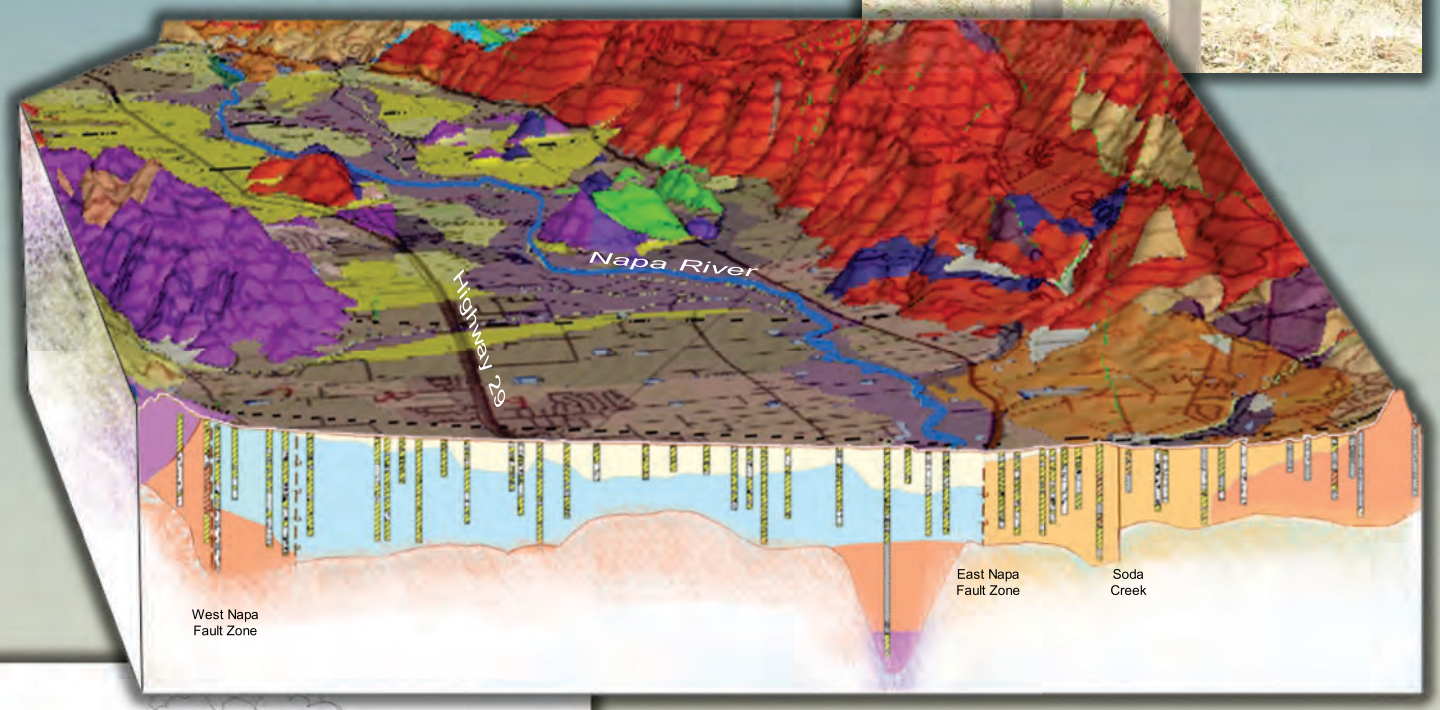
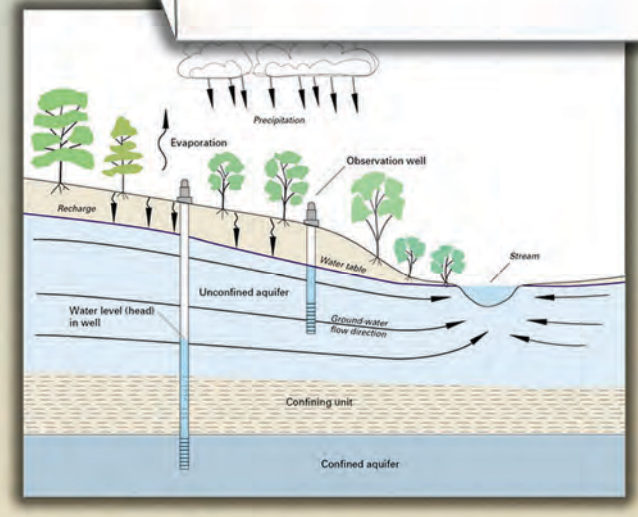
Updated Hydrogeologic Conceptualization and Characterization of Conditions





January, 2013

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Updated Hydrogeologic Conceptualization and Characterization of Conditions

Prepared for

Napa County

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EXECUTIVE SUMMARY

Groundwater and surface water are highly important natural resources in Napa County. Currently, municipal and private stakeholders are actively engaged in assessing the reliability of current and future demands and supplies. Important sources of water include both groundwater and surface water of good quality and quantity, to meet future urban, rural, and agricultural water demands. Similar to other areas in California, businesses and residents of Napa County face many water-related challenges. To address these challenges, long-term, systematic monitoring programs are essential to provide data that allow for improved evaluation of water resources conditions and to facilitate effective water resources planning. Establishment of a groundwater and surface water monitoring network results in the collection of data necessary to distinguish long-term trends from short-term fluctuations, anticipate unintended consequences due to current and historical land uses, identify emerging issues, and design appropriate water resources planning and management strategies.

ES 1.1 Background

In 2009, Napa County embarked on a countywide project referred to as the "Comprehensive Groundwater Monitoring Program, Data Review, and Policy Recommendations for Napa County's Groundwater Resources" (Comprehensive Groundwater Monitoring Program), to meet identified action items in the 2008 General Plan update (Napa County, 2008). Napa County's Comprehensive Groundwater Monitoring Program involved many tasks that led to the preparation of five technical memorandums and a report on Napa County Groundwater Conditions and Groundwater Monitoring Recommendations (LSCE, 2011a). This report and the other related documents can be found at: http://www.countyofnapa.org/bos/grac/.

The program emphasizes developing a sound understanding of groundwater conditions and implementing an expanded groundwater monitoring and data management program as a foundation for future coordinated, integrated water resources planning and dissemination of water resources information. The program covers the continuation and refinement of countywide groundwater level and quality monitoring efforts (including many basins, subbasins and/or subareas throughout the county) for the purpose of understanding groundwater conditions (i.e., seasonal and long-term groundwater level trends and also quality trends) and availability. This information is critical to enable integrated water resources planning and the dissemination of water resources information to the public and state and local decision-makers.

Napa County's combined efforts through the Comprehensive Groundwater Monitoring Program along with the related AB 303 Public Outreach Project on groundwater (CCP, 2010) and the efforts of the Watershed Information Center and Conservancy (WICC) of Napa County create a foundation for the County's continued efforts to increase public outreach and participation in water resources understanding, planning, and management.

On June 28, 2011, the County Board of Supervisors adopted a resolution establishing a Groundwater Resources Advisory Committee (GRAC). Two of the tasks assigned to the GRAC include: 1) assisting with the synthesis of the existing groundwater information and identifying critical data needs; and 2) providing input on the furtherance of the ongoing countywide groundwater monitoring program. During the implementation of the study discussed herein, input from this committee was coordinated to optimize additional groundwater monitoring locations that serve to meet the objectives of the County's Comprehensive Groundwater Monitoring Program and also the California Statewide Groundwater Elevation Monitoring (CASGEM) program, which is a subset of the countywide groundwater monitoring program.

ES 1.2 Purpose

The purpose of this Napa County Updated Hydrogeologic Conceptualization and Characterization of Conditions Report (Report) is to describe the work conducted by Luhdorff and Scalmanini, Consulting Engineers (LSCE) together with MBK Engineers (MBK) on behalf of the County to implement a number of the recommendations pertaining to the County's Comprehensive Groundwater Monitoring Program, including:

1. Prepare an updated hydrogeologic conceptualization and characterization of conditions in various areas of Napa County;
2. Analyze the potential for surface water/groundwater interactions;
3. Refine and further characterize areas of the greatest recharge potential; and
4. Link well construction information to groundwater level monitoring data, and provide groundwater monitoring recommendations.

Forthcoming in a separate document, the County is also developing an approach to determine whether there are locations where groundwater pumping near a surface water course (such as might occur for a proposed project) would be anticipated to effect groundwater discharge to the surface water available for endangered species. Conversely, the approach is also intended to enable the determination of locations where groundwater pumping would not have such an effect. The approach will be informed by the updated hydrogeologic conceptualization of conditions (as can be identified with existing data), including the accompanying groundwater monitoring recommendations, summarized in this Report.

ES 1.3 Updated Hydrogeologic Conceptualization and Characterization of Conditions

The Napa Valley study area is located in the southern-central Coast Range Province north of the San Francisco Bay region. This region of the Coast Range is characterized by northwest trending low mountainous ridges separated by intervening stream valleys. The Napa Valley is a

relatively narrow, flat-floored stream valley drained by the Napa River. The valley floor descends from elevations of about 420 feet at the northwest end of the Valley to about sea level at the southern end.

ES 1.3.1 Geologic and Hydrogeologic Conditions

Historical Geologic and Hydrogeologic Studies and Mapping Efforts

Understanding the hydrogeology of Napa County is essential to determine how much water is available and to what extent it can be sustainably produced. Previous hydrogeologic studies have focused on the Milliken-Sarco-Tulucay (MST) Subarea and northern portion of the Napa Valley without much attention to the other areas within the county. With the exception of the Farrar and Metzger (2003) study, which looked at the MST, all of these studies are more than 30 years old. Since these studies, hundreds of new wells have been drilled to greater depths than previously reached, supplying a potential abundance of new data.

The surficial geology of the Napa Valley area has been mapped by various authors for over a hundred years. The reports and geologic maps differ through time in the detail of mapping, characterization of rock types, and nomenclature of various units. In the last forty years, the development of radiometric-age dating techniques and the evolution of plate tectonic theory have led to a better understanding of the geologic history of the region.

However, even the most recent geologic reports and maps exhibit conflicting map units, lithology, and nomenclature. Since the earliest geologic maps, three major geologic units in the Napa Valley area have been recognized and remain largely unchanged, except in details, names, and interpretation of how they were formed. These three units are Mesozoic rocks, Tertiary volcanic and sedimentary rocks, and Quaternary sedimentary deposits.

Previous hydrogeologic studies have focused on the Quaternary alluvium and most studies did not attempt to subdivide the Sonoma Volcanics in the subsurface. Previous geologic cross-sections were largely in the City of Napa area (Kunkel and Upson, 1960). Faye (1973) presented no cross-sections north of the City of Napa, but he mapped the thickness of the alluvium. In the MST area, Johnson (1977) and Farrar and Metzger (2003) subdivided the Sonoma Volcanics on their cross sections. Sweetkind and Taylor (2010) presented digital cross-sections, but the data used were pre-1952 drillers' reports from Kunkel and Upson (1960). As such, the data represent wells drilled before 1952 and located largely in the southern portion of the valley. As a result, there are sixty years of additional water well construction information which encompasses over 5,600 new wells, not considered in Sweetkind and Taylor's and other more recent reports.

Extremely Complex Geologic and Hydrogeologic Setting

The structural geology of the Napa Valley area is extremely complex. This Report examines in greater detail the geology below the Napa Valley Floor in relation to groundwater. From a previous reconnaissance study of the entire county (LSCE, 2011a), it was known that several thousand water well drillers' reports existed on the Napa Valley Floor. A majority of these drillers' reports post-dated 1970 and apparently had not been used in more recent published geologic and hydrogeologic reports. Accordingly, a series of geologic cross-sections were recommended to examine the subsurface geology, including derivative maps of alluvium thickness and Sonoma Volcanics rock types. This Report summarizes the work conducted to implement these recommendations.

As part of this study to update the hydrogeologic conceptualization and further evaluate the subsurface geology of the Napa Valley, eight geologic cross-sections have been prepared. During this study, over 1,300 wells were located by using the information on drillers' reports. These were for lithologic control for the development of the cross sections; however, wells were also located outside the cross section areas to evaluate the thickness and nature of the alluvium. The alluvium deposits are represented by the facies of the depositional environment which formed them, including the fluvial facies, the alluvial plain facies formed by alluvial fans of tributary channels, and the sedimentary facies which consist of finer-grained deposits near the southern end of the Napa Valley with some thicker sand and gravel beds interbedded that represent a broader floodplain to deltaic depositional environment.

Concurrent with the process to locate wells and identify the alluvium thickness, the nature of the underlying older Sonoma Volcanic-aged deposits was examined. The initial step was to subtract the alluvium thickness from the surface elevation to yield the elevation of the older deposits at each well site. These elevations were then contoured to produce the structure contour, or elevation map, on the top of the Sonoma Volcanics-aged geologic units. Classification of the Sonoma Volcanics-aged units was problematic due to the wide and varied drillers' descriptions of these units. In most areas, it was necessary to examine all of the located wells to interpret the rock type encountered. It became advantageous to construct working cross sections in different areas to show to scale the various rock types in numerous wells. From these broader patterns, rock types and relationships became apparent.

Cross-sections constructed in this study depict the interpreted subsurface shape and thickness of geologic units and movement of faults based on surface geologic mapping and subsurface lithology from well information. **Figure ES-1** illustrates how geologic interpretations from surface and subsurface geologic information can be visualized to understand the geologic setting and relate subsurface geologic features to surface geology and topography at a cross-section in the vicinity of the City of Napa.

The distribution and quantity of groundwater recharge occurring in Napa County is primarily a function of the geologic units which precipitation encounters, either as rainfall or runoff. Groundwater recharge to the alluvium of the Napa Valley Floor (specifically the Calistoga, St. Helena, Yountville, and Napa Subareas) occurs by infiltration of precipitation, percolation from streams/rivers, and subsurface inflow from the surrounding subareas. The high permeability of the alluvial sediments permits precipitation and surface water to readily infiltrate and recharge groundwater throughout the majority of the Valley. These high permeability soils combined with the large volume of water that flows through the Napa River create the potential for significant recharge to occur.

ES 1.3.2 Groundwater/Surface Water Interaction

The nature of interactions between groundwater and surface water depend largely on the gradient for water flow between groundwater and surface water systems. Water flows from higher elevations to lower elevations. Groundwater elevation contours represent lines of equal groundwater elevation and are independent of ground surface topography. Contours of groundwater elevation provide a snapshot of the direction and relative magnitude of the groundwater flow gradient. Characterizing the relationship between surface water elevations and groundwater elevations is important for understanding the nature of groundwater-surface water communication. In an unconfined groundwater setting, groundwater and surface water will interact and exchange water according to the elevation gradient between these water bodies. The hydrogeologic synthesis and groundwater elevation contours presented in this Report provide the foundation for better understanding this component of the Napa Valley hydrologic system.

The groundwater surface elevation and the estimated stream thalweg elevation data are important components for characterizing the groundwater-surface water relationship in the Napa Valley area. The Spring 2010 contours of equal groundwater elevation are used to provide a snapshot representation of groundwater conditions with which to compare the vertical relationship between the groundwater and surface water (see Section 7). This spatial relationship assists in developing an understanding of the nature of water exchange between the groundwater and surface water systems. This analysis focuses specifically on the degree of connectivity between the Napa River thalweg and the elevation of the regional groundwater surface in the Napa Valley in Spring 2010.

Groundwater/surface water interaction is characterized in this Report by comparing the elevation of surface water to the shallowest adjacent groundwater. Detailed remotely sensed elevation data of the mainstem Napa River and several major tributaries were obtained for this purpose. These LiDAR data provide sub-meter precision elevation data and have been sampled at 3 foot intervals along each watercourse. These data are paired with groundwater level data to evaluate

the interconnectedness of groundwater and surface water, particularly in the main Napa Valley Floor.

Calculated depths to groundwater below the estimated thalweg alignment indicate that for Spring 2010 the interpreted groundwater elevation was above the bottom of the Napa River thalweg. The data suggest areas where a direct connection between the water table and the river may have existed in Spring 2010 and where groundwater has the potential to discharge into the stream channel. In other areas, the depth to groundwater is below the bottom of the Napa River thalweg such that surface flows in the river have the potential to percolate and recharge the groundwater system. The results of this study provide an insight into reaches where a direct connection between the Napa River and the alluvial aquifer are not likely under the conditions documented in Spring 2010. These areas include reaches along the northern boundary of the Napa and MST subareas at the Soda Creek Fault, adjacent to a previously documented area of lower groundwater elevations.

Despite the uncertainty in the data in parts of the valley, depths to groundwater (both measured and calculated) show generally shallow groundwater throughout much of the valley, particularly in the northern end of the valley. Areas where calculated depth to water is negative generally coincide with areas of the valley lacking sufficient monitoring site density. The calculated depths to groundwater appear to be reasonably represented in the Napa Subarea because this area has the greatest density of monitored sites, particularly along the lower elevation eastern edge.

Future expansion of the groundwater/surface water evaluation using more refined spatial representations of the groundwater surface and at different time periods will improve the understanding of the dynamics in this relationship. A definitive evaluation of the relationship between the river and groundwater would require accurate data for the river stage (i.e., elevation of water in the river) and more data about depth to groundwater in areas adjacent to the river at the time for which the depth to groundwater is represented. The product of such an evaluation depends greatly on the ability to accurately interpret groundwater levels throughout the valley. This Report recommends an expanded groundwater monitoring network to provide data for a more refined interpretation of the groundwater surface.

ES 1.3.3 Characterization of Groundwater Recharge

Updating the hydrogeologic conceptualization and characterization of conditions in Napa County involves refining understanding of the hydrologic processes for groundwater storage and movement, particularly in the aquifer system underlying the main Napa Valley Floor. These processes involve many complex pathways at many different time scales. A key County General Plan goal (Napa County, 2008) is to “Conserve, enhance and manage water resources on a

sustainable basis to attempt to ensure that sufficient amounts of water will be available for the uses allowed by this General Plan, for the natural environment, and for future generations." Construction of a water budget, also known as a water balance, is a tool scientists can employ to assess the quantity of groundwater in storage. A conceptual illustration of the components of a water balance in a watershed is shown in **Figure ES-2** (figure from Healy et al., 2007).

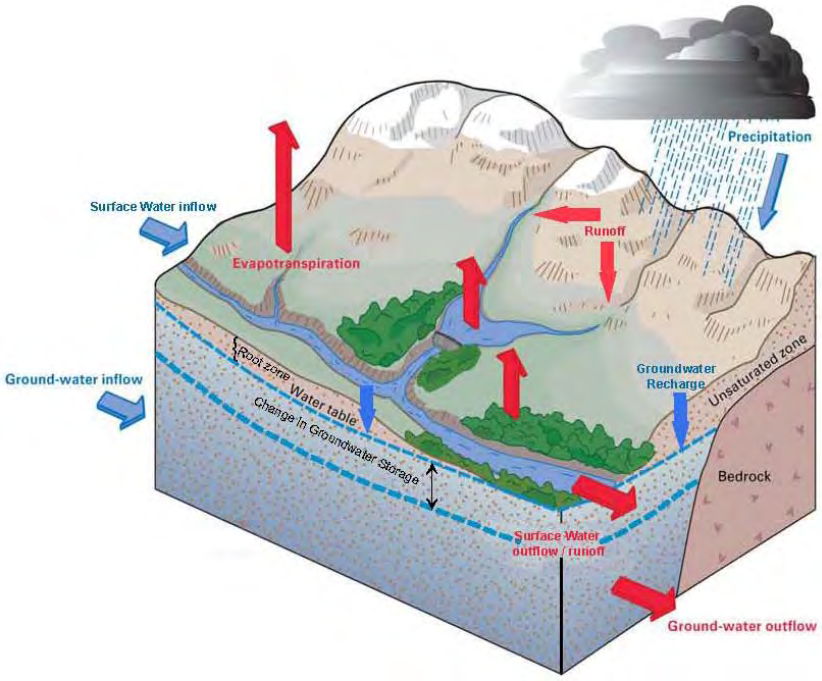


Figure ES-2. Conceptual Diagram of a Watershed Water Balance

A water balance can be used to observe how the quantity of groundwater in storage may vary over time. This tool relies upon a defined accounting unit of volume, for example a groundwater basin or other hydrologic unit of analysis. Measurements of water flowing into and out of the defined unit are used to determine the change in water storage. In the simplest form, the equation for this is:

Inflows – Outflows = Change in Storage

Typical Inflows and Outflows are summarized below (DWR, 2003):

Inflows

- Natural recharge from precipitation;
- Seepage from surface water channels;
- Intentional recharge via ponds, ditches, and injection wells;
- Net recharge of applied water for agricultural and other irrigation uses;
- Unintentional recharge from leaky conveyance pipelines; and
- Subsurface inflows from outside basin boundaries.

Outflows

- Groundwater extraction by wells;
- Groundwater discharge to surface water bodies and springs;
- Evapotranspiration; and
- Subsurface outflow across basin or subbasin boundaries.

Calculating change in storage using data for each inflow and outflow component provides the best approximation of the change in storage. A simple way of estimating the change in storage in a basin is through the determination of the average change in groundwater elevations over the groundwater basin for a period of time. This change in water levels is then multiplied by the area overlying the basin and the average specific yield (in the case of an unconfined aquifer system, or storativity in the case of a confined aquifer system). Change in groundwater levels is best determined over a specific study period that considers different water year types (wet, normal, dry, multiple dry years), but it is common for shorter time periods (e.g., one year's spring to spring groundwater elevations) to be used. This simplistic approach to calculating a change in storage does not provide an indication of the total volume of groundwater storage or the storage available for use. Rather, this computation provides a "snapshot" perspective of short-term trends. The quick calculation should only be considered as an indicator; a more complete groundwater balance evaluation is much preferred (e.g., groundwater flow model). For example, if stresses on the aquifer system induce additional surface water infiltration, the change in groundwater storage may not be apparent (DWR, 2003).

Groundwater recharge is a key component when assessing the water budget of a groundwater basin. Understanding recharge and other fluxes is important in evaluating groundwater conditions and understanding the effects of land development on groundwater resources. This study included characterizing groundwater recharge with an emphasis on the Napa Valley.

The groundwater recharge process begins in the shallow soil column when precipitation or applied water infiltrates below the ground surface. At shallow depths within the plant root-zone water is consumed by plant evapotranspiration and can also be stored as soil moisture. When soil moisture exceeds its holding capacity, water percolates below the root-zone as groundwater recharge. If plant consumptive needs are met and soil moisture storage is below its holding capacity, infiltrated water is stored within the root zone.

Root-Zone Water Balance

In this Report, a mass balance method is used to estimate regional and local recharge. Groundwater recharge can be estimated based on a mass balance analysis of the root zone to estimate the amount of groundwater recharge occurring below the root zone. Flux terms for the "natural" root-zone water balance include precipitation (P), runoff (RO), evapotranspiration (ET), recharge (R), and change in soil moisture storage (ΔS). The natural root-zone water balance expression can be written as:

$$P - RO - ET - R = \Delta S \qquad [1]$$

Figure ES-3 illustrates the components of the root-zone water balance.

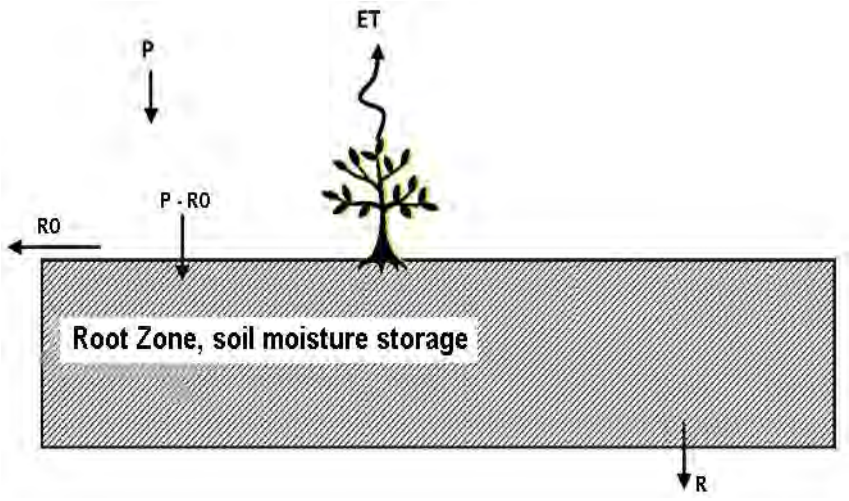


Figure ES-3. Conceptual Diagram of the Water Balance within the Root Zone

Infiltration is defined as precipitation minus runoff and is implicit in the root-zone water balance expression [1]. The natural root-zone water balance can also be expressed to solve for recharge as $R = P - RO - ET - \Delta S$. Although this expression shows a solution for natural groundwater recharge with respect to the root-zone water balance, the estimations of groundwater recharge derived as part of this study are based on methods of calculating recharge from physical

processes within the root zone. Instead, this analysis calculates natural groundwater recharge using three physical processes models as a function of ending soil moisture storage and soil texture parameters. Change in soil moisture storage (ΔS) becomes the closing term. A spreadsheet, referred to as the root-zone water balance model, was developed on monthly time-steps to calculate this natural root-zone water balance in the Napa Valley area and is described in this Report.

Mass balance recharge estimates are presented for the Napa River watershed and major tributary watersheds using a range of available data. Available records for streamflow, precipitation, land use, and vegetative cover throughout these watersheds have been used to develop spatially-distributed estimates of annual hydrologic inputs and outputs in order to solve for the volume of groundwater recharge. This Report describes the quantification of: the distribution of precipitation across the land surface, the amount of water returned to the atmosphere by evapotranspiration, and the hydraulic properties of soil and alluvial materials through which water must infiltrate to reach groundwater. Recharge estimates developed through the mass balance approach are evaluated using a sensitivity analysis to determine the degree to which any individual or set of inputs affects the estimate. The results of the mass balance recharge estimates are summarized in **Table ES-1**.

Table ES-1. Summary of Water Balance Model Results

	Average Annual (acre-feet)					Range (acre-feet)	Recharge (% of Precip.)
Watershed	**Precip.**	**Outflow**	**Infilt.**	**ET**	**Recharge**	**Recharge**	**Recharge**
Napa River near Napa	**418,500**	**146,800**	**271,700**	**201,900**	**70,600**	**8,300 - 185,900**	**17%**
- Conn Creek	98,200	24,600	73,600	52,200	21,100	4,300 - 40,700	21%
- Dry Creek	33,000	14,200	18,700	16,400	2,000	500 - 6,300	6%
- Napa River at St. Helena	161,400	67,000	94,400	72,500	22,000	2,500 - 60,900	14%
-- Napa River at Calistoga	54,200	23,600	30,600	19,700	10,500	2,000 - 17,200	19%
Milliken Creek	**33,000**	**16,800**	**16,200**	**13,500**	**2,500**	**100 - 7,100**	**8%**
Tulucay Creek	**19,500**	**9,100**	**10,400**	**9,500**	**1,000**	**100 - 2,300**	**5%**
Redwood Creek	**19,300**	**7,800**	**11,500**	**9,500**	**1,900**	**400 - 5,000**	**10%**
Napa Creek at Napa	**32,100**	**14,800**	**17,300**	**13,700**	**3,600**	**600 - 6,900**	**11%**

Results from the recharge analysis showed that recharge (on a % of precipitation basis) within the Napa River near Napa watershed groundwater recharge is higher in the Conn Creek

watershed in the northern portion of the watershed above Calistoga. Precipitation also is higher in these areas, which may contribute to higher groundwater recharge amounts in this area. Estimates from the root-zone water balance model indicate that the Tulucay Creek watershed has the lowest amount of groundwater recharge. This may be because approximately 23 percent of the Tulucay Creek watershed is represented by urban land uses, the highest of all watersheds analyzed.

Potential explanations for the spatial variability of recharge are presented, including differences in watershed soils and geology, slope, and land uses. Previous work by LSCE (2011) analyzed geology and slope in Napa County and developed a map showing areas of highest recharge potential. This map is presented in this Report and illustrates identified geologic units with the greatest recharge potential and areas where ground surface slopes exceed 30 degrees. This Report summarizes the land area for the geologic units of greatest recharge potential by watershed.

ES 1.4 Groundwater Level Monitoring and Recommendations

An important element in Napa County's Comprehensive Groundwater Monitoring Program is an evaluation of the construction information for wells with water level monitoring data. Understanding the exposure of monitored wells to aquifers in their vicinity is critical to analyzing the data collected from those wells. The two most important pieces of construction information for monitored wells, in addition to accurate location information, are information about the geologic material encountered when the well was drilled and a record of the depth of the well screens. These things allow the data collected from a well to be placed in a larger hydrogeologic context, enabling a better understanding of subsurface conditions. This Report presents the results of an inventory of wells in Napa County with any record of water level data. Findings from the inventory are presented in light of results from the updated hydrogeologic characterization and provide information to support the refinement and expansion of on-going monitoring efforts.

Construction records for current and historic groundwater level monitoring wells have been reviewed and compiled. In cases where construction information was incomplete or missing, efforts were made to locate missing information. Construction details were also cross referenced with results from the current hydrogeologic characterization of geologic and aquifer units in order to identify the aquifers in which wells are completed. This Report presents the results of that inventory of water level monitoring wells.

Due to the large proportion of wells lacking complete construction information, efforts to locate construction information for monitored wells focused on the high priority subareas in the Napa

Valley Floor and the Carneros Subarea. Additional efforts were made to identify monitored wells adjacent to the Napa River to evaluate potential groundwater/surface water monitoring sites.

Although this Report focuses on the extent of groundwater level monitoring in Napa County, a summary review of current groundwater quality monitoring sites has been conducted for the Napa County Groundwater Monitoring Plan 2013. That review found 177 sites in Napa County, across all monitoring networks, with groundwater quality data collected since 2008 (LSCE, 2013). The current monitoring networks for groundwater levels and groundwater quality differ according to monitoring entity, data collection frequency, and monitoring goals. Given these differences, a similar inventory of the groundwater quality monitoring networks is advisable in light of the County's intention to increase its capacity to consider groundwater quality in future groundwater resources management decisions.

The proposed inventory should include an effort to locate construction information and identify aquifers encountered by sites monitored for groundwater quality. The updated hydrogeologic conceptualization presented here as well as previously published studies would guide the inventory. Goals of the proposed inventory include an evaluation of the extent and quality of data provided by currently monitored groundwater quality sites and historically monitored sites with the potential for reactivation. The proposed inventory should also consider Napa County's groundwater quality monitoring needs and develop proposals to meet those needs with data from currently monitored wells, where feasible, or wells added to the Napa County monitoring network.

ES 1.4.1 Recommendations to Expand Groundwater Monitoring Well Network

Figure ES-4 illustrates the distribution of current groundwater level monitoring locations, which is primarily located in the Napa Valley Floor-Napa and MST Subareas. Very little groundwater level monitoring is currently conducted elsewhere in Napa County outside these two subareas. A few scattered locations of groundwater level monitoring occur in the Berryessa, Pope Valley, the southern portion of the Central Interior Valleys, Jameson/American Canyon, and in the NVF-Calistoga, NVF-St. Helena, and NVF-Yountville Subareas. Groundwater level monitoring is not currently conducted in the Carneros, Livermore Ranch, Angwin, Southern Interior Valleys, and Western Mountains Subareas. Section 9 of this Report summarizes the number of wells in each subarea that are currently monitored for groundwater levels. Groundwater level measurements have been recorded at a total of 87 sites since 2011. Of these sites where groundwater levels are measured, some type of well construction information (depth and/or perforated interval(s)) is available for 67 sites (41 non-regulated sites and 26 regulated sites). Most current groundwater level monitoring occurs on a semi-annual frequency.

A preliminary ranking and priorities for improving or expanding groundwater level monitoring were prepared for each county subarea. Six subareas are given a relatively higher priority for improving the groundwater level monitoring network based on factors of current population and groundwater utilization relative to other parts of the county, and/or the need to improve understanding of groundwater/surface water interactions. Some factors are given greater consideration in areas that currently use more groundwater than other areas. These areas include:

- NVF-Calistoga,
- NVF-St. Helena,
- NVF-Yountville,
- NVF- MST,
- NVF-Napa, and
- Carneros Subareas

The monitoring network gaps in these six subareas might be addressed by:

1) Investigating the potential to restart monitoring where historical records are available but monitoring was discontinued;
2) Identifying existing wells of suitable construction that might be volunteered for inclusion through County and GRAC education and outreach efforts (this may include wells that are already being monitored for groundwater quality); and
3) Constructing new dedicated monitoring wells if suitable existing wells either do not exist in the area of interest or are otherwise not available.

Monitoring in other subareas with relatively medium to lower priorities is suggested to be addressed with volunteered wells. The Napa County CASGEM Network Plan submitted to DWR in September 2011 (LSCE, 2011b) also describes the County's intent to include at least one additional monitoring well in the Pope Valley and Berryessa Valley Groundwater Basins.

The County will conduct additional public outreach to inform more private well owners of the value of understanding the groundwater resources in the County and to encourage their voluntary participation in the Comprehensive Groundwater Monitoring Program and/or CASGEM program (LSCE, 2013). The County anticipates additional wells to be included in the CASGEM program over the coming years. Wells will be included based upon input from the County's GRAC and in concert with their work to meet the objectives of the County's Comprehensive Groundwater Monitoring Program and the CASGEM program.

For each county subarea, this Report describes the existing groundwater monitoring sites, provides recommendations for the number and location of additional monitoring areas, and describes the key groundwater level monitoring objectives to be addressed. Altogether, it is recommended that approximately six groundwater/surface water monitoring sites for purposes of

evaluating groundwater/surface water interactions and about 18 other areas of interest be added to the network (**Figure ES-4**).

The six proposed groundwater monitoring sites are located along the main Napa Valley Floor from the City of Napa north to St. Helena adjacent to the Napa River system (**Figure ES-4**). These facilities are planned to be located near to existing stream gaging stations and/or near areas where stream monitoring can also be conducted. The proposed groundwater monitoring facilities are also being sited, where possible, adjacent to existing groundwater monitoring facilities (i.e., typically water supply wells constructed to greater depths in the aquifer system). The proposed monitoring wells will enable focused data collection regarding groundwater elevations and water quality to identify and characterize interactions with surface water.

ES 1.5 Additional Recommendations

This study led to a broader awareness of the available geologic data, including drillers' reports, that were used to update the hydrogeologic conceptualization of Napa Valley Floor. This work also identified factors related to future assessment of groundwater availability. Spatial data coverage for stream gaging stations and groundwater level monitoring was good for some County subareas; however, for other subareas, additional stream gaging locations and monitoring network enhancements are needed. It was also learned better data are needed to develop aquifer characteristics that more accurately represent aquifers developed for groundwater utilization. Recommendations are presented to enhance and expand countywide monitoring to facilitate understanding of groundwater availability and integrated regional water management and planning efforts. Some of these recommendations, particularly recommendations related to the Carneros, Jameson/American Canyon, and Napa River Marshes Subareas, were previously discussed in reconnaissance work for the County's Comprehensive Groundwater Monitoring Program (LSCE, 2011). The scope of the present study did not include the latter two subareas, so these recommendations still apply. The present study did attempt to develop a geologic cross-section in the Carneros Subarea and found geologic information to be lacking.

ES 1.5.1 Carneros Subarea Hydrogeology

Limited data are available that describe the hydrogeologic setting of the Carneros Subarea. The available data suggest that groundwater resources are limited due to the generally low yielding nature of the formations in this area and poor groundwater quality at some location (LSCE, 2011a). Future planning decisions require knowledge of current groundwater conditions and the possible impacts that may result from additional pumping. A complete analysis of the Carneros Subarea is recommended, including:

- Monitoring groundwater levels[1];
- Monitoring groundwater quality[1];
- Collection and interpretation of geologic data (primarily from well drillers' reports)
- Estimation of groundwater recharge using both mass balance;
- Determination of the extent and properties of aquifer materials; and
- Investigation of the influence of natural and induced hydrologic stresses occurring in neighboring subareas.

Since stream gaging information are lacking in the south part of the county, it is recommended that the focus be on enhancing the groundwater monitoring network (as discussed below) and development of additional geologic data, as feasible.

ES 1.5.2 Hydrogeology and Saltwater Intrusion Potential for the Jameson/American Canyon and Napa River Marshes Subareas

Similar to the Carneros Subarea, limited data are available for the Jameson/American Canyons and Napa River Marshes Subareas which make up the southern County area. The two main issues facing this area are potential saltwater intrusion and the possibility that current water resources will not be sufficient to meet future demand. To establish current conditions and obtain information necessary for future development planning, further analysis is recommended that includes:

- Monitoring groundwater levels;
- Monitoring groundwater quality;
- Collection and interpretation of geologic data (primarily from well drillers' reports);
- Analysis of streamflow and precipitation;
- Estimation of recharge and discharge using both mass balance and streamflow infiltration methods; and
- Determination of the extent and properties of aquifer materials.

The current lack of groundwater data makes it difficult to determine the source and distribution of salinity in the southern County area with any certainty. A series of multi-level monitoring well clusters installed stepping south from the City of Napa toward San Pablo Bay would help in determining the geology of the Napa River Marsh Subarea and distribution of high salinity groundwater. This further subsurface exploration and characterization of the aquifer system, in conjunction with efforts to estimate subsurface outflow from the Napa Valley, would also help determine if freshwater within the Napa River Marshes Subarea could possibly be used to sustain increasing demand in the Jameson/American Canyon Subarea.

[1] Actions to implement additional groundwater level and quality monitoring are underway (LSCE, 2013).

Aquifer Testing

As explained in this Report, the distribution of the hydraulic conductivities in the Napa Valley as presented by Faye (1973) was based on data recorded on historical drillers' reports. During the current study, it became evident, based on the approximately 1,300 reports reviewed, that most of the "test" data are insufficient to adequately determine or estimate aquifer characteristics, since most of these data were recorded during airlift operations rather than a pumping test. Currently, test methods accepted in the County's Well and Groundwater Ordinance allow bailing, airlifting, pumping, or any manner of testing generally acceptable within the well drilling industry to determine well yield. Recommendations for modifying the Napa County's Well and Groundwater Ordinance (Title 13, Chapter 13.04) have been proposed to improve the quality of data received by Environmental Management concerning reporting of well yield (LSCE, 2011). These recommendations included removal of bailing and airlifting as acceptable methods; pumping is recommended to gather the appropriate data to reliably determine well yield, particularly in areas where such information along with aquifer characteristics is determined to be important to accomplish other County groundwater objectives.

Stream Gaging Stations

One of the major limitations in this study is the spatial and temporal availability of streamflow gage data. The limited availability of data from gaged streamflow locations precludes developing a more spatially distributed estimate of recharge using this method. Because streamflow as measured at a gage is an aggregate for the upstream drainage area, infiltration is assumed to be uniform throughout each gaged watershed and across all land use categories.

In order to estimate streamflow from ungaged watersheds, a rainfall-runoff model could be developed and calibrated with records from gaged watersheds. A rainfall-runoff model may also help improve the spatial resolution of infiltration within gaged watersheds. Several different platforms are available for these types of models.

The Putah Creek watershed represents approximately 46 percent of Napa County and is an ungaged watershed; however, it may be possible to estimate runoff from this watershed by calculating inflow to Lake Berryessa. Reservoir inflow calculations require close quality control of inputs and may not be possible if flood control releases from Monticello Dam are not accurate. If it is possible to calculate inflow to Lake Berryessa, this time-series could be used as the outflow component in the water balance model to estimate groundwater recharge for this area of the county.

ES 1.5.3 Future Groundwater Modeling Efforts

As described earlier in this Report, a groundwater flow model was developed for the Napa River watershed which was generally conceptualized as a large basin of impermeable rock overlain in three distinct areas by more permeable units (DHI, 2006a). The three areas that were the focus of the groundwater model were the north Napa Valley area and the MST and Carneros Subareas. The groundwater model encompasses the Napa River watershed and consists of two layers. The upper layer was designated as being unconfined and the lower layer was designated as confined. Each of the three modeled areas was represented as a separate water-producing geologic unit. The geologic unit that was conceptualized as the primary source for groundwater in the north Napa Valley area was the alluvium. Aquifer parameters and their distribution were based on previous work presented in Faye (1973), and extrapolated to the rest of the Napa Valley Floor to the south.

A model is a tool that can help facilitate the examination of water resources management scenarios, including the effects of climate change and other stresses on surface and groundwater resources. Large regional models can be especially useful tools to examine complicated scenarios. As described in this Report, the geologic and hydrogeologic setting in Napa County and specifically the Napa Valley Floor is extremely complex. The updated hydrogeologic conceptualization presented herein shows that the subsurface is so complex that the current two-layer model for the north Napa Valley area, which focuses on the alluvium with unconfined and semi-confined aquifer characteristics, needs significant refinement for future use and to improve the models' predicative utility. Such refinement includes, but is not limited to, incorporation of the updated physical hydrogeologic conceptualization in the model structure and consideration of revised aquifer parameters and/or sensitivity analyses of parameters until such parameters can be refined through proper testing.

1 INTRODUCTION

Groundwater and surface water are highly important natural resources in Napa County. Currently, municipal and private stakeholders are actively engaged in assessing the reliability of current and future demands and supplies. Important sources of water include both groundwater and surface water of good quality and quantity, to meet future urban, rural, and agricultural water demands. Similar to other areas in California, businesses and residents of Napa County face many water-related challenges. To address these challenges, long-term, systematic monitoring programs are essential to provide data that allow for improved evaluation of water resources conditions and to facilitate effective water resources planning. Establishment of a groundwater and surface water monitoring network results in the collection of data necessary to distinguish long-term trends from short-term fluctuations, anticipate unintended consequences due to current and historical land uses, identify emerging issues, and design appropriate water resources planning and management strategies.

1.1 Background

In 2009, Napa County embarked on a countywide project referred to as the "Comprehensive Groundwater Monitoring Program, Data Review, and Policy Recommendations for Napa County's Groundwater Resources" (Comprehensive Groundwater Monitoring Program), to meet identified action items in the 2008 General Plan update (Napa County, 2008). The program emphasizes developing a sound understanding of groundwater conditions and implementing an expanded groundwater monitoring and data management program as a foundation for future coordinated, integrated water resources planning and dissemination of water resources information. The program covers the continuation and refinement of countywide groundwater level and quality monitoring efforts (including many basins, subbasins and/or subareas throughout the county) for the purpose of understanding groundwater conditions (i.e., seasonal and long-term groundwater level trends and also quality trends) and availability. This information is critical to enable integrated water resources planning and the dissemination of water resources information to the public and state and local decision-makers. Napa County's combined efforts through the Comprehensive Groundwater Monitoring Program along with the related AB 303 Public Outreach Project on groundwater (CCP, 2010) and the efforts of the Watershed Information Center and Conservancy (WICC) of Napa County create a foundation for the County's continued efforts to increase public outreach and participation in water resources understanding, planning, and management. Napa County's Comprehensive Groundwater Monitoring Program involved many tasks that led to the preparation of five technical memorandums and a report on Napa County Groundwater Conditions and Groundwater Monitoring Recommendations (LSCE, 2011a). This report and the other related documents can be found at: http://www.countyofnapa.org/bos/grac/.

1.2 Groundwater Resources Advisory Committee

On June 28, 2011, the County Board of Supervisors adopted a resolution establishing a Groundwater Resources Advisory Committee (GRAC). Two of the tasks assigned to the GRAC include: 1) assisting with the synthesis of the existing groundwater information and identifying critical data needs; and 2) providing input on the furtherance of the ongoing countywide groundwater monitoring program. During the implementation of the study discussed herein, input from this committee was coordinated to optimize additional groundwater monitoring locations that serve to meet the objectives of the County's Comprehensive Groundwater Monitoring Program and also the California Statewide Groundwater Elevation Monitoring (CASGEM) program, which is a subset of the countywide groundwater monitoring program.

1.3 Purpose

The purpose of this Napa County Updated Hydrogeologic Conceptualization and Characterization of Conditions Report (Report) is to describe the work conducted by Luhdorff and Scalmanini, Consulting Engineers (LSCE) together with MBK Engineers (MBK) on behalf of the County to implement a number of the recommendations pertaining to the County's Comprehensive Groundwater Monitoring Program, including:

1. Prepare an updated hydrogeologic conceptualization and characterization of conditions in various areas of Napa County;
2. Analyze the potential for surface water/groundwater interactions;
3. Refine and further characterize areas of the greatest recharge potential; and
4. Link well construction information to groundwater level monitoring data, and provide groundwater monitoring recommendations.

Forthcoming in a separate document, the County is also developing an approach to determine whether there are locations where groundwater pumping near a surface water course (such as might occur for a proposed project) would be anticipated to effect groundwater discharge to the surface water available for endangered species. And, conversely, whether there are locations where groundwater pumping would not have such an effect. The approach being developed is being informed by the updated hydrogeologic conceptualization of conditions (as can be identified with existing data), including the accompanying groundwater monitoring recommendations, summarized in this Report.

1.3.1 Updated Hydrogeologic Conceptualization

Understanding the hydrogeology of Napa County is essential to determine how much water is available and to what extent it can be sustainably produced. Previous hydrogeologic studies have focused on the Milliken-Sarco-Tulucay (MST) Subarea and northern portion of the Napa Valley without much attention to the other areas within the county. With the exception of the Farrar and Metzger (2003) study, which looked at the MST, all of these studies are more than 30 years old. Since these studies, hundreds of new wells have been drilled to greater depths than previously reached, supplying a potential abundance of new data. Due in part to the scarcity of hydrogeologic data available for the majority of Napa County, data collection and analysis need to be prioritized; the highest priority needs are presented below.

Published hydrogeologic studies of the Napa County have been largely based on pre-1970 water well drillers' reports and focused on the higher yielding Quaternary alluvium deposits of Napa Valley (Kunkel and Upson, 1960; Faye, 1973). Most previous hydrogeologic cross sections have been constructed in the southern portion of the valley near and to the east of the City of Napa (Kunkel and Upson, 1960; Sweetkind and Taylor, 2010; Farrar and Metzger 2003). The northern valley has been characterized by alluvium thickness maps (Faye, 1973) with little attention paid to the older deposits and Sonoma Volcanics.

Since the Kunkel and Upson study, plate tectonics theory has been introduced, which significantly expanded the understanding of the relationship between individual geologic units within the County and the structures (faults, folds, and fractures) that accompany these relationships. Also, a large number of new wells (and therefore new well logs) have been added to the Valley, which expanded the breadth and depth of the aquifer materials explored and developed for groundwater production.

Groundwater/surface water interaction is characterized in this Report by comparing the elevation of surface water to the shallowest adjacent groundwater. Detailed remotely sensed elevation data of the mainstem Napa River and several major tributaries have been obtained for this purpose. These LiDAR data provide sub-meter precision elevation data and have been sampled at 3 foot intervals along each watercourse. These data are paired with groundwater level data to evaluate the interconnectedness of groundwater and surface water, particularly in the main Napa Valley Floor.

1.3.2 Characterization of Groundwater Recharge

Another important feature of the updated hydrogeologic conceptualization presented in this Report is the development of improved characterization of groundwater recharge in the areas of greatest groundwater development, with an emphasis on Napa Valley. Understanding the

volume of and mechanisms driving groundwater recharge in the county is essential in determining where and how much groundwater can be produced without incurring negative impacts (LSCE, 2011a). Currently, evaluation of recharge mechanisms and volumes within Napa County has been limited to the Napa Valley (Faye, 1973) and the MST Subarea (Johnson, 1977; Farrar and Metzger, 2003).

The high permeability of the alluvial sediments in the Napa Valley permits precipitation and surface water to readily infiltrate and recharge groundwater throughout the majority of the valley. These high permeability soils combined with the large volume of water that flows through the Napa River create the potential for significant recharge to occur under the hydrologic circumstances and hydraulic gradient that allow for recharge from the river to groundwater to occur.

In this Report, mass balance and streamflow infiltration methods are used to estimate regional and local recharge. Mass balance recharge estimates are presented for the Napa River watershed and major tributary watersheds using a range of available data. Available records for streamflow, precipitation, land use, and vegetative cover throughout these watersheds have been used to develop spatially-distributed estimates of annual hydrologic inputs and outputs in order to solve for the volume of groundwater recharge. This Report describes the quantification of: the distribution of precipitation across the land surface, the amount of water returned to the atmosphere by evapotranspiration, and the hydraulic properties of soil and alluvial materials through which water must infiltrate to reach groundwater. Recharge estimates developed through the mass balance approach are evaluated using a sensitivity analysis to determine the degree to which any individual or set of inputs affects the estimate.

1.3.3 Groundwater Level Monitoring and Recommendations

As part of the updated hydrogeologic characterization, existing monitoring well construction data from all available public sources were reviewed to determine the distribution of aquifer-specific monitoring data in Napa Valley. This effort addresses recommendations of the Comprehensive Groundwater Management Program to identify and fill data gaps that will allow for analysis of groundwater occurrence and flow as a more robust understanding of the extent of groundwater resources in the county is developed. A major component of this work has been to identify construction information for previously monitored wells in Napa Valley.

Groundwater level monitoring needs identified through the Comprehensive Groundwater Management Program include improved spatial distribution of groundwater level monitoring, additional characterization of subsurface geologic conditions in each subarea to identify aquifer characteristics, further examination of well construction information to define which portion of the aquifer system is represented by water levels measured in the currently monitored wells (and

in many cases to link construction information to the monitored wells), and improve the understanding of surface water/groundwater interactions and relationships.

1.4 Report Organization

The results of this work provide the updated physical hydrogeologic conceptualization and characterization necessary to ensure that future groundwater evaluations consider the structure and hydrologic mechanisms, including recharge to and discharge from groundwater basins and mountain recharge areas that govern groundwater conditions. This Report addresses the following key components:

1. Updated hydrogeologic conceptualization and characterization of conditions in various areas of Napa County;
2. Potential for surface water/groundwater interactions;
3. Characterization of areas of the greatest recharge potential; and
4. Description of the current groundwater monitoring level monitoring network and groundwater monitoring recommendations.

This Report includes the following sections:

Section 2: Regional Geology and Previous Studies

- DWR Basins/Subbasins and County Subareas
- Regional Geologic Setting
- Significant Previous Studies

Section 3: Surficial Geology

- Mesozoic Rocks
- Late Tertiary Volcanic and Sedimentary Rocks

Section 4: Structural Geology

- Late Tertiary Deformation
- Quaternary Faulting

Section 5: Subsurface Geology

- Subsurface Information
- Methodology

Section 6: Hydrogeology

- Alluvium
- Sonoma Volcanics and Tertiary Sediments

Section 7. Surface Water/Groundwater Interactions

- Napa Valley Groundwater Levels
- Stream Thalweg Mapping

- Surface Water/Groundwater Interactions in Napa Valley

Section 8. Groundwater Recharge

- Estimating Recharge
- Physical Processes
- Data Development
- Results and Summary
- Sensitivity Analysis
- Extrapolation to Remaining Areas
- Future Considerations
- Considerations Related to Overall Water Balance

Section 9. Supplemental Groundwater Monitoring in High Priority Subareas

- Available Location and Construction Information for Groundwater Level Monitoring Sites
- Completion of Groundwater Level Monitoring Sites Relative to Aquifer System and Geologic Units
- Recommendations for Napa County Groundwater Level Monitoring Network Expansion

Section 10. Recommendations

- Carneros Subarea Hydrogeology
- Hydrogeology and Saltwater Intrusion Potential for Jameson/American Canyon and Napa River Marshes Subareas
- Aquifer Testing
- Stream Gaging
- Groundwater Monitoring Network
- Future Groundwater Modeling Efforts

2 REGIONAL GEOLOGY AND PREVIOUS STUDIES

2.1 DWR Basins/Subbasins and County Subareas

DWR has identified the major groundwater basins and subbasins in and around Napa County; these include the Napa-Sonoma Valley (which in Napa County includes the Napa Valley and Napa-Sonoma Lowlands Subbasins), Berryessa Valley, Pope Valley, and a very small part of the Suisun-Fairfield Valley Groundwater Basins (**Figure 2-1**). These basins and subbasins are generally defined based on boundaries to groundwater flow and the presence of water-bearing geologic units. These groundwater basins defined by DWR are not confined within county boundaries, and DWR-designated "basin" or "subbasin" designations do not cover all of Napa County.

Groundwater conditions outside of the DWR-designated areas are also very important in Napa County. An example of such an area is the MST area, a locally identified groundwater deficient area. For purposes of local planning, understanding, and studies, the County has been subdivided into a series of groundwater subareas (**Figure 2-2**). These subareas were delineated based on the main watersheds, groundwater basins, and the County's environmental resource planning areas. These subareas include the Knoxville, Livermore Ranch, Pope Valley, Berryessa, Angwin, Central Interior Valleys, Eastern Mountains, Southern Interior Valleys, Jameson/American Canyon, Napa River Marshes, Carneros, Western Mountains Subareas and five Napa Valley Floor Subareas (Calistoga, St. Helena, Yountville, Napa, and MST). The County subarea nomenclature is sometimes referred to in this study.

2.2 Regional Setting

The Napa Valley study area is located in the southern-central Coast Range Province north of the San Francisco Bay region. This region of the Coast Range is characterized by northwest trending low mountainous ridges separated by intervening stream valleys. The Napa Valley is a relatively narrow, flat-floored stream valley drained by the Napa River. The valley floor descends from elevations of about 420 feet at the northwest end to about sea level at the southern end.

The Napa Valley is bound by the north, east, and west by mountainous areas. The mountains to the north are dominated by Mount St. Helena at a height of 4,343 feet. The lower mountainous area to the east of the Valley is the Howell Mountains declining from 2,889 feet southward through lower elevations at 2,037 feet above Stag's Leap, 1,877 feet at Mount George, and 1,630 feet at Sugarloaf south of the MST area. To the west of Napa Valley, the Mayacamas Mountains decline from peaks to 2,200 feet in the north, to about 1,500 feet northwest of Napa. Farther

south, the mountainous area declines to elevations of 200 to 100 feet, then disappears beneath the plains of the Carneros area that borders the San Pablo Bay.

2.3 Napa Valley Floor Geologic Subareas

The Napa Valley Floor is informally divided into four areas for this Report. The upper valley extends from the northern end of the valley just north of the town of St. Helena. This area is about nine miles long and about one mile or less in width. Except for near St. Helena, the upper valley was not examined for this study.

Calistoga to St. Helena – Upper Valley

The upper valley area encompasses the County's Calistoga subarea and the northern mile of the County's St. Helena subarea. The upper valley area was defined by the width of the valley floor and the nature of the geologic units found beneath the valley floor during the course of this study.

St. Helena to Oakville – Middle Valley

The middle valley extends from St. Helena to the town of Oakville. This area is about seven miles long, and the Valley Floor widens to about two miles at the north to about 3 ½ miles at the south. The middle valley area corresponds roughly to the County's St. Helena Subarea, except as noted above.

Yountville Narrows

The next area is termed the Yountville Narrows, which extends about five miles to Ragatz Lane, about half-way between Yountville and Oak Knoll. This area is characterized by numerous low knobs and hills of older geologic units that rise like islands above the stream valley. The central valley floor narrows to less than a mile. The entire valley encompasses the County's Napa Subarea. From the main mountainous side slopes, the total valley width ranges up to about three miles.

Napa to Suscol – Lower Valley

The lower valley extends about ten miles to the south beyond the City of Napa and trends more southerly to Suscol. The valley floor widens to about three miles north of Napa and then narrows to about 2 miles. At the southern end at Suscol, the valley floor narrows to about 2,000 feet constricted by older geologic units.

Lower Valley

To the east of the City of Napa, there is a unique feature of a low elevation nearly circular ring around a central low highland. The area is drained by the tributary Milliken, Sarco, and Tulucay Creeks headed on the higher mountainous area to the north, east, and south. This area is termed the MST area from the contraction of the tributary creeks. The MST area has been extensively studied previously by others and was not examined further for this study.

South of Suscol the Napa Valley merges with the marshland and tidal flats of the County's Napa River Marshes Subarea. To the north of the marshlands occurs the County's Carneros Subarea, a low southward sloping plain. Both of these areas (Carneros and Napa River Marshes) were not extensively examined for this study. The County's Jameson/American Canyon Subarea lies to the east of the Napa River marshes and was not examined for this study.

2.3.1 Major Geologic Units

In the Napa Valley area, the geologic units are divisible into two broad categories based on geologic age, degree of lithification (i.e., the hardness or rock-like nature), and the amount of deformation (i.e., deformed by folding and faulting). These two categories are Mesozoic (older than 63 million years (m.y.)) rocks and Cenozoic (younger than 63 m.y.) rocks and unconsolidated deposits.

The Mesozoic rocks are considered the bedrock in the area as they are very old, well lithified, and highly deformed resulting in limited groundwater in fractures (crack-like openings in the rocks). The Mesozoic rocks are divisible into two main groups: the Franciscan Complex and the Great Valley Complex. The Mesozoic rocks occur beneath all of the Napa Valley, but these rocks are most widely exposed at the surface in the adjacent mountain areas. Beneath the Napa Valley and the San Pablo Bay to the south, the Mesozoic rocks are covered by great thicknesses (possibly several thousands of feet) of younger rocks and deposits. The sole exception to this is a small area in the eastern Yountville Narrows where the Mesozoic rocks are exposed by deformation uplift. The Mesozoic rocks will be described further in a later section.

The Cenozoic geologic units are divisible into two main groups: 1) the older Tertiary (post 63 m.y. – 2.5 m.y.) volcanic and sedimentary rocks, 2) and the Quaternary (2.5 m.y. – present) sedimentary deposits. The Tertiary rocks include a group of the oldest Tertiary sedimentary rocks which occur south of the Napa Valley below the San Pablo Bay, some small exposures near the south end of the Mayacamas Mountains, and south of the Howell Mountains. These rocks are largely low-groundwater yielding, of limited extent, and outside the Napa Valley study area.

The main Tertiary rocks in the Napa Valley area are of the youngest age, largely Pliocene (5 m.y to 2.5 m.y). These consist of volcanic rocks and sedimentary rocks which are interfingered and interbedded. The volcanic rocks are composed of a complex sequence, including lava flows and fine-grained volcanic ejecta composed of ash and flow tuffs. Variations in mineral composition, types of volcanic processes, and the location of eruption sites lead to complex relationships in the volcanic deposits which make surface mapping difficult.

The Tertiary volcanic rocks have been termed the Sonoma Volcanics; these rocks extend across much of the Napa Valley area and across much of Sonoma County to the west. In the Napa Valley area, the Sonoma Volcanics are exposed at the surface over large areas around the upper valley, across large areas in the Howell Mountains to the east, and at more limited areas along the west margin of the Napa Valley. Beneath the Napa Valley Floor, the Sonoma Volcanics occur largely buried beneath younger geologic units. In the Yountville Narrows, there are many small knobs of Sonoma Volcanics. In the MST area, the Sonoma Volcanics occur in the surrounding mountains, the central upland, and beneath the entire area.

The Tertiary sedimentary rocks are more limited in surface exposures and commonly referred to as the Huichica Formation. North of Conn Creek, these rocks occur in a small area on the Napa Valley Floor margin and a larger area occurs in the adjacent mountainous area. In the MST area, Tertiary sedimentary rocks occur on the north margin and lap into the Napa Valley Floor margin. A large area of Tertiary sedimentary rocks is exposed across most of the Carneros area to the southwest of the Napa Valley. The relationship between these three areas and to the Sonoma Volcanics is not entirely clear. The possible presence and extent of the Tertiary sedimentary rocks below the Napa Valley Floor were examined in this study.

The Sonoma Volcanics units which were formed at high temperatures as (e.g., lava flows and flow tuffs) appear to be well lithified, Sonoma Volcanics units formed at lower temperatures, such as landslide tuffs, ash falls, and volcanic-sedimentary interbeds appear to be weakly to moderately lithified. The thicker Tertiary sedimentary rocks also appear to be moderately to well lithified. Both the Sonoma Volcanics and the Tertiary sedimentary rocks are strongly deformed as evidenced by the commonality of steeply dipping beds, folding, and faulting.

The Quaternary (post 2.5 m.y) sedimentary deposits collectively termed alluvium cover the Napa Valley Floor. The youngest deposits of the current streams and alluvial fans are of Holocene age (100,000 years to present). Older deposits exposed as terraces, alluvial fans, and beneath the Holocene deposits are of Pleistocene age (2.5 m.y. to 100,000 years). At the south end of the Napa Valley marshland, tidal flat and estuary deposits occur. The Quaternary deposits appear to be only slightly deformed and weakly consolidated to unconsolidated.

2.4 Significant Previous Studies

Previous hydrogeologic studies of Napa County and also mapping efforts are divisible into geologic studies and groundwater studies. The more significant studies and mapping efforts are mentioned in this section. **Table 2-1** shows the chronological sequence of these efforts that span more than six decades.

Charles E. Weaver (1949) compiled geologic maps covering much of the Napa Valley and the Coast Range from the Sacramento Valley to the ocean. His geologic mapping was conducted between 1903 and 1933. Detailed additional work and manuscript preparation continued for 15 years until final publications. Weaver's geologic observations, mapping and interpretations have remained the foundation for the study area.

Kunkel and Upson's study (1960) is the hydrogeologic equivalent to Weaver's work and covers the groundwater in Napa and Sonoma Valleys. Field work, geologic mapping, and well locating were conducted between 1949 and 1952. Notably, most well information predates 1952. Geologic cross sections presented in Napa Valley are all in the lower valley area near the City of Napa.

The next significant reports are a pair of more detailed geologic maps of the Napa Valley area (Fox and others, 1973, and Sims and others, 1973). Besides the more detailed mapping, especially of the Sonoma Volcanics, these maps have more modern, detailed topographic base maps than Weaver's or Kunkel and Upson's maps. These maps have remained the main source for recent digital map compilations, with some additional new mapping, by the U.S. Geological Survey (USGS), including Graymer and others (2002) and Graymer and others (2007).

The California Geological Survey (CGS) has been releasing a series of even more detailed geologic maps of the Napa Valley area, which are based on 7 ½ minute topographic quadrangles (scale: 1 inch = 24,000 inches, or 2,000 feet). These quadrangles include the Cuttings Wharf (Bezore and others, 2002), Napa (Clahan and others, 2004), Mount George (Bezore and others, 2004), and Yountville Rutherford (Clahan and others 2005). (Bezore and others, 2005). The advantages of these maps are their uniform size, and the maps subdivide the Sonoma Volcanics into named members based on rock type, age, and stratigraphic position.

A series of reports and geologic maps have focused on the Quaternary deposits of Napa Valley. The U.S. Soil Conservation Service published the soil survey of Napa County (Lambert and Kashimagi, 1978). A study of the Quaternary flatland deposits of the entire San Francisco Bay region, including Napa Valley, is contained in Helley and others (1979). A more recent publication on the Quaternary geologic deposits is in Sowers and others (1998).

Following Kunkel and Upson (1960), the USGS continued hydrogeologic studies in the Napa Valley. A series of publications collected additional information on wells by 7 ½ minute quadrangle: Napa 1973, Rutherford 1973, Yountville 1973, and Calistoga 1973. Faye (1973) examined the groundwater of the northern Napa Valley from Oak Knoll Avenue north, an area largely unexamined in detail by Kunkel and Upson. Faye's report was largely concerned with groundwater contained in the Quaternary alluvium beneath the Napa Valley and included an isopach (equal-thickness) map of the alluvium and other derivative maps of hydraulic

conductivity and groundwater levels. Similar to Kunkel and Upson, Faye did not present geologic cross-sections for the northern valley; he also did not present subdivisions of the Sonoma Volcanics, probably due to the lack of deep well control, the complexity of the units, and the low water yielding nature of the Sonoma Volcanics.

Michael Johnson (1977) studied the MST area east of Napa. Groundwater extraction in this area is mostly from the Sonoma Volcanics, and declining groundwater levels have been observed. The MST area is somewhat unique in that it is considered a collapsed volcanic structure (caldera) and contains a sequence of Sonoma Volcanics which may be unique to the MST area. Johnson presented a series of geologic cross-sections across the MST area.

Farrar and Metzgar (2003) reviewed conditions in the MST area since Johnson and re-presented Johnson's geologic cross-sections. Because these two reports are detailed studies of the MST area, this study did limited evaluation of the area (see Section 5 of this Report). Sweetkind and Taylor (2010) presented digital information of water well information extracted from selected previous USGS studies. In Napa Valley, the data appear to be drawn from Kunkel and Upson (1960). As such, the data represent wells drilled before 1952 and located largely in the southern portion of the valley. As a result, there are sixty years of additional water well construction information which encompasses over 5,600 new wells, not considered in Sweetkind and Taylor's more recent reports.

The following reports are about regional geologic relationships or the plate tectonic setting. Mankinen (1972) reported radiometric age dating results for the Sonoma Volcanics. Wagner and Bortugno (1982) present a regional scale geologic map that covers much of the southern portion of the Coast Range and summarizes the stratigraphic and age relationships. Fox (1983) summarizes the tectonic setting of the Tertiary and Quaternary rocks in the area. Fox and others (1985a) relate the implications of a series of volcanic rocks along coastal California, including the Sonoma Volcanics, in relationship to the evolution of the San Andreas Fault zone.

Langenheim and others (2006) present an isostatic gravity map of the Sonoma Volcanics field in the Napa and Sonoma County area. The principle behind that study is that the bedrock Mesozoic rocks are of higher density than the overlying Tertiary volcanic and sedimentary rocks. In the Napa Valley area, the gravity map shows two gravity low basins where thick Tertiary rocks occur over the Mesozoic bedrock. The north gravity basin extends north westward from the middle valley to the end of the upper valley. The second smaller gravity basin extends from south of the Yountville Narrows to below Napa at the Suscol Narrows. To the east of Napa, a complex semi-circular gravity pattern appears to reflect the MST area caldera feature. South of Suscol, the gravity map shows a deep, large gravity low beneath the San Pablo Bay.

In 2005 to 2007, DHI Water & Environment (DHI) contributed to the 2005 Napa County Baseline Data Report (DHI, 2006b and Jones & Stokes et al., 2005) which was part of the County's General Plan update (Napa County, 2008). A groundwater model was developed by DHI in conjunction with the Napa Valley and Lake Berryessa Surface Water models to simulate existing groundwater and surface water conditions on a regional basis primarily in the North Napa Valley and the MST and Carneros Subareas (DHI, 2006a). In the Napa River watershed, the model was generally conceptualized as a large basin of impermeable rock overlain in three distinct areas by more permeable units. The three areas that were the focus of the groundwater model were the north Napa Valley area and the MST and Carneros Subareas. The groundwater model encompasses the Napa River watershed and consists of two layers. The upper layer was designated as being unconfined and the lower layer was designated as confined. Each of the three modeled areas was represented as a separate water-producing geologic unit. The geologic unit that was conceptualized as the primary source for groundwater in the north Napa Valley area was the alluvium. Values and distribution of hydraulic conductivity for the north Napa Valley area reflected a similar distribution as was presented in Faye (1973), and extrapolated to the rest of the Napa Valley Floor to the south. A 2007 technical memorandum, Modeling Analysis in Support of Vineyard Development Scenarios Evaluation (DHI, 2007), was prepared to document the groundwater model update which was used to evaluate various vineyard development scenarios.

Additional geologic maps, groundwater studies, and reports are listed in the references of the Groundwater Report (LSCE, 2011a). As recommended in the Groundwater Report and described in this Report, LSCE and MBK have conducted additional work to update the hydrogeologic conceptualization and characterization of conditions, particularly for the Napa Valley Floor. As elaborated later in this Report, this updated hydrogeologic characterization and conceptualization of the hydrostratigraphy is key to the County's successful, future use of modeling tools and for improvement of the models' predicative utility.

Table 2-1. Summary and Chronology of Hydrogeologic and Geologic Studies and mapping Efforts in Napa

Hydrogeologic and/or Geologic Studies and Mapping Efforts	Year of Report or Map Publication							
	1940s	1950s	1960s	1970s	1980s	1990s	2000s	2010-2019
Weaver, 1949	◆							
Kunkel and Upson,1960		◆						
DWR 1962			◆					
Koenig, 1963			◆					
Fox et al., 1973				◆				
Sims et al., 1973				◆				
Faye, 1973				◆				
Johnson, 1977				◆				
Helley et al., 1979				◆				
Wagner and Bortugno, 1982					◆			
Fox, 1983					◆			
Graymer et al., 2002							◆	
Farrar and Metzger, 2003							◆	
Graymer et al., 2007							◆	
DHI, 2006 and 2007							◆	
LSCE, 2011								◆
LSCE and MBK, 2013 (this Report)								◆

◆ = Report and Map produced

◆ = Report only

◆ = Map only

3 SURFICIAL GEOLOGY

The surficial geology of the Napa Valley area has been mapped by various authors for over a hundred years. The reports and geologic maps differ through time in the detail of mapping, characterization of rock types, and nomenclature of various units. In the last forty years, the development of radiometric-age dating techniques and the evolution of plate tectonic theory have led to a better understanding of the geologic history of the region.

However, even the most recent geologic reports and maps exhibit conflicting map units, lithology, and nomenclature. Since the earliest geologic maps, three major geologic units in the Napa Valley area have been recognized and remain largely unchanged, except in details, names, and interpretation of how they were formed. These three units are Mesozoic rocks, Tertiary volcanic and sedimentary rocks, and Quaternary sedimentary deposits. This report presents a review of previous surficial geology mapping efforts, developed to inform the interpretations of subsurface geology and hydrogeology presented in Sections 5 and 6. **Figure 3-1a** highlights the major rock types and deposits in the Napa Valley study area, presenting them according to relative time of formation. **Figure 3-1a** also serves as a legend for surficial geologic units presented throughout the report. Minor rock types and deposits are not described in this report; however, they are available from the original sources published by Bezore and others (2002, 2004 and 2005) and Clahan and others (2004 and 2005) by the California Geological Survey and Graymer and others (2002, 2006 and 2007) by the United States Geological Survey. **Figure 3-1b** depicts the study area surficial geology.

3.1 Mesozoic Rocks

The oldest geologic unit in the Napa Valley area is the Mesozoic (pre-63 m.y.) rocks which are largely exposed in the surrounding mountains. The Mesozoic rocks are highly deformed and well lithified. The two main divisions are the Great Valley Complex and the Franciscan Complex.

3.1.1 Great Valley Complex

The Great Valley Complex is composed of the Coast Range ophiolite and the Great Valley Sequence. The ophiolite consists largely of fault-bound masses of serpentinite (rock type based on the mineralogy) in the Napa Valley area and igneous rocks elsewhere in the region; Coast Range ophiolite represents former oceanic crust tectonically accreted to the North American Plate.

The Great Valley Sequence consists of deep-water marine deposited sedimentary rocks of sandstone, shale, and conglomerate. The sequence is divided into an older lower member and a younger upper member that contains conglomerate beds. The Great Valley Sequence was

originally deposited on the Coast Range ophiolite, but this relationship has largely been destroyed by tectonic deformation.

The Great Valley Sequence is largely exposed in the Macaymas Mountain west of Napa Valley. Smaller areas occur east of the valley and in the Yountville Narrows area. The Coast Range ophiolite occurs as smaller fault-band areas in the mountainous areas.

The Great Valley Complex is considered low-groundwater yielding; at best, it produces a few gallons per minute to water wells, which is sufficient for domestic supply. The low yield results from the highly deformed and well-lithified nature of the rocks, where groundwater is mostly contained in fractures and cracks within the rocks.

3.1.2 Franciscan Complex

The second main Mesozoic rock group is the Franciscan Complex, which is composed of weakly to strongly metamorphosed, deep-marine deposited sedimentary rocks, (sandstone with high clay-sized content (greywacke), shale, clay, chert, and limestone), and igneous rocks of basalt and serpentinites. A complex rock type is termed mélange, composed of sheared shale, clay, and greywacke matrix containing small (pebble-sized) to large (several hundred feet) blocks and lenses of other rock types.

The complex nature of the Franciscan Complex reflects the complicated history of its formation. The Complex was formed in a tectonic subduction zone where the oceanic crust beneath the Pacific Ocean was carried below the Great Valley Complex attached to the North American Plate. Fragments of the oceanic plate and overlying sedimentary deposits were sheared and mixed in the subduction process. Blocks of Great Valley Complex were added to the mixing process probably by tectonic movements and marine landsliding in the subduction trench. The contact between the Great Valley Complex and the Franciscan Complex is almost always a fault contact in the Napa Valley area.

The Franciscan Complex is exposed in the mountainous regions surrounding the Napa Valley area. The Franciscan Complex is considered low to non-groundwater yielding. Water wells constructed in the Complex at best produce a few gallons per minute, which is sufficient for domestic supply. However, the Franciscan Complex tends to have more “dry” test holes drilled in it than any other geologic unit. This occurs due to the fine-grained texture and well-lithified nature of the rock types, and the high degree of deformation.

3.2 Late Tertiary Volcanic and Sedimentary Rocks

The next major geologic unit in the Napa Valley area is the late Tertiary, largely Pliocene (5.0-2.5 m.y.), volcanic rocks of the Sonoma Volcanics and the interrelated sedimentary rocks. The Sonoma Volcanics are widely exposed in the mountainous areas especially to the east and north surrounding the valley. The Sonoma Volcanics are more limited to the west in smaller faulted exposures along the valley side and small hills in the Yountville Narrows. The late Tertiary sedimentary rocks are limited to exposures in the Conn Creek area, the MST area, and the Carneros area.

3.2.1 Sonoma Volcanics

Weaver (1949) named the Sonoma Volcanics from his mapping of Napa and Sonoma Counties, superseding an earlier division of the unit into three named units: the Mark West Andesite, the Sonoma Tuff, and the St. Helena Rhyolite in decreasing age. Weaver did not map separately 'the Andesite and Sonoma Tuff' units, but he did map the St. Helena Rhyolite. His mapping and nomenclature remained the basis for subsequent reports for over twenty years (Kunkel and Upson 1960; Faye, 1973).

USGS geologists (Fox and others, 1973; Sims and others, 1973) performed more detailed geologic mapping based on the various rock types of the volcanic rocks. However, no stratigraphic or age relationships were proposed for the Sonoma Volcanics. From their mapping, the St. Helena Rhyolite was found to be more complex than previously envisioned. Separate and discrete rhyolite bodies occurred within the entire Sonoma Volcanics as opposed to being a single unit of one age.

Subsequent studies, including radiometric age-dating, subdivided the Sonoma Volcanics into the informal lower and upper members (Fox and others, 1983; Fox and others 1985a; Fox and others, 1985b). The lower member is dominated by andesite lava flows with some tuffs with radiometric ages of 5.4 to 4.2 m.y. near Mount George east of Napa indicating a largely early Pliocene age. The lower member roughly corresponds to the previously named Mark West Andesite. The upper member corresponds to the previously named Sonoma Tuff and occurs largely to the north around the upper valley area. The age of a tuff is reported as 3.4 m.y., and the rhyolite on Mount St. Helena is reported as 2.6 m.y. indicating a Pliocene age.
Lower Member – Andesite Flows

The lower member of the Sonoma Volcanics occurs in the Howell Mountains from Conn Creek south through Atlas Peak, Mount George, and around the south side of the MST area. The member is dominated by basalt, andesite, and dacite lava flows representing variable mineralogic, chemical, and crystalline composition. Weaver (1949) notes that individual lava flows show great variability and change in a short distance from a few feet thick to several

hundred feet thick; the flows are dense and vesicular (numerous gas-formed bubble spheres). Similarly, lava flow texture can change over short distances from dense and fine-grained, to vesicular, to flow breccias (foot-sized or larger blocks). Interbedded with the lava flows are subordinate pyroclastic (aerially ejected from a volcanic vent) beds of ash and tuff flows, rhyolite flows, and thin beds of volcano-sedimentary rocks. Interbedded with the lava flows are subordinate fewer ash flows and rhyolite flows and flow breccias.

The lower member was termed by Fox and others (1985a) as the Andesite of Atlas Peak. Recent mapping by the CGS (Bezore and others, 2005; Clahan and others, 2005) of the same geologic unit in the Howell Mountains termed them as andesite flows and flow breccias of Stag's Leap. Similar to Fox and others, (1985a), these maps show the lower member andesite extending across the valley in the hills of the Yountville Narrows. However, the CGS maps differentiate an andesite flow breccias unit across the Narrows and along the west side of the Valley.
MST Caldera Area East of Napa, the MST area is a unique feature in the Sonoma Volcanics. The semi-circular area is considered a collapse caldera (Fox and others, 1985a), where a 'plug' like mass of volcanic materials subsides into an underlying magma chamber. The low hills in the center of the caldera are believed to be a resurgent dome of dacite breccias formed after the collapse.

The groundwater hydrology and geology in the MST area were studied in detail by Johnson (1977) and Farrar and Metzger (2003). Recent geologic maps include Bezore and others (2004) and Clahan and others (2004). The stratigraphy in the caldera consists of a lower member andesite unit overlain by a tuff unit (?). Unