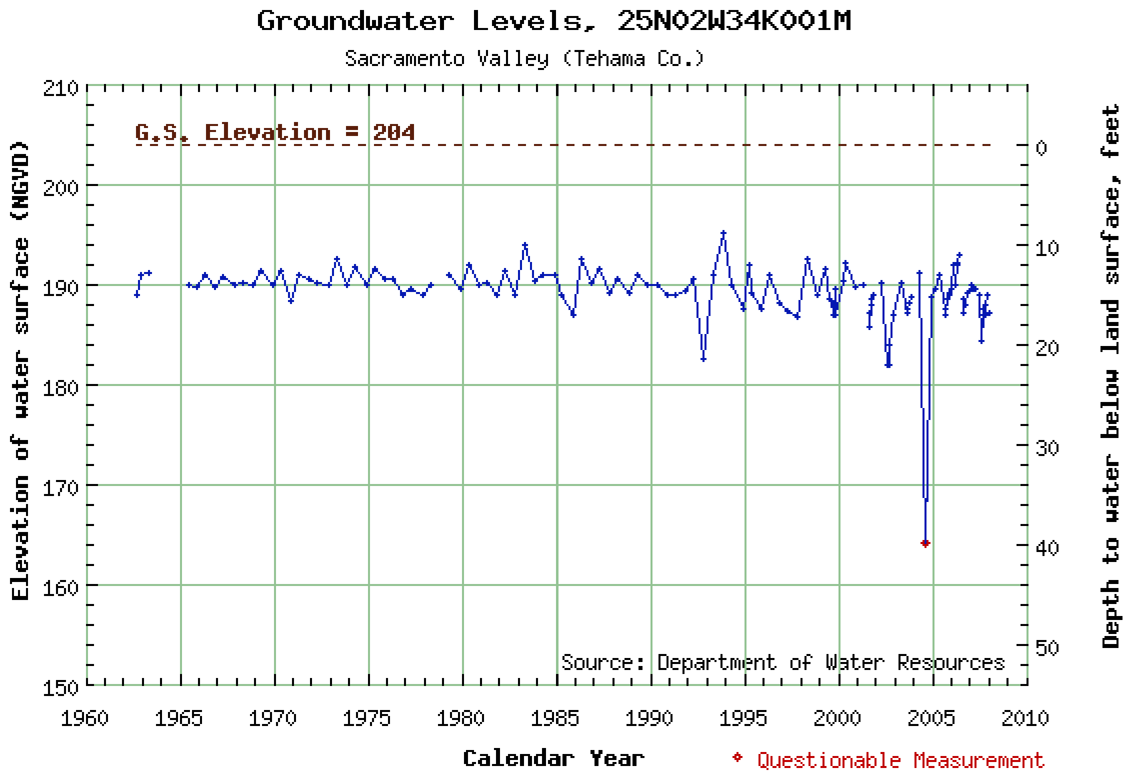


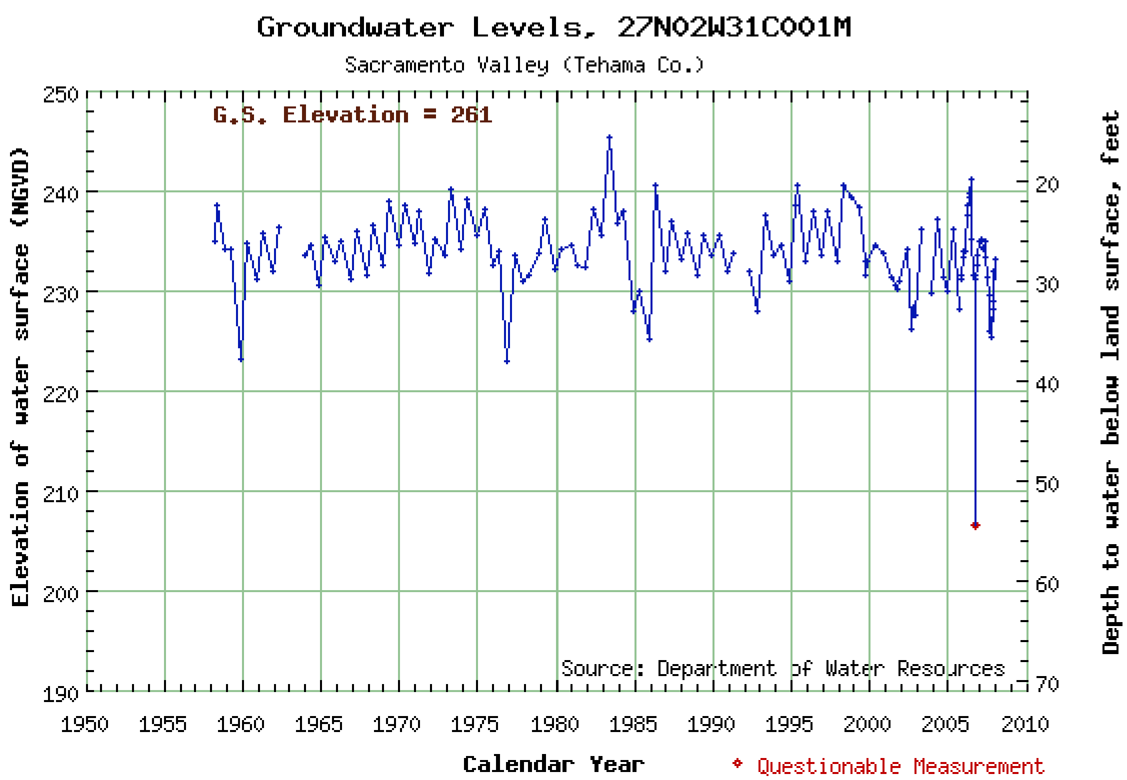
NOTE:
Water source data is based on 1999 DWR land & water use survey. Water source areas represent potential water source, rather than actual water type used during any given year.

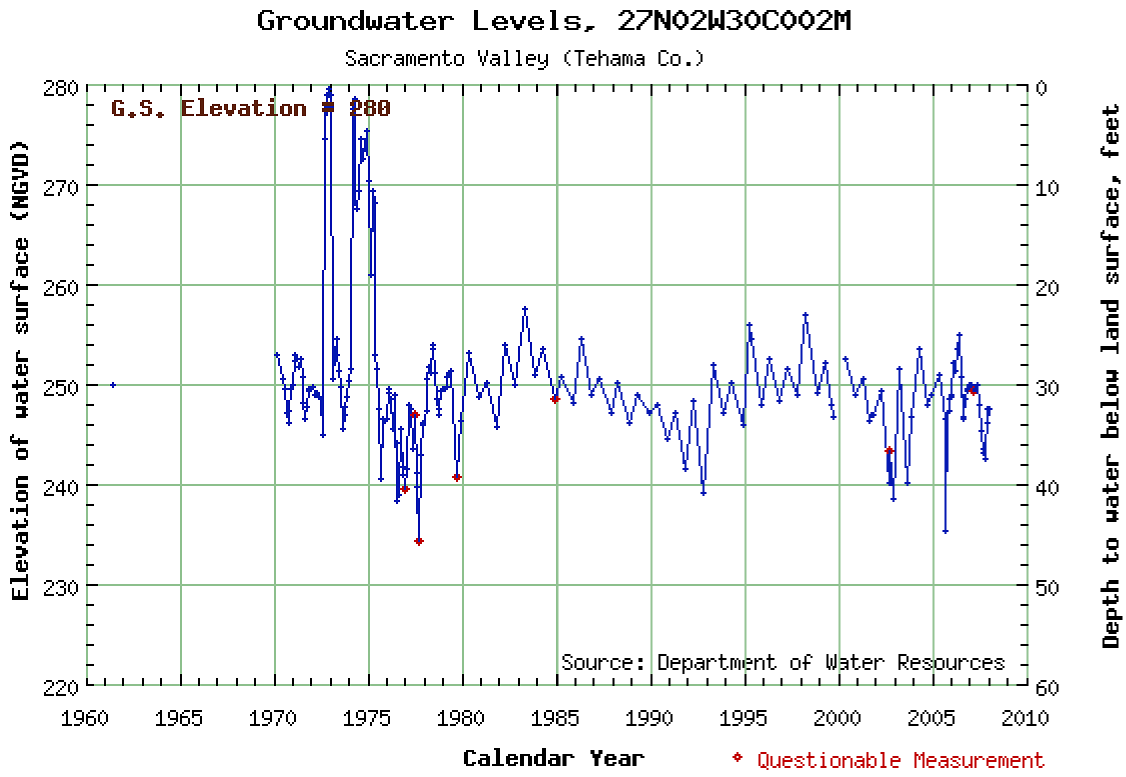
Appendix A. Hydrographs

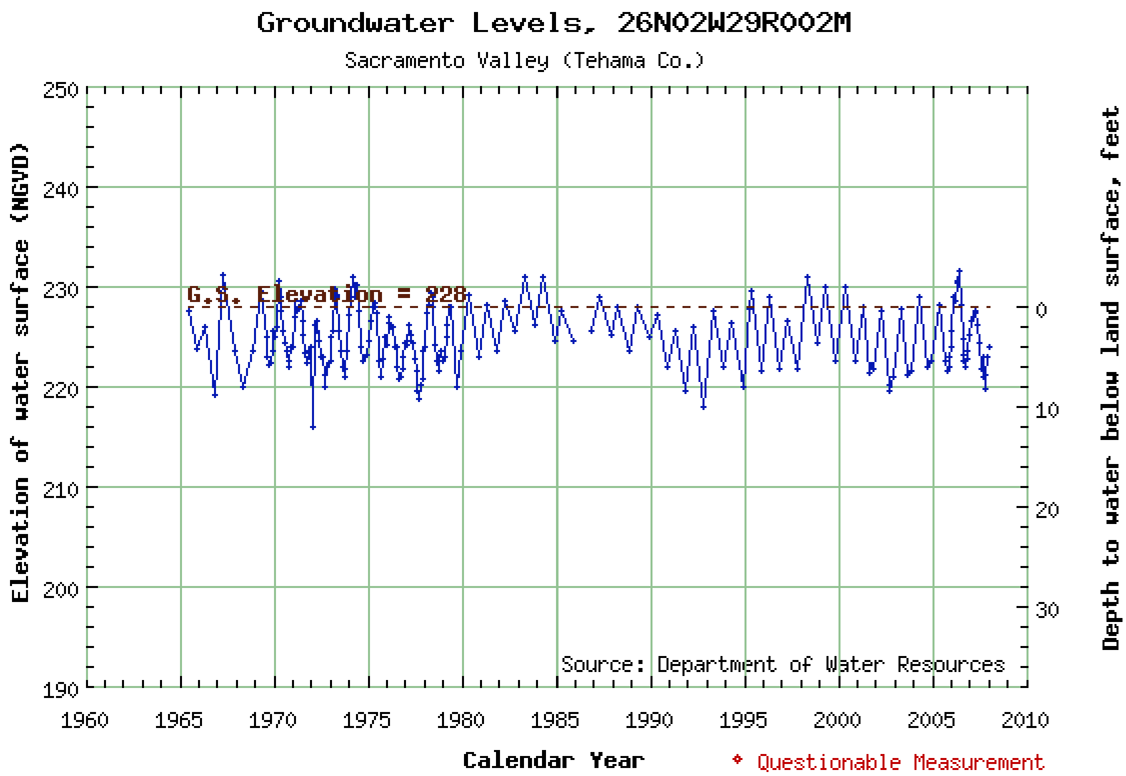


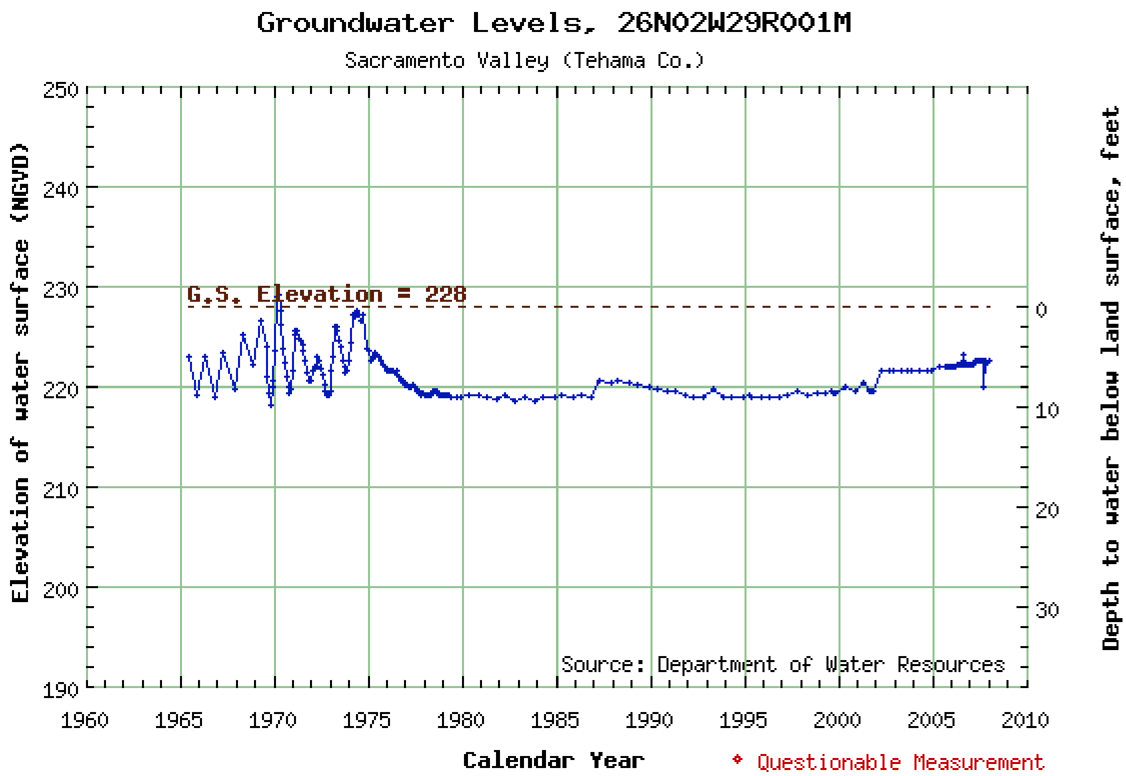


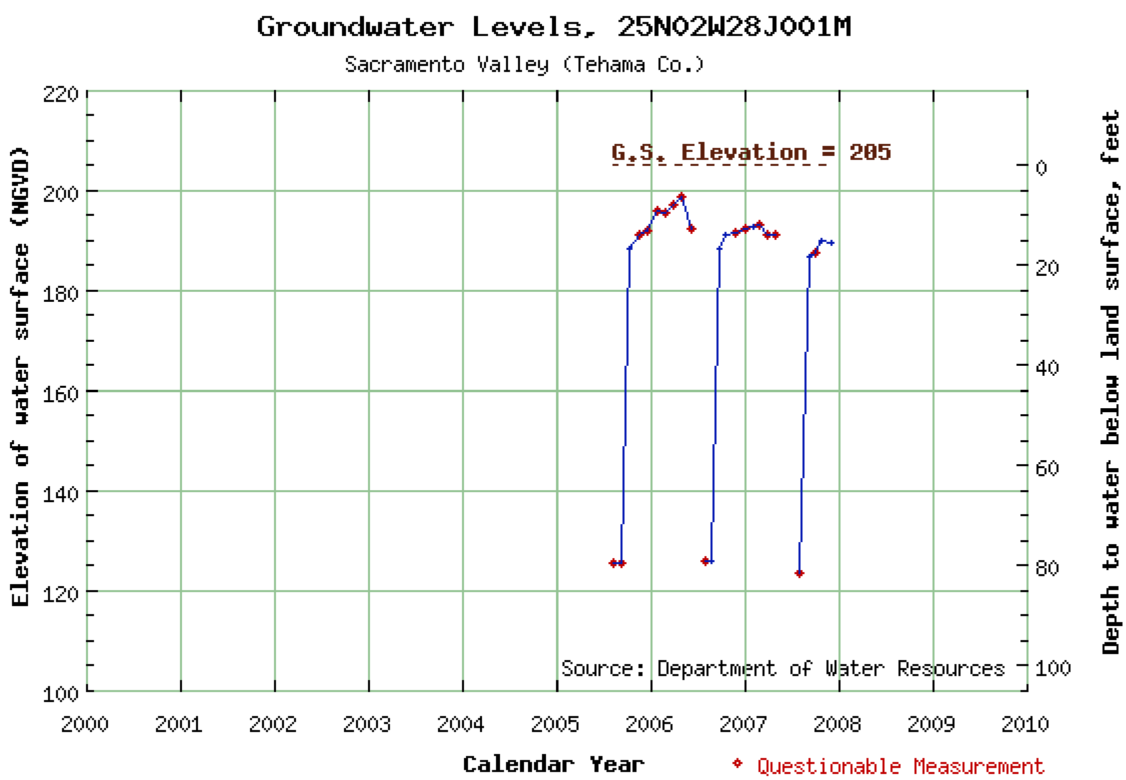

Groundwater Levels, 25N02W34K001M
Sacramento Valley (Tehama Co.)
G.S. Elevation = 204
Elevation of water surface (NGVD)
Depth to water below land surface, feet
210
200
190
180
170
160
150
0
10
20
30
40
50
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
Source: Department of Water Resources
Calendar Year
Questionable Measurement

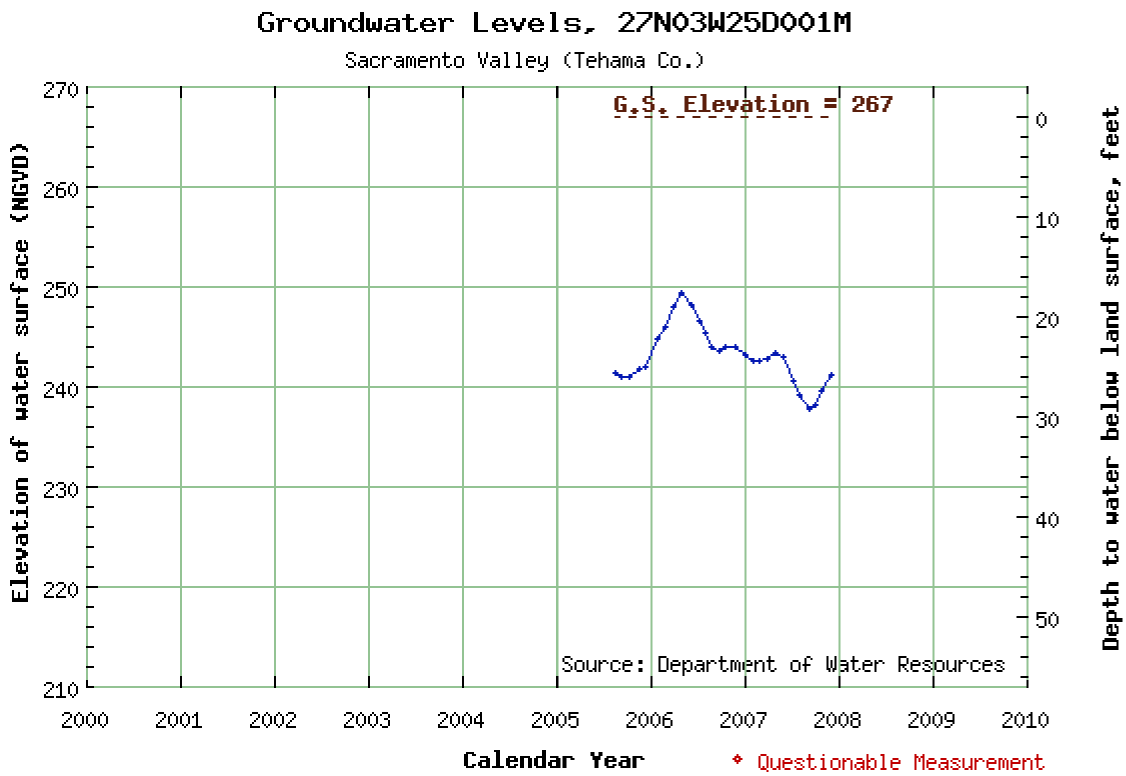

Groundwater Levels, 27N02W31C001M
Sacramento Valley (Tehama Co.)
G.S. Elevation = 261
Elevation of water surface (NGVD)
Depth to water below land surface, feet
250
240
230
220
210
200
190
20
30
40
50
60
70
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
Source: Department of Water Resources
Calendar Year
Questionable Measurement

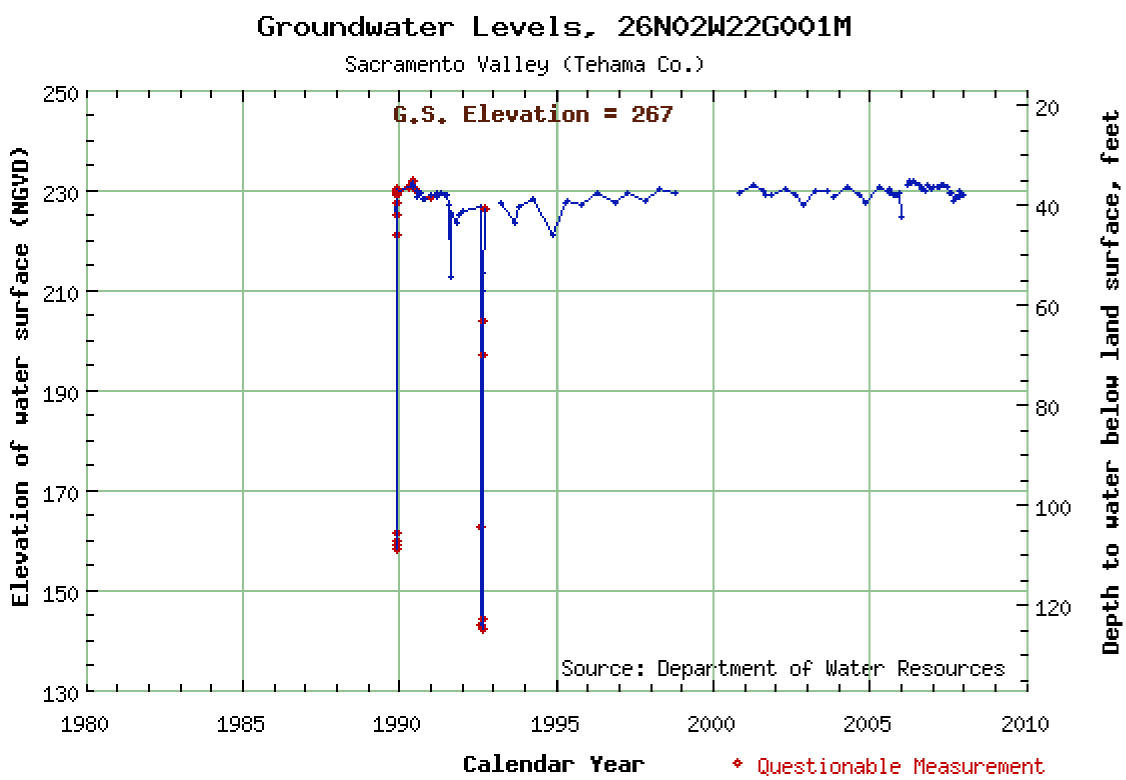

Groundwater Levels, 27N02W30C002M
Sacramento Valley (Tehama Co.)
G.S. Elevation = 280
Elevation of water surface (NGVD)
Depth to water below land surface, feet
280
270
260
250
240
230
220
0
10
20
30
40
50
60
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
Source: Department of Water Resources
Calendar Year
Questionable Measurement

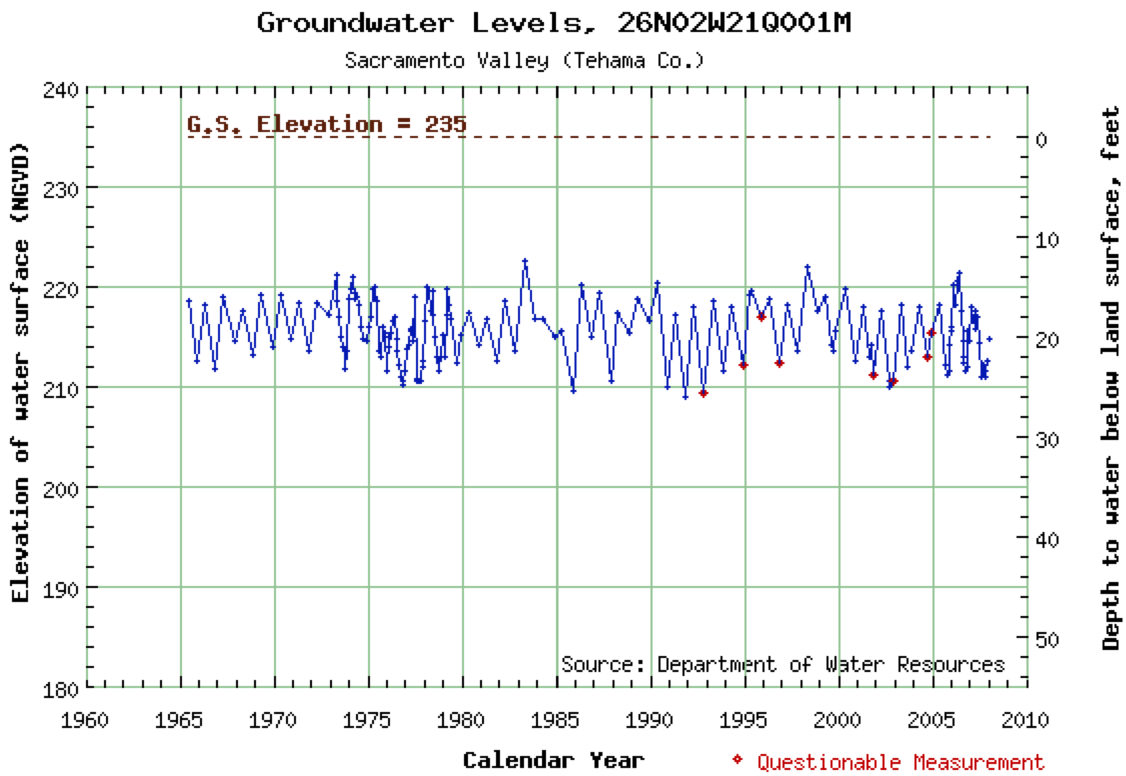

Groundwater Levels, 26N02W29R002M
Sacramento Valley (Tehama Co.)
G.S. Elevation = 228
Elevation of water surface (NGVD)
Depth to water below land surface, feet
250
240
230
220
210
200
190
0
10
20
30
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
Source: Department of Water Resources
Calendar Year
Questionable Measurement

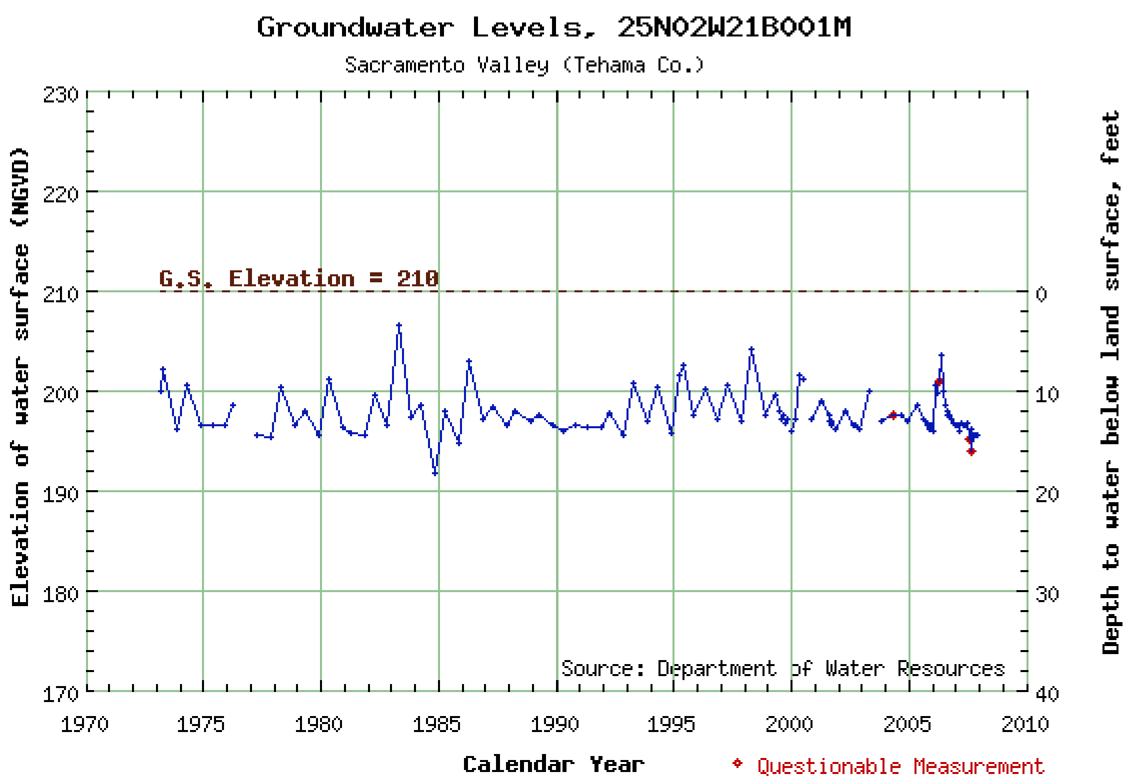

Groundwater Levels, 26N02W29R001M
Sacramento Valley (Tehama Co.)
Elevation of water surface (NGVD)
Depth to water below land surface, feet
G.S. Elevation = 228
Source: Department of Water Resources
250
240
230
220
210
200
190
0
10
20
30
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
Calendar Year
Questionable Measurement

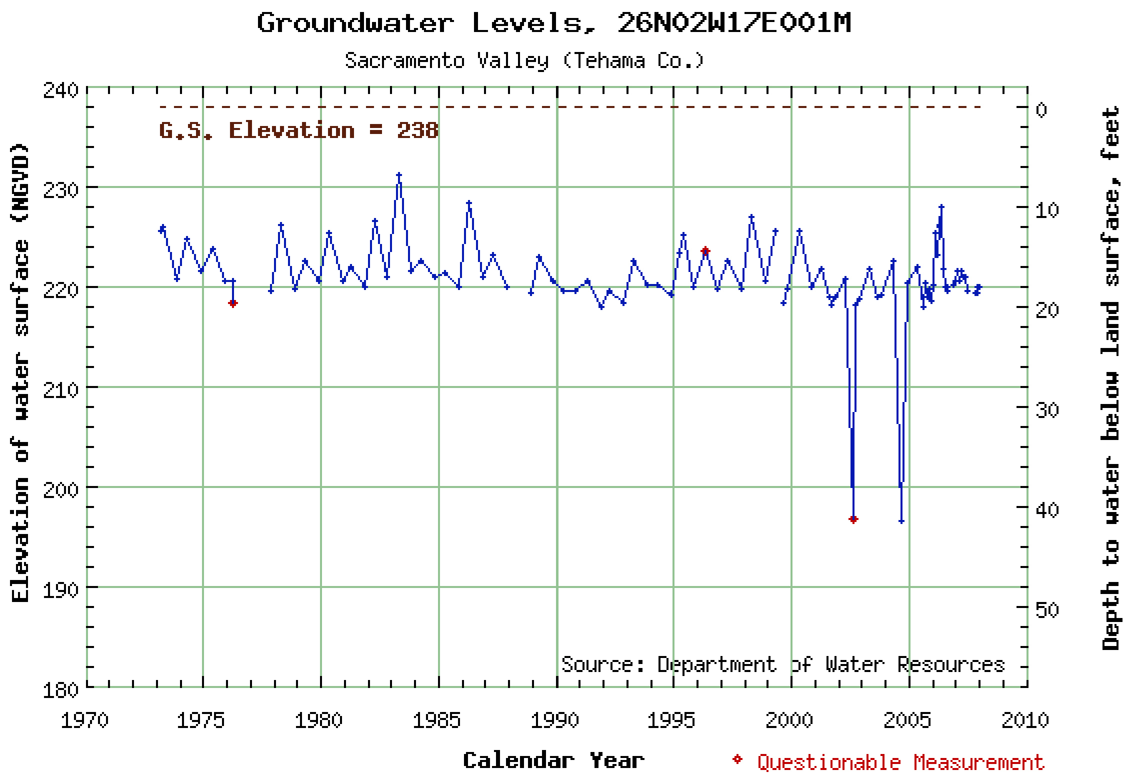

Groundwater Levels, 25N02W28J001M
Sacramento Valley (Tehama Co.)
Elevation of water surface (NGVD)
Depth to water below land surface, feet
G.S. Elevation = 205
Source: Department of Water Resources
220
200
180
160
140
120
100
0
20
40
60
80
100
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
Calendar Year
Questionable Measurement

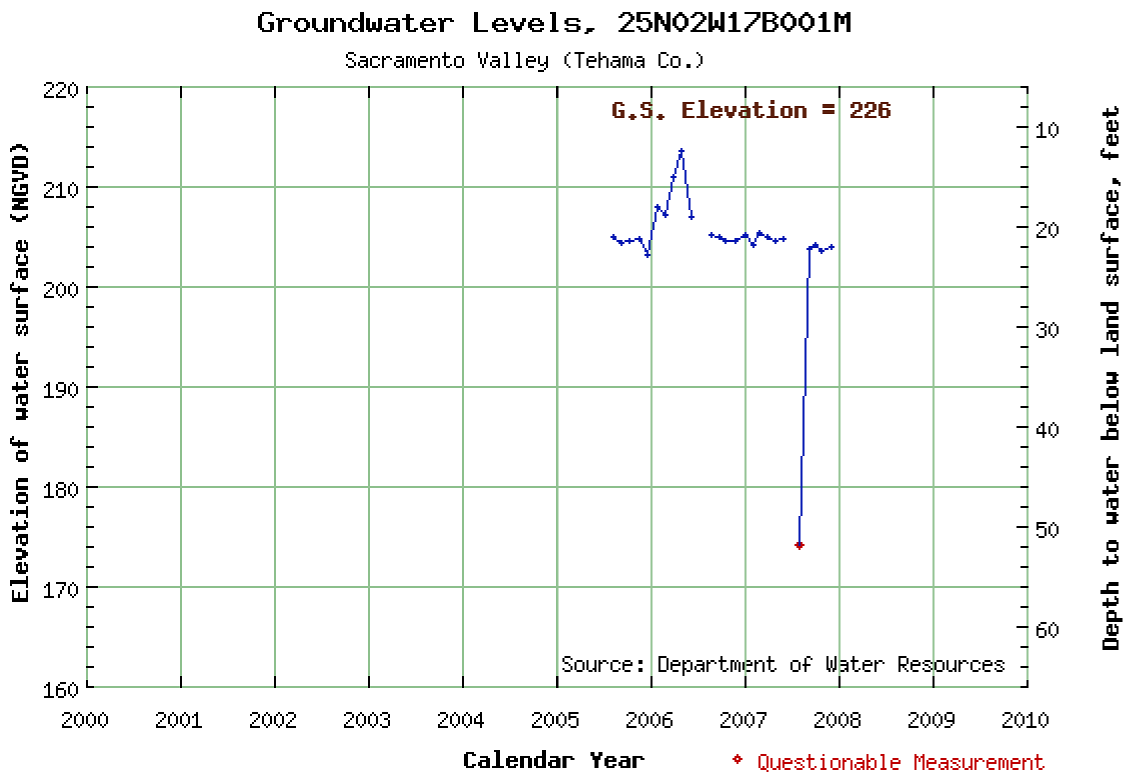

Groundwater Levels, 27N03W25D001M
Sacramento Valley (Tehama Co.)
G.S. Elevation = 267
Elevation of water surface (NGVD)
Depth to water below land surface, feet
270
260
250
240
230
220
210
0
10
20
30
40
50
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
Source: Department of Water Resources
Calendar Year
Questionable Measurement

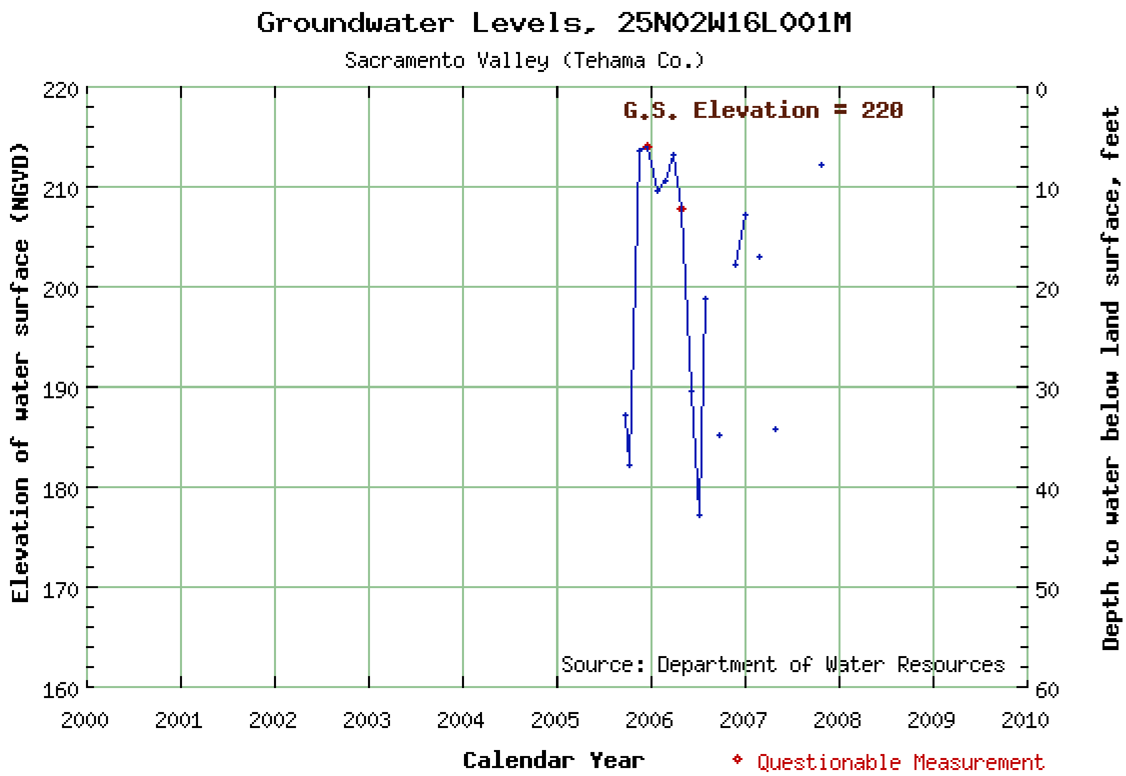

Groundwater Levels, 26N02W22G001M
Sacramento Valley (Tehama Co.)
G.S. Elevation = 267
Elevation of water surface (NGVD)
Depth to water below land surface, feet
250
230
210
190
170
150
130
20
40
60
80
100
120
1980
1985
1990
1995
2000
2005
2010
Source: Department of Water Resources
Calendar Year
Questionable Measurement

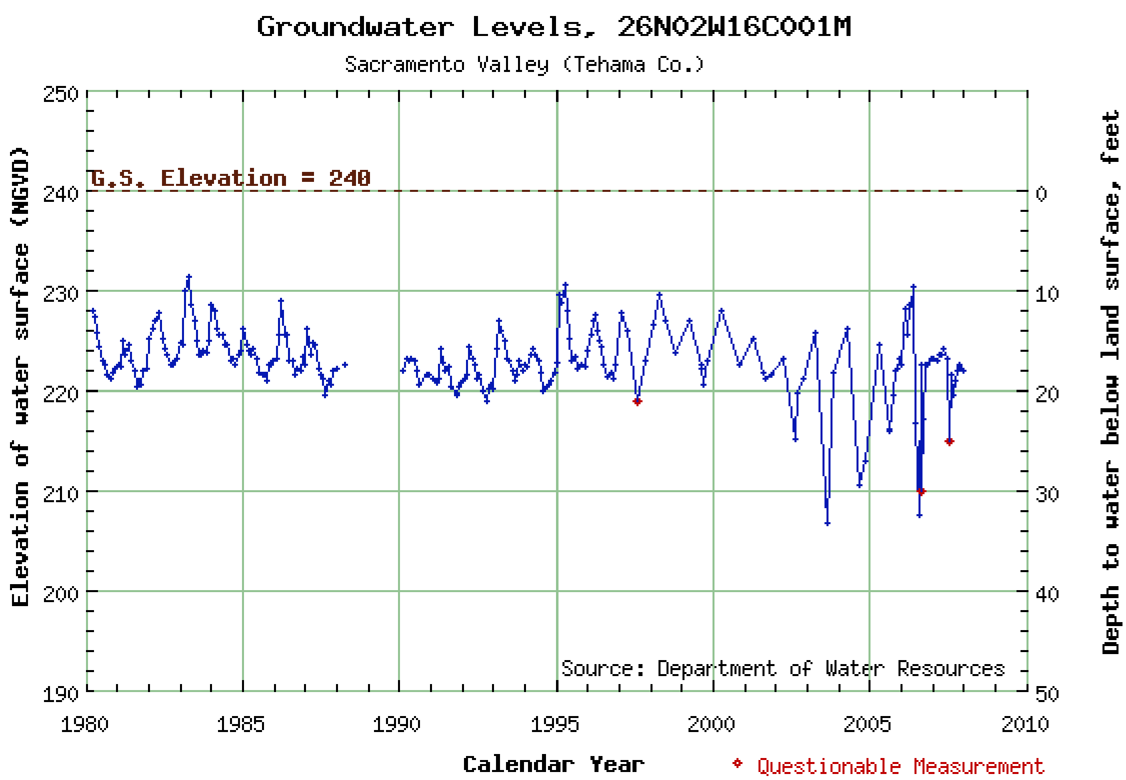

Groundwater Levels, 26N02W21Q001M
Sacramento Valley (Tehama Co.)
G.S. Elevation = 235
Elevation of water surface (NGVD)
Depth to water below land surface, feet
Source: Department of Water Resources
Calendar Year
Questionable Measurement
240
230
220
210
200
190
180
0
10
20
30
40
50
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010

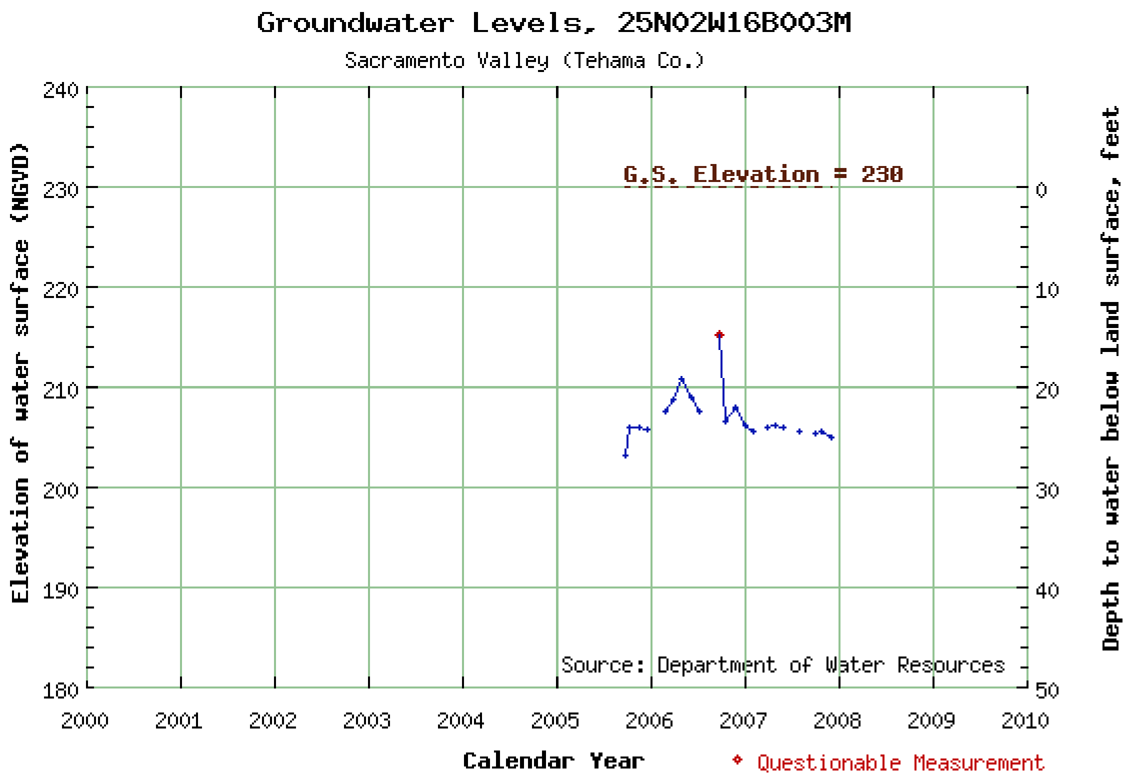

Groundwater Levels, 25N02W21B001M
Sacramento Valley (Tehama Co.)
G.S. Elevation = 210
Elevation of water surface (NGVD)
Depth to water below land surface, feet
Source: Department of Water Resources
Calendar Year
Questionable Measurement
230
220
210
200
190
180
170
0
10
20
30
40
1970
1975
1980
1985
1990
1995
2000
2005
2010

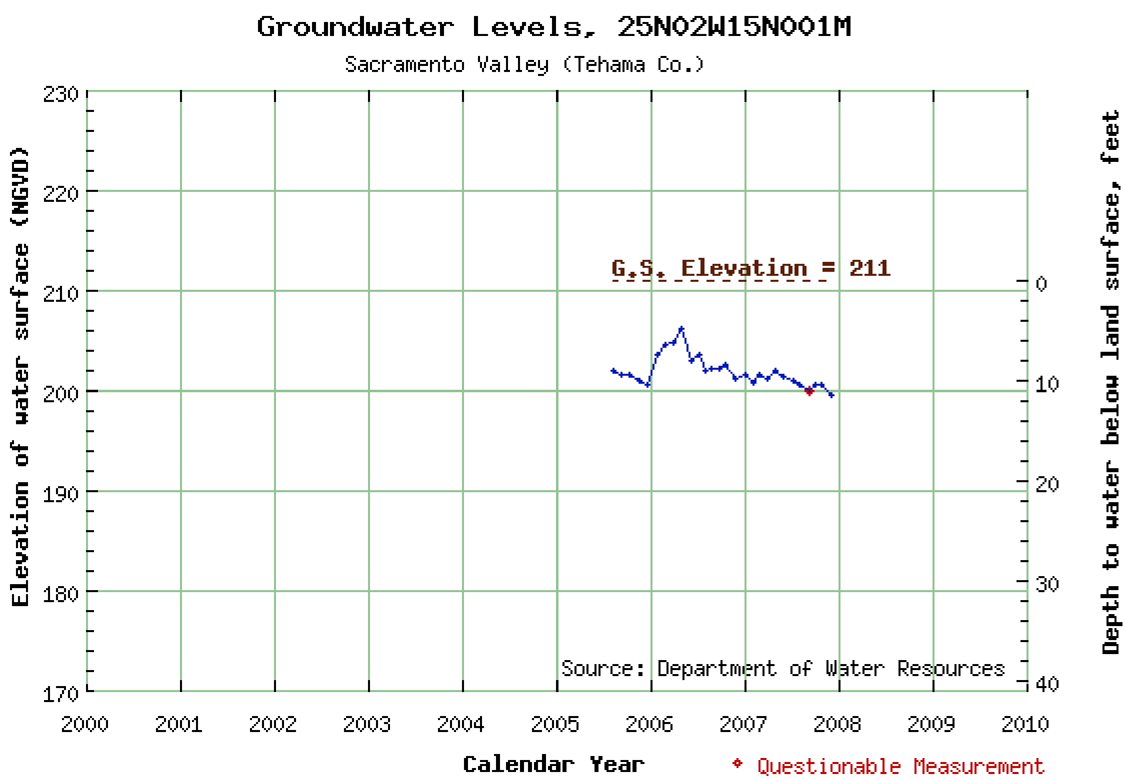

Groundwater Levels, 26N02W17E001M
Sacramento Valley (Tehama Co.)
G.S. Elevation = 238
Elevation of water surface (NGVD)
Depth to water below land surface, feet
240
230
220
210
200
190
180
0
10
20
30
40
50
1970
1975
1980
1985
1990
1995
2000
2005
2010
Source: Department of Water Resources
Calendar Year
Questionable Measurement

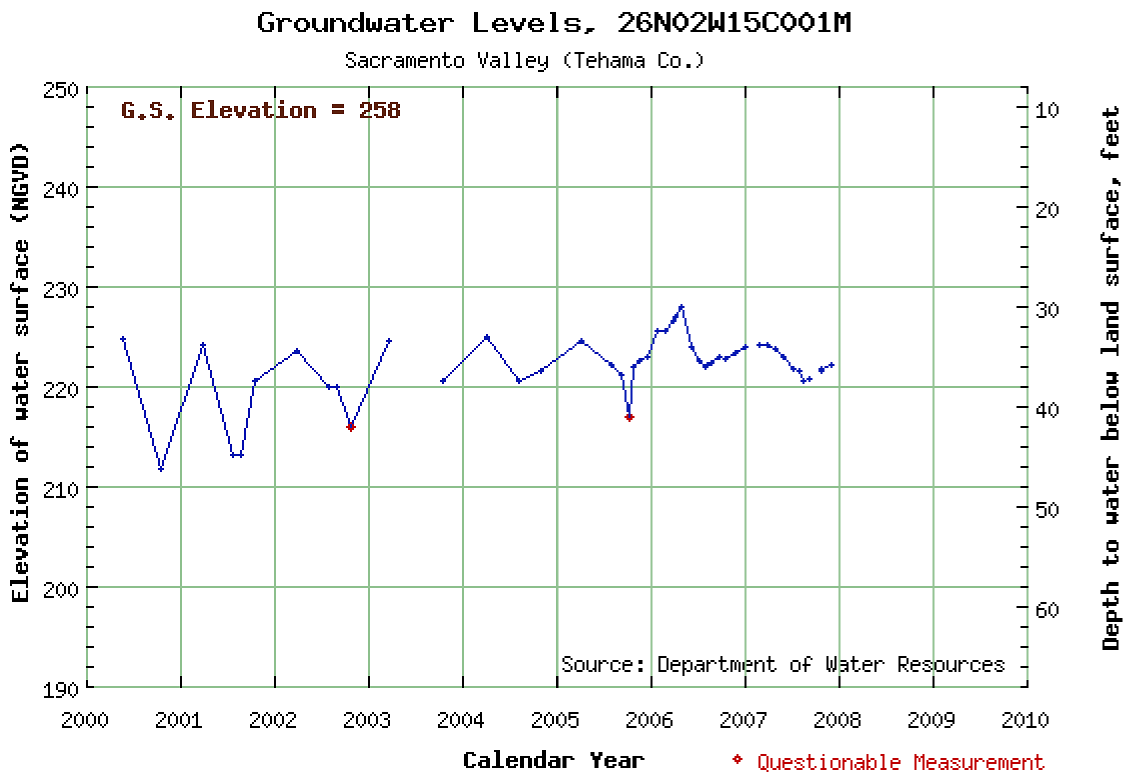

Groundwater Levels, 25N02W17B001M
Sacramento Valley (Tehama Co.)
G.S. Elevation = 226
Elevation of water surface (NGVD)
Depth to water below land surface, feet
220
210
200
190
180
170
160
10
20
30
40
50
60
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
Source: Department of Water Resources
Calendar Year
Questionable Measurement

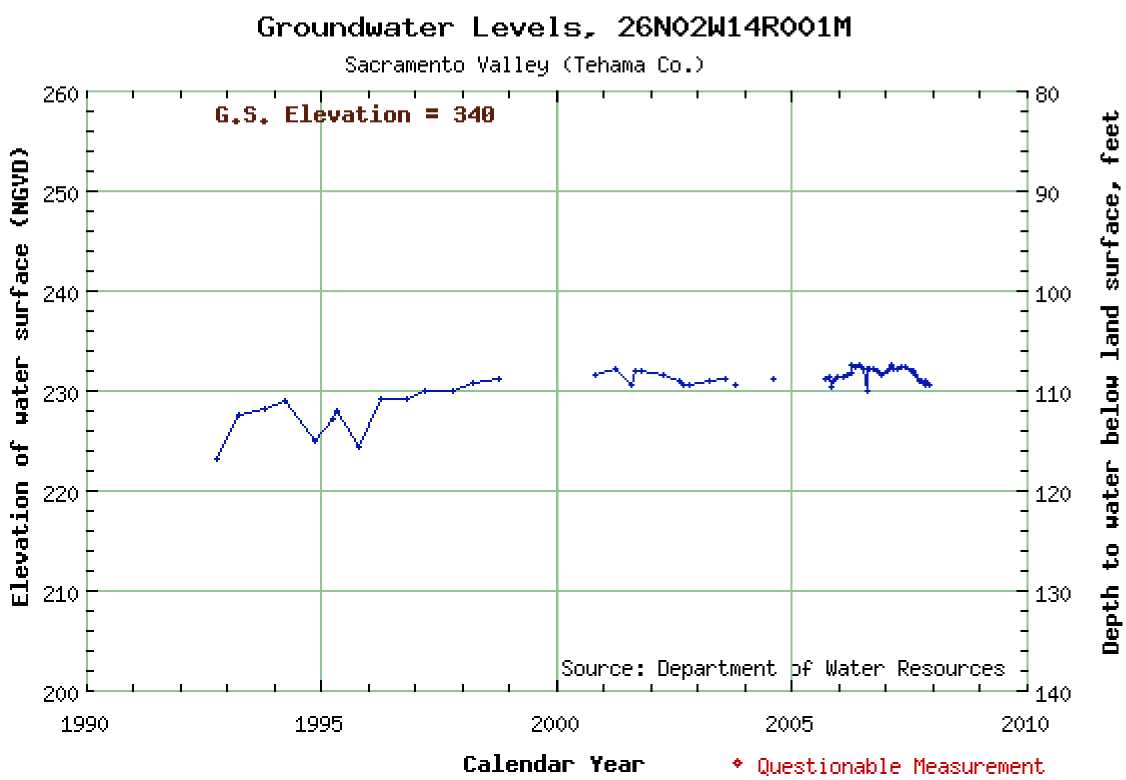

Groundwater Levels, 25N02W16L001M
Sacramento Valley (Tehama Co.)
G.S. Elevation = 220
Elevation of water surface (NGVD)
Depth to water below land surface, feet
220
210
200
190
180
170
160
0
10
20
30
40
50
60
Source: Department of Water Resources
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
Calendar Year
Questionable Measurement

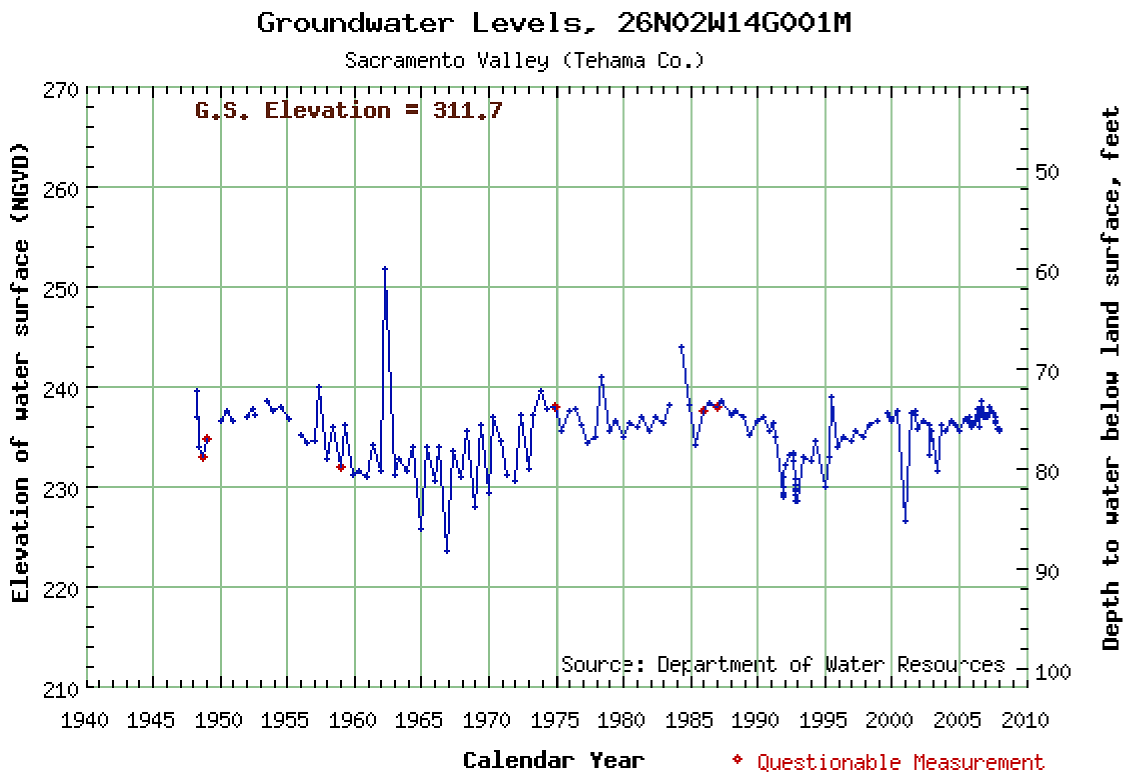

Groundwater Levels, 26N02W16C001M
Sacramento Valley (Tehama Co.)
G.S. Elevation = 240
Elevation of water surface (NGVD)
Depth to water below land surface, feet
250
240
230
220
210
200
190
0
10
20
30
40
50
Source: Department of Water Resources
1980
1985
1990
1995
2000
2005
2010
Calendar Year
Questionable Measurement

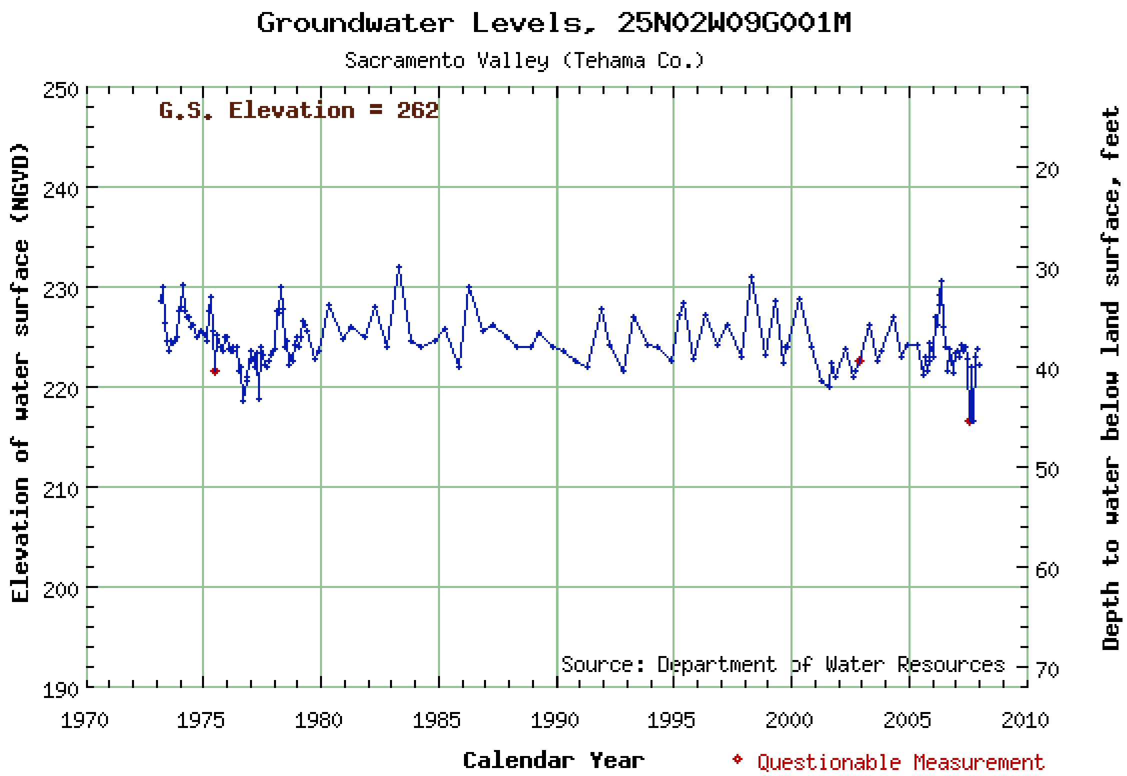

Groundwater Levels, 25N02W16B003M
Sacramento Valley (Tehama Co.)
G.S. Elevation = 230
Source: Department of Water Resources
Elevation of water surface (NGVD)
Depth to water below land surface, feet
240
230
220
210
200
190
180
0
10
20
30
40
50
2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010
Calendar Year
Questionable Measurement

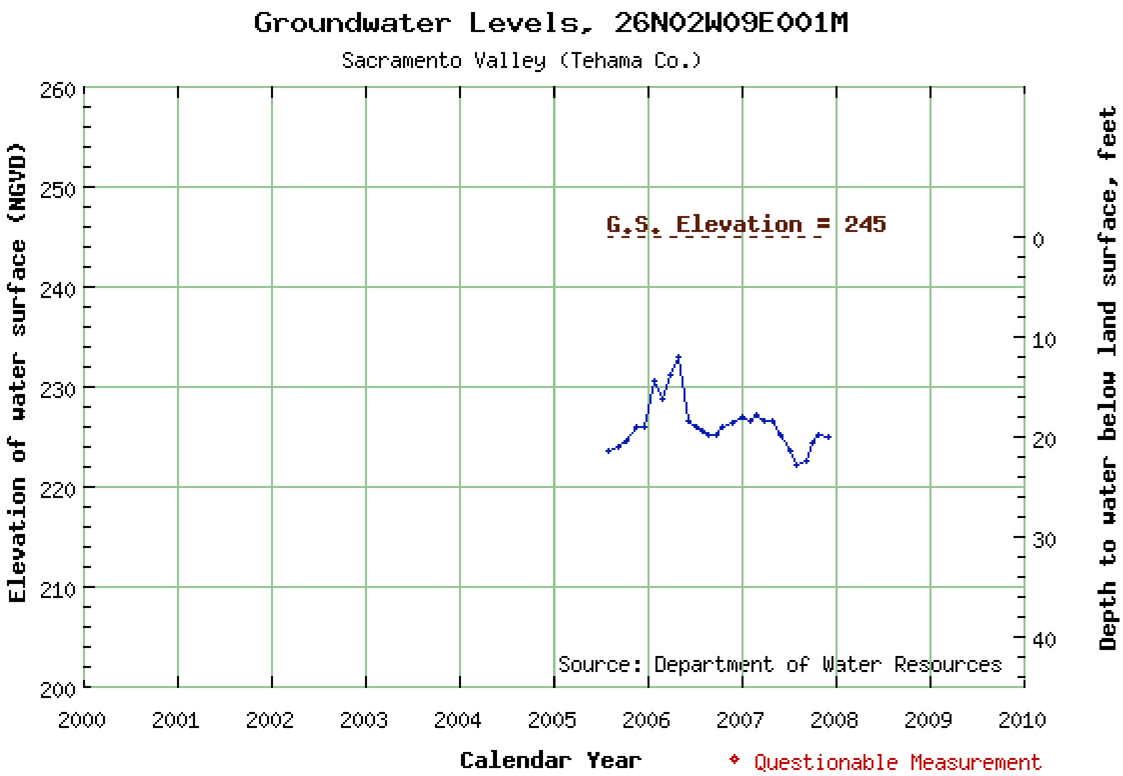

Groundwater Levels, 25N02W15N001M
Sacramento Valley (Tehama Co.)
G.S. Elevation = 211
Source: Department of Water Resources
Elevation of water surface (NGVD)
Depth to water below land surface, feet
230
220
210
200
190
180
170
0
10
20
30
40
2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010
Calendar Year
Questionable Measurement

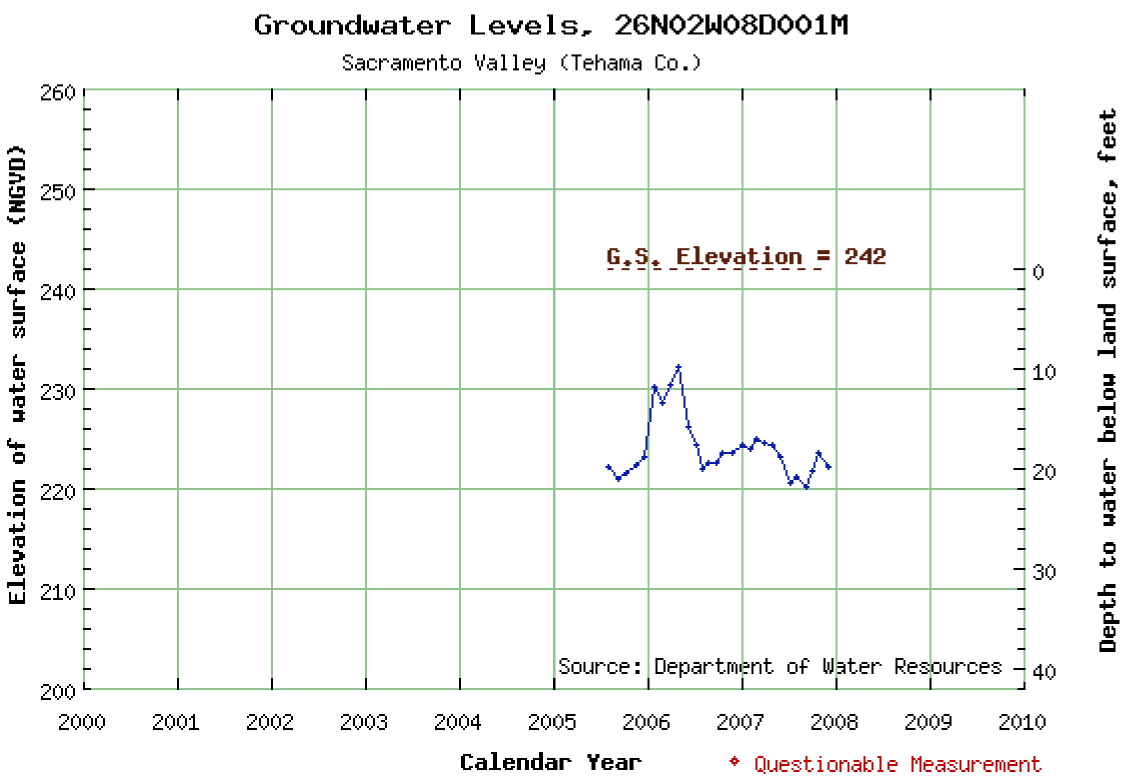

Groundwater Levels, 26N02W15C001M
Sacramento Valley (Tehama Co.)
G.S. Elevation = 258
Elevation of water surface (NGVD)
Depth to water below land surface, feet
250
240
230
220
210
200
190
10
20
30
40
50
60
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
Source: Department of Water Resources
Calendar Year
Questionable Measurement

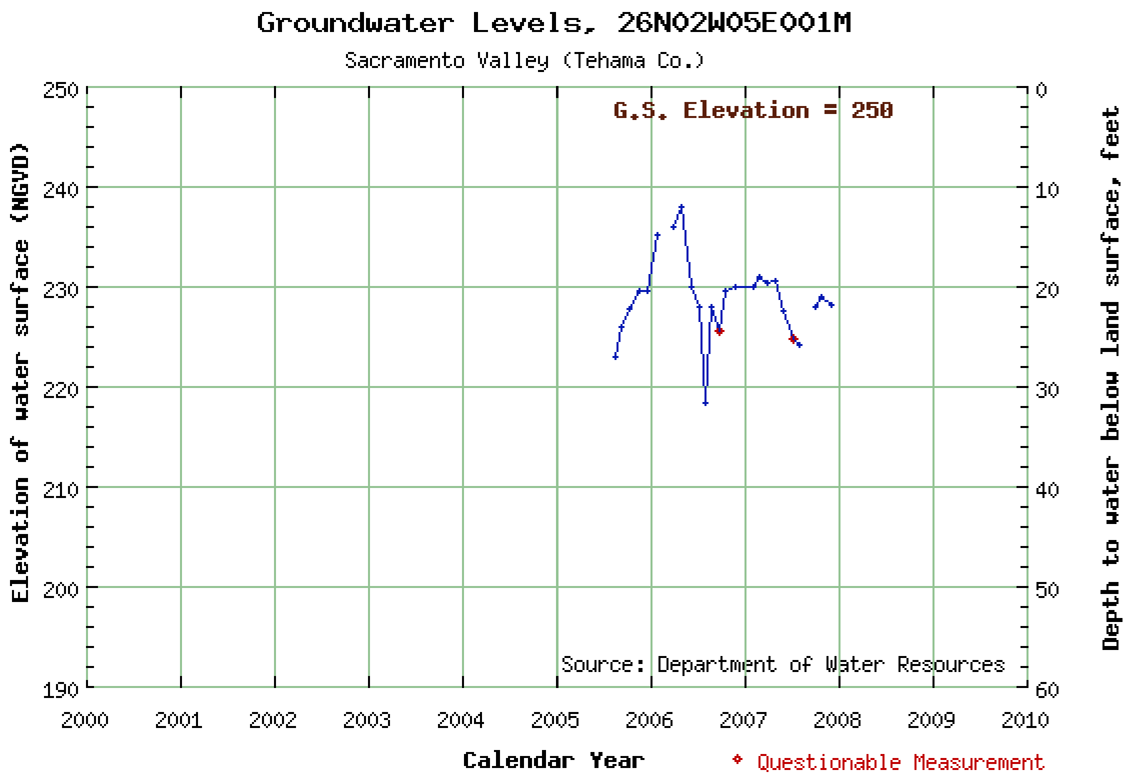

Groundwater Levels, 26N02W14R001M
Sacramento Valley (Tehama Co.)
G.S. Elevation = 340
Elevation of water surface (NGVD)
Depth to water below land surface, feet
260
250
240
230
220
210
200
80
90
100
110
120
130
140
1990
1995
2000
2005
2010
Source: Department of Water Resources
Calendar Year
Questionable Measurement

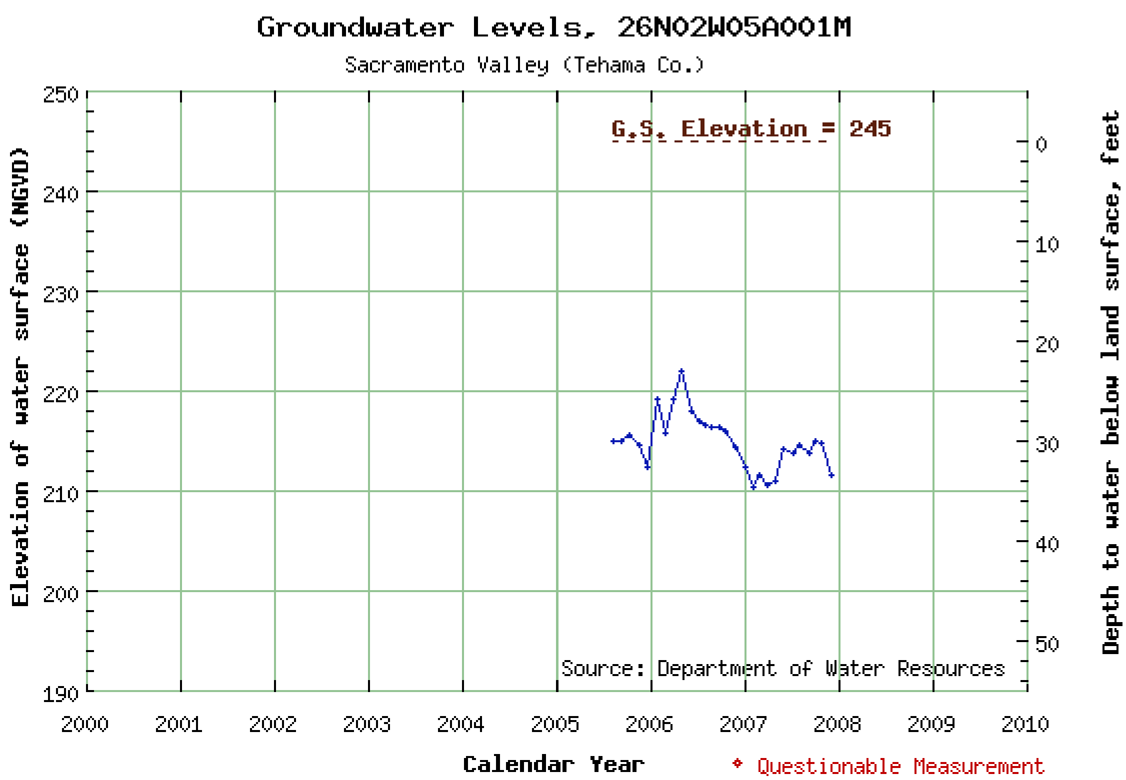

Groundwater Levels, 26N02W14G001M
Sacramento Valley (Tehama Co.)
G.S. Elevation = 311.7
Elevation of water surface (NGVD)
Depth to water below land surface, feet
Source: Department of Water Resources
Calendar Year
Questionable Measurement


Groundwater Levels, 25N02W09G001M
Sacramento Valley (Tehama Co.)
G.S. Elevation = 262
Elevation of water surface (NGVD)
Depth to water below land surface, feet
Source: Department of Water Resources
Calendar Year
Questionable Measurement


Groundwater Levels, 26N02W09E001M
Sacramento Valley (Tehama Co.)
Elevation of water surface (NGVD)
Depth to water below land surface, feet
G.S. Elevation = 245
Source: Department of Water Resources
Calendar Year
Questionable Measurement


Groundwater Levels, 26N02W08D001M
Sacramento Valley (Tehama Co.)
Elevation of water surface (NGVD)
Depth to water below land surface, feet
G.S. Elevation = 242
Source: Department of Water Resources
Calendar Year
Questionable Measurement


Groundwater Levels, 26N02W05E001M
Sacramento Valley (Tehama Co.)
G.S. Elevation = 250
Elevation of water surface (NGVD)
Depth to water below land surface, feet
250
240
230
220
210
200
190
0
10
20
30
40
50
60
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
Source: Department of Water Resources
Calendar Year
Questionable Measurement


Groundwater Levels, 26N02W05A001M
Sacramento Valley (Tehama Co.)
G.S. Elevation = 245
Elevation of water surface (NGVD)
Depth to water below land surface, feet
250
240
230
220
210
200
190
0
10
20
30
40
50
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
Source: Department of Water Resources
Calendar Year
Questionable Measurement

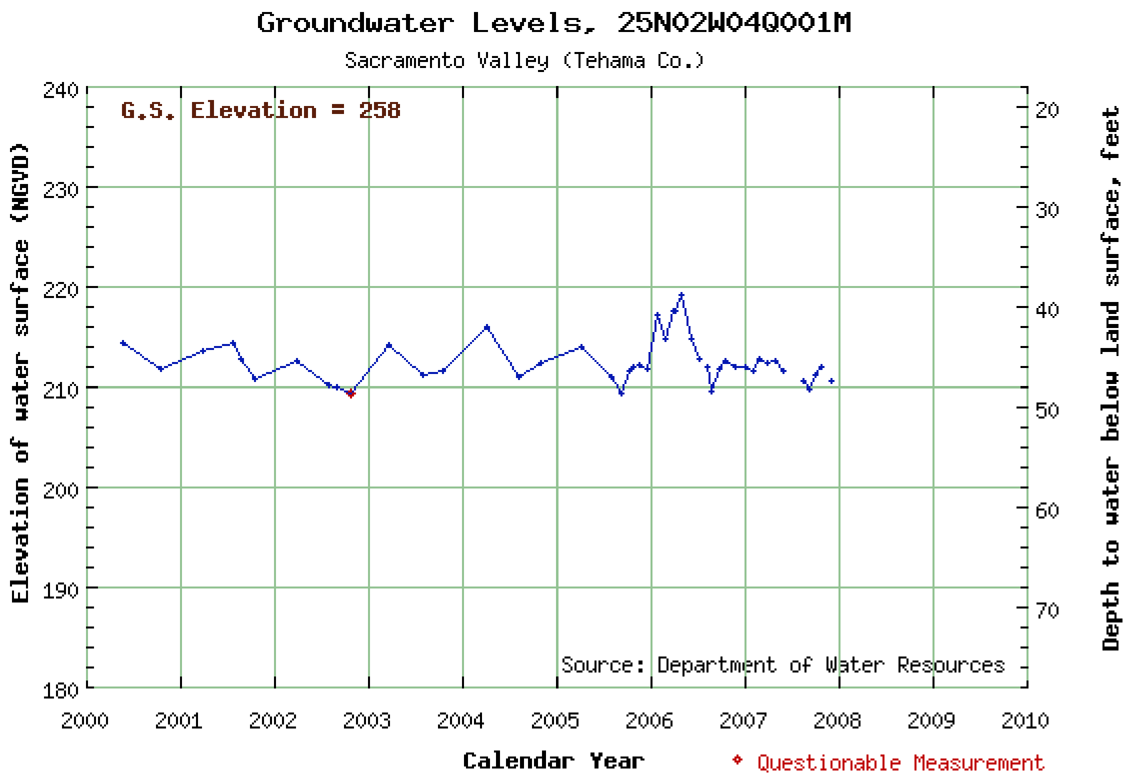

Groundwater Levels, 25N02W04Q001M
Sacramento Valley (Tehama Co.)
G.S. Elevation = 258
Elevation of water surface (NGVD)
Depth to water below land surface, feet
240
230
220
210
200
190
180
20
30
40
50
60
70
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
Source: Department of Water Resources
Calendar Year
Questionable Measurement

Plate 1: Regional Geology and Cross Section Locations

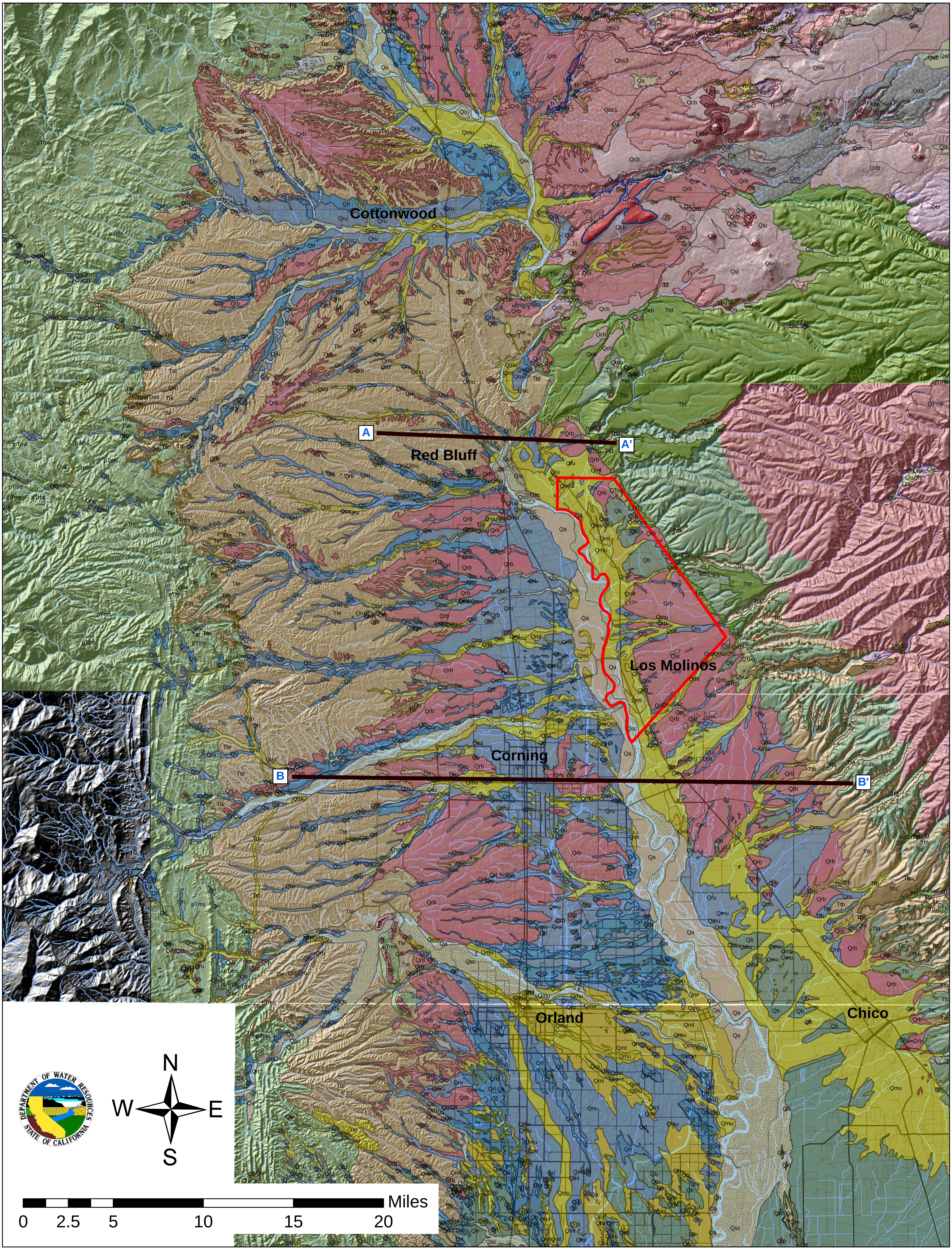


Plate 2: Geologic Legend

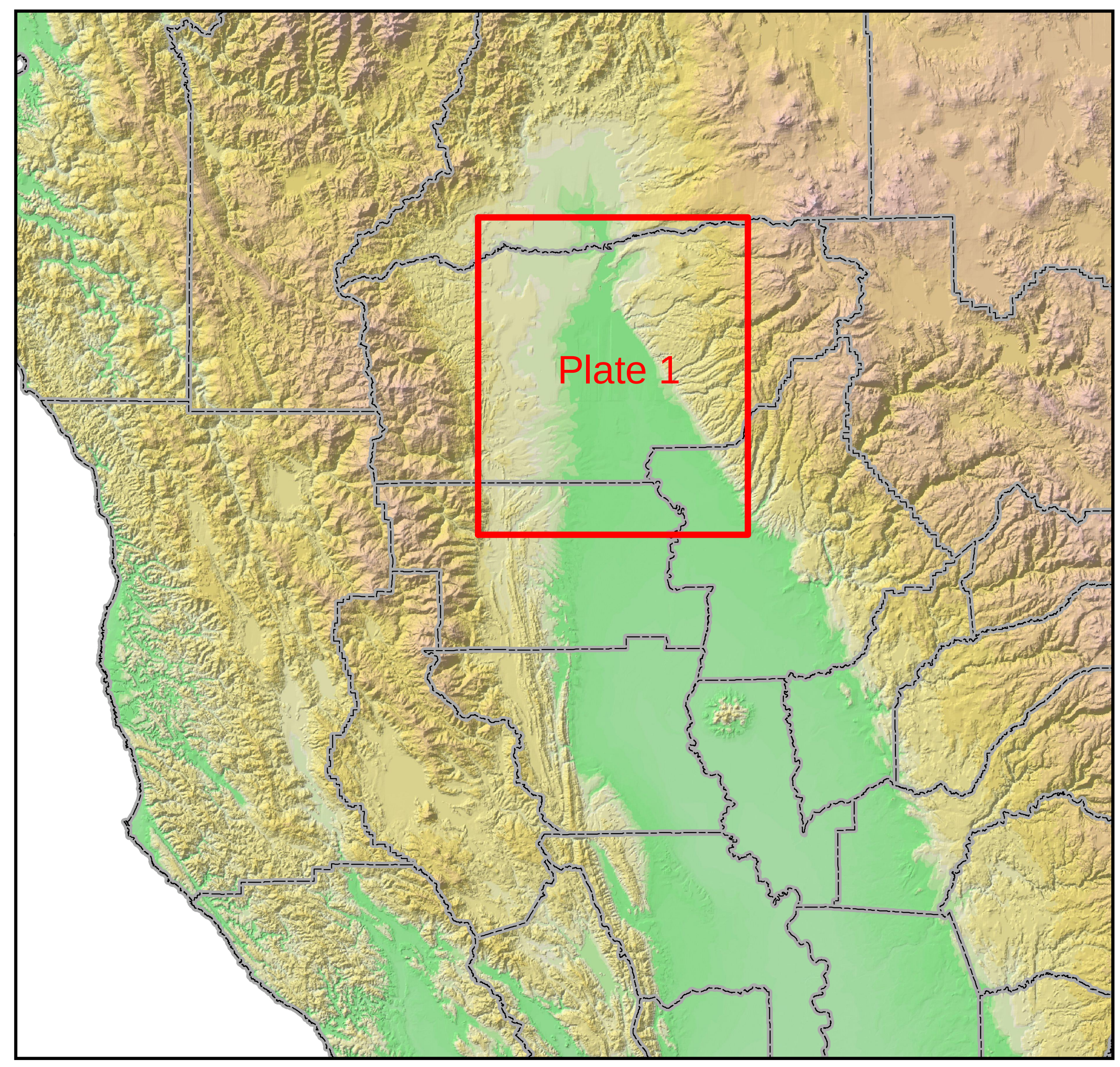
Description of Geologic Units

Qsc	Stream Channel Deposits (Holocene): Deposits of open, active stream channels without permanent vegetation; consequently they are light tan and gray, unweathered and usually in contact with modern surface waters. Thickness can be as much as 25 m near Sacramento River.
Qa	Alluvium (Holocene): Unweathered gravel, sand and silt deposited by present day stream and river systems. These units lie outboard of unit Qsc but inside the first low terraces flanking modern stream channels.
Qo	Overbank Deposits (Holocene): Sand, silt and minor lenses of gravel deposited by floods and during high water stages, form low terraces adjacent to present-day alluvial stream channels, coincident with tan and gray organic-rich sediments. Less than 3 m in thickness.
Qb	Basin Deposits, Undivided (Holocene): Fine grained silt and clay derived from the adjacent mountain ranges. The dark-gray to black deposits are the distal facies of unit Qa and can be as much as 60 m thick. (Includes Marsh Deposits).
Qls	Landslides (Holocene and Pleistocene): Slumped, rotated, chaotic mixtures of underlying bedrock units and colluvium.
Qmu	Upper Member, Modesto Formation (Pleistocene): Unconsolidated, unweathered gravel, sand, silt and clay. It forms alluvial fans along the east side of the Sacramento Valley from Red Bluff to Oroville. This members deposits are only a few meters thick.
Qml	Lower Member, Modesto Formation (Pleistocene): Unconsolidated, slightly weathered gravel, sand, silt and clay. Much more extensive and thick than Qmu. The Lower Member gets as much as 70 m thick.
Qru	Upper Member, Riverbank Formation (Pleistocene): Unconsolidated but compact, dark-brown to red alluvium composed of gravel, sand, silt and contains some minor clay. The Riverbank members are usually divided by at least 3 m. The members can be more than 70 m thick.
Qrl	Lower Member, Riverbank Formation (Pleistocene): Red semiconsolidated gravel, sand, and silt. Comprises the higher of the two Riverbank terraces and remnants of dissected alluvial fans.
Qrb	Red Bluff Formation (Pleistocene): A thin veneer of distinctive, highly weathered bright-red gravels beveling and overlying the Tehama, Tuscan and Laguna Formations.
Qif	Flank Fissure Flows, Undivided (Qif 1,2,3) (Pleistocene): Several small, blocky basalt flows originating from vents along two parallel, northeast-trending fissures on the north slope of Little Inskip Hill, located northeast of Red Bluff. Likely to be less than 5 m thick.
Qic	Cinder Cone Deposits of Inkip Hill (Pleistocene): Red and black basaltic cinders forming the prominent cones of Inskip Hill.
Qiu	Undifferentiated Basalt Flows of Inskip Hill (Pleistocene): Includes Qip. Thin, black to dark gray basalt flows. Flow is about 8 m thick.
Qbbb	Cinder Blanket Deposits of Black Butte (Pleistocene): Black, well-bedded basaltic cinder deposits forming a dissected ejects blanket that ranges in thickness from about 10 to 1.5 m.
Qbbf	Basalt Flow of Black Butte (Pleistocene): Dark-gray to black basalt similar to Qip. Olivine and clinopyroxene phenocrysts are scattered in a diktytaxitic matrix of clinopyroxene and plagioclase.
Qbs	Basalt of Shingletown Ridge, Undifferentiated (Pleistocene): Composed of three subunits of dark-gray, fine-grained, diktytaxitic and locally porphyritic basalt with rounded phenocrysts of brownish-green olivine scattered in an openwork mesh matrix of plagioclase and clinopyroxene. Basalt ranges in thickness from 30 to 5 m.
Qab	Andesite of Brokeoff Mountain (Pleistocene): Flow of porphyritic hypersthene andesite that contain abundant white plagioclase phenocrysts, minor amounts of hypersthene, and sparse augite phenocrysts set in a fine-grained matrix of plagioclase microlites and brown glass. North of Manton the total thickness is about 30 m.
Qar	Rockland Ash (Pleistocene): Unit is equivalent to ash of Mount Maidu. White loosely aggregated pumice lapilli ash with scattered coarse pumice fragments as large as 20 cm in diameter form a major dacitic to rhyolitic ash-flow tuff deposit. Ash is 60 m thick near Digger Buttes but less than 5 m in west patches
Qeb	Basalt of Eagle Canyon (Pleistocene): Dark-gray, vesicular, diktytaxitic olivine basalt underlying the broad plain carved by Battle Creek.
Qcb	Basalt of Coleman Forebay (Pleistocene): Light-rusty-gray-weathering, dark-gray olivine basalt with pronouced diktytaxitic texture and scattered large vessicles and voids that form from large rounded pits on the weathered surfaces. The basalt underlies the Red Bluff Formation in several isolated areas. Has a maximum thickness of 10 m.
Qbdc	Olivine Basalt of Deer Creek (Pleistocene): Dark-gray to greenish-black, sparsely vesicular olivine basalt flows locally exposed on the north and south rims of the canyon of Deer Creek.
Qtog	Older Gravel Deposits (Pleistocene and/or Pliocene): Moderately well indurated, coarse to very coarse to very coarse gravel with minor coarse sand resting uncomformably on the Tuscan Formation.
Ta	Andesite (Pliocene): Undivided flows of predominantly two pyroxene andesite, commonly platy, medium to light gra, rarely dark gray, locally pink flows with minor interbedded tuff and tuff breccia
TPa	Platy Andesite (Pliocene): Light to dark gray, bluish-gray and brick red, sparsely porphyritic, slab weathering to massive, locally streaked and flow banded platy andesited exposed on the Battle Creek escarpment at Bailey Creek and Tuscan Buttes.
Tbc	Olivine Basalt of Cohasset Ridge (Pliocene): Gray vesicular porphyritic basalt flows with olivine phenocrysts as much as 6 mm in diameter set in a diktaxitic matrix of plagioclase and clinopyroxene. Maximum thickness is about 25 m.
Tba	Basaltic Andesite of Antelope Creek (Pliocene): Dark Gray to greenish-gray, massive to highly fractured, fine-grained, sparsely vesicular basaltic andesite exposed in Antelope Creek, locally altered to brickred and reddish-gray.
Tte	Tehama Formation (Pliocene): Pale-green, gray and tan sandstone and siltstone with lenses of cross bedded pebble and cobble conglomerate derived from the Coast and Klamath Ranges. Can be over 600 m thick.
Tt	Tuscan Formation (Pliocene): Interbedded lahars, volcanic conglomerate, volcanic sandstone, siltstone, and pumiceous tuff, divided into four categories; Tuscan A, B, C, and D.
Ttd	Unit D of Tuscan Formation (Pliocene): Predominantly fragmental deposits characterized by large monolithological masses of gray hornblende and basaltic andesites, black pumice and smaller fragments of black obsidian in a grayish-tan pumiceous mudstone matrix. The unit ranges from 10 to 50 m thick.
Ttc	Unit C of Tuscan Formation (Pliocene): Lahars with some interbedded volcanic conglomerate and sandstone. Lahars with contain abundant casts of wood fragments and prominent cooling fractures. Unit C can be more than 50 m thick.
Ttb	Unit B of Tuscan Formation (Pliocene): Interbedded lahars, volcanic conglomerate, volcanic sandstone and siltstone similar to Unit C, but underlying the Ishi Tuff Member. Unit B is about 130 m thick.
Tta	Unit A of Tuscan Formation (Pliocene): Interbedded lahars, volcanic conglomerate, volcanic sandstone and siltstone all containing scattered fragments of metamorphic rocks. Metamorphic rock fragments are as much as 20 cm in diameter. Unit A is about 65 m thick along the Chico Monocline.
Ttn	Nomlaki Tuff Member (Pliocene): White, light-gray, locally reddish-tan to salmon diactic tuff and pumice lapilli tuff underly both the Tuscan and Tehama Formations.
Tc	Channel Deposits (Pliocene and/or Miocene): Tan, yellowish-tan to reddish-brown , interbedded fluvial conglomerate and lesser amounts of sandstone exposed in some of the deeper canyons below the Tuscan Formation.
Tl	Lovejoy Basalt (Miocene): Black, dense, hard, microcrystalline to extremely grained, equigranular to sparsely porphyritic basalt. Maximum thickness of about 20 m.
Tmc	Montgomery Creek Formation (Eocene): Gray, yellowish-orange-weathering, arkosic sandstone with conglomerate and shale. The rock is commonly massive to thick-bedded nonmarine sandstone with scattered lenses of pebble conglomerate and shale.
Kc	Chico Formation (Cretaceous): Tan, yellowish-brown to light gray, fossiliferous marine sandstone with lenticular beds of pebble to fine cobble conglomerate and minor siltstone. The thickness can be as much as 650 m.
pTms	Bedrock; Metamorphic, Intrusive and Sedimentary Rocks (Pre-Tertiary): Undivided metamorphosed Paleozoic and Mesozoic volcanic and sedimentary rocks intruded by Mesozoic and older granitic rocks.

Geologic Map Legend

- Major Roadways
- Waterways
- Ishi Tuff Boundary Under Tuscan Formation
- Project Study Area
- A — A' Cross-Sectional Location
- Lithology Unit Boundary
- Man Made Material: Dredge tailings and other disturbed ground.
- Unk — Unknown

Location Map



Correlation of Map Units

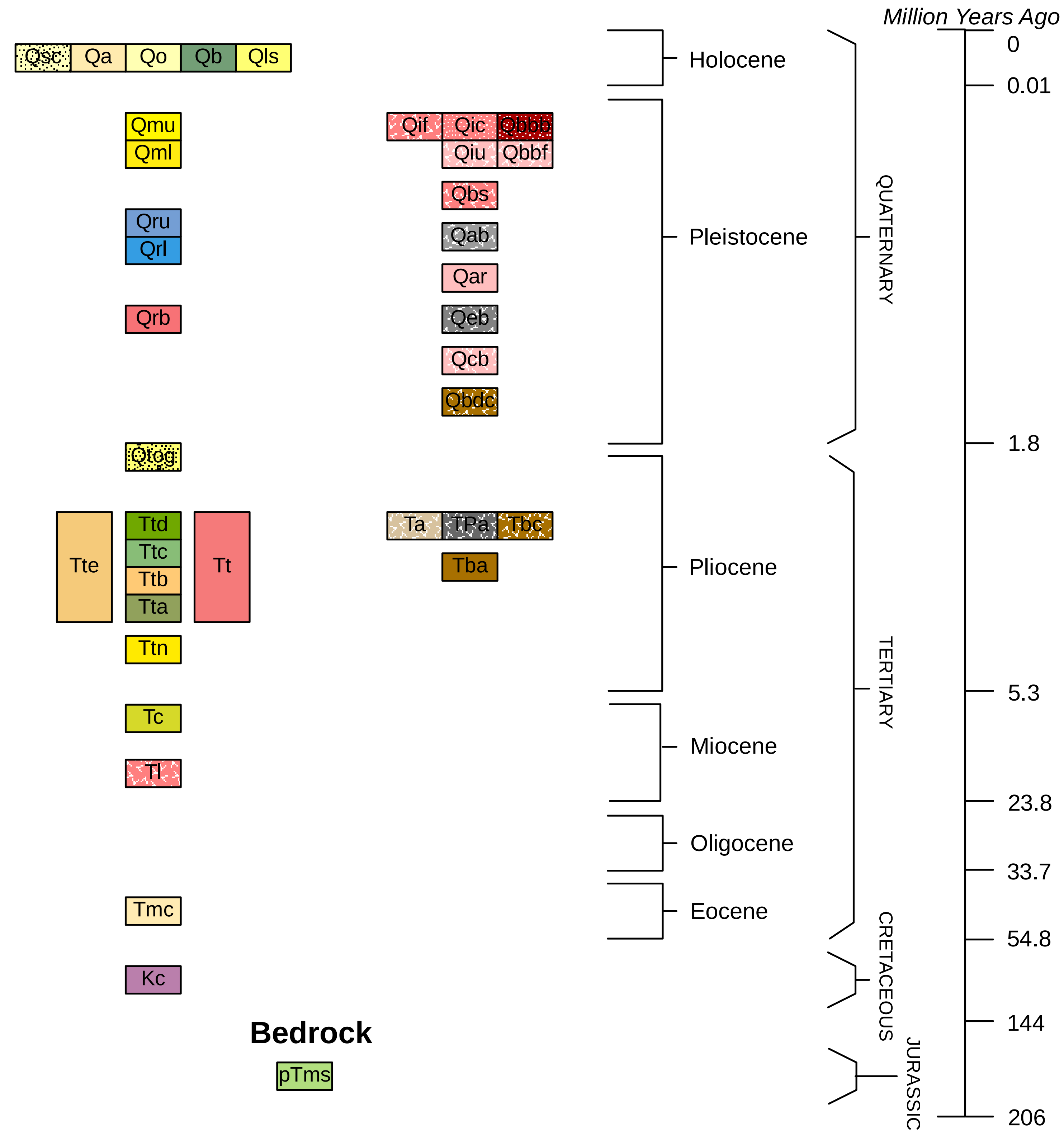
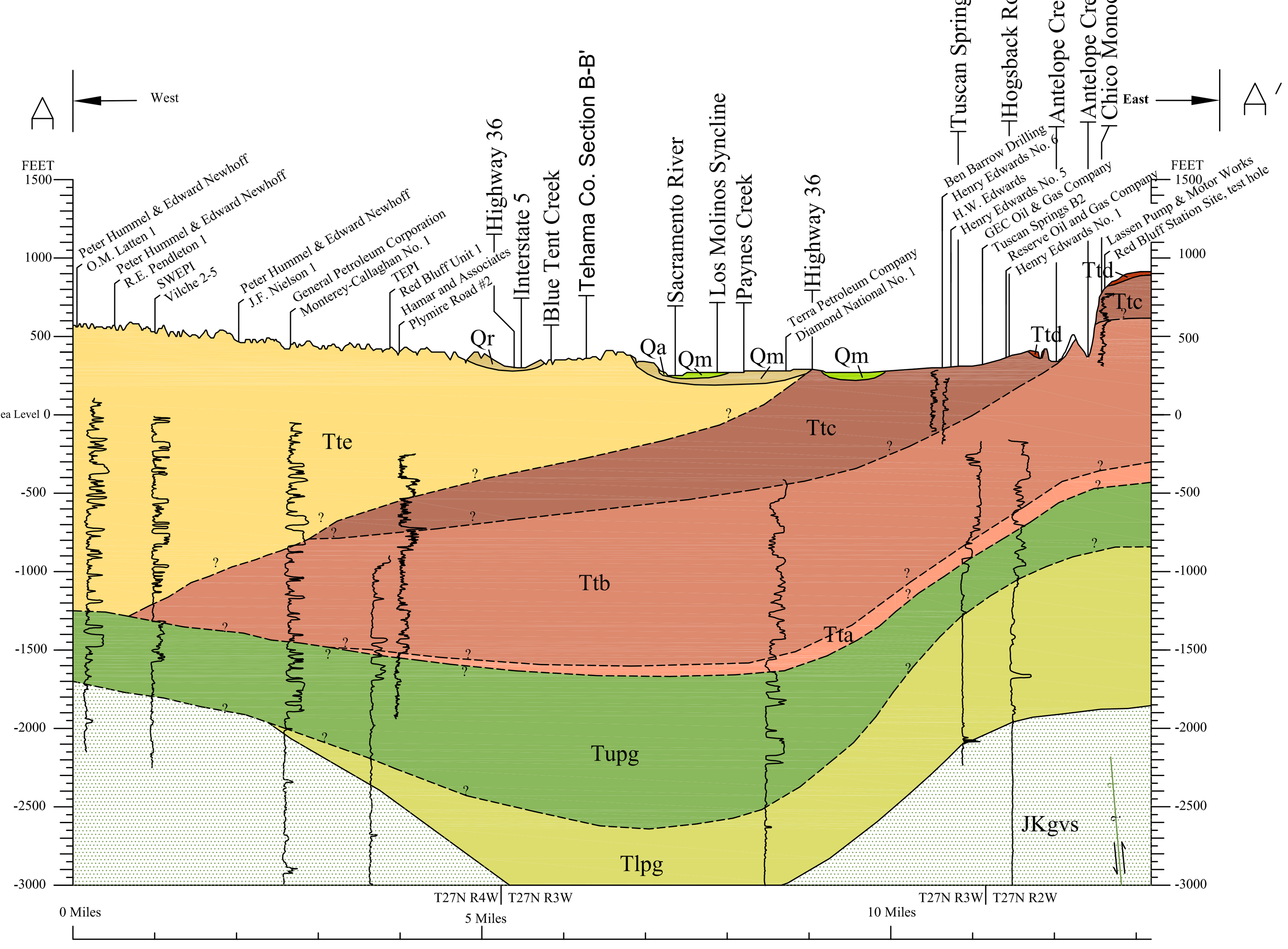
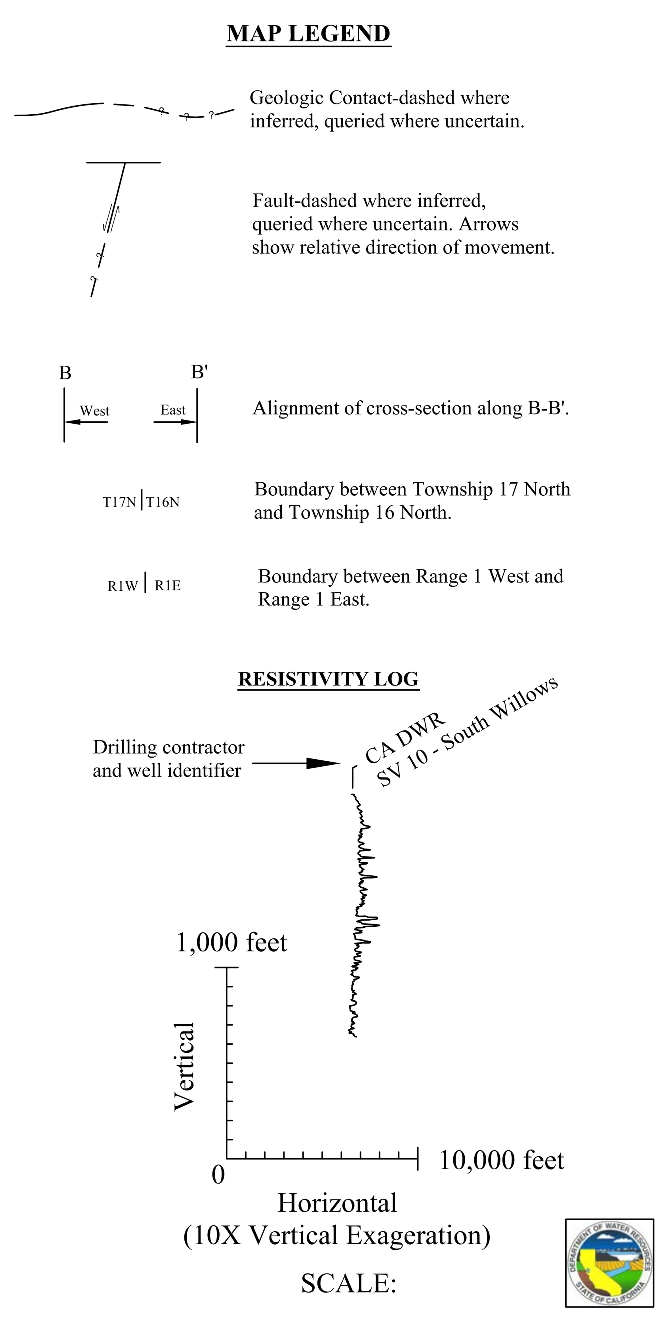


Plate 3: Geologic Cross Sections

Cross Section A-A'

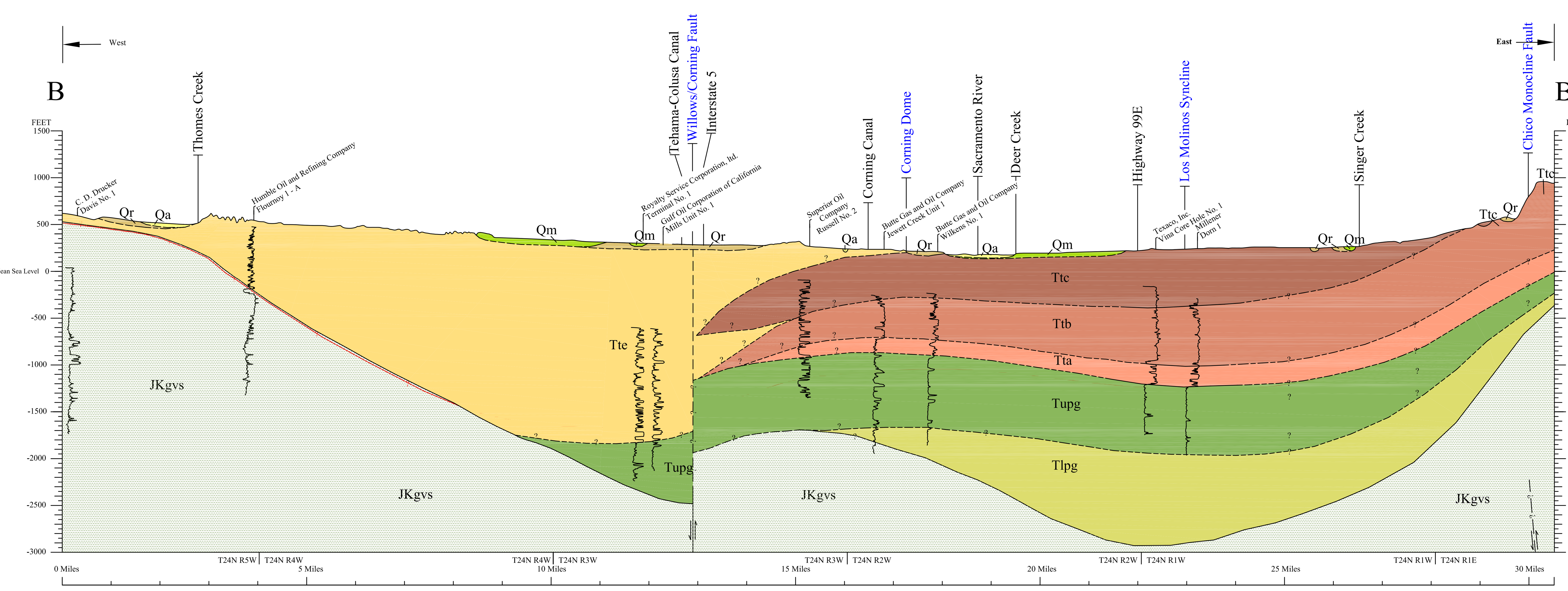


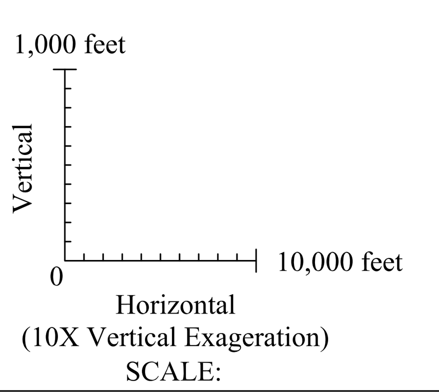


DESCRIPTION OF MAP UNITS

Qa	**Alluvium** (Holocene)-Includes surficial alluvium and stream channel deposits of unweathered gravel, sand and silt, maximum thickness 80 ft. *(adapted from Helley & Harwood, 1985)*.
Qb	**Basin Deposits** (Holocene)-Fine-grained silt and clay derived from adjacent mountain ranges, maximum thickness up to 200 ft. *(adapted from Helley & Harwood, 1985)*.
Qm	**Modesto Formation**, undifferentiated (Pleistocene)-Alluvial fan and terrace deposits consisting of unconsolidated weathered and unweathered gravel, sand, silt and clay; maximum thickness approximately 200 ft. *(adapted from Helley & Harwood , 1985).*
Qr	**Riverbank Formation**, undifferentiated (Pleistocene)-Alluvial fan and terrace deposits consisting of unconsolidated to semi-consolidated gravel, sand and silt; maximum thickness approximately 200 ft. *(adapted from Helley & Harwood, 1985).*
Tte	**Tehama Formation** (Plio-Pleistocene)-Includes Red Bluff Formation on west side. Pale green, gray and tan sandstone and siltstone with lenses of pebble and cobble conglomerate; maximum thickness 2,000 ft. *(adapted from Helley & Harwood, 1985).*
Ttd	**Tuscan Unit D** (Plio-Pleistocene)-Fragmental flow deposits characterized by monolithic masses containing gray hornblende and basaltic andesites and black pumice, maximum thickness 160 ft. *(adapted from Helley & Harwood, 1985).*
Ttc	**Tuscan Unit C** (Plio-Pleistocene)-Includes Red Bluff Formation on east side. Volcanic lahars with some interbedded volcanic conglomerate and sandstone, and reworked sediments; maximum thickness 600 ft. *(adapted from Helley & Harwood, 1985, DWR Bulletin 118-7, 2001, draft report).*
Ttb	**Tuscan Unit B** (Pliocene)-Layered, interbedded lahars, volcanic conglomerate, volcanic sandstone and siltstone; maximum thickness 600 ft. *(adapted from Helley and Harwood, 1985; DWR Bulletin 118-7, 2001, draft report).*
Tta	**Tuscan Unit A** (Pliocene)-Interbedded lahars, volcanic conglomerate, volcanic sandstone, and siltstone containing metamorphic rock fragments; maximum thickness 400 ft. *(adapted from Helley & Harwood, 1985; DWR Bulletin 118-7 (in progress), 2001).*
Tl	**Lovejoy Basalt** (Miocene)-Black, dense, hard microcrystalline basalt; maximum thickness 65 ft. *(adapted from Helley & Harwood, 1985).*
Tupg	**Upper Princeton Valley Fill** (Late Oligocene to Early Miocene)-Non-marine sediments composed of sandstone with interbeds of mudstone and occasional conglomerate and conglomerate sandstone; maximum thickness 1,400 ft. *(adapted from Redwine, 1972).*
Ti	**Ione Formation** (Eocene)-Marine to non-marine deltaic sediments, light colored, commonly white conglomerate, sandstone and siltstone, which is soft and easily eroded; max. thickness 650 ft. *(adapted from DWR Bulletin 118-6, 1978; Creely, 1965).*
Tlpg	**Lower Princeton Submarine Valley Fill** (Eocene)-includes Capay Formation. Marine sandstone, conglomerate and interbedded silty shale, maximum thickness 2,400 ft. (*adapted from Redwine, 1972*)
JKgvs	**Great Valley Sequence** (Late Jurassic to Upper Cretaceous)-Marine clastic sedimentary rock consisting of siltstone, shale, sandstone and conglomerate; maximum thickness 15,000 ft.
JKf	**Franciscan Formation** (Jurassic to Cretaceous)-Dominated by greenish-grey greywackes with lesser amounts of dark shale, limestone and radiolarian chert, maximum thickness up to 25,000 ft. *(adapted from strand, 1962 and Norris & Webb, 1990).*

Cross Section B-B'





Note: DWR's geologic interpretation of cross sections A-A' and B-B' are currently being updated. The most current version is not reflected on this draft.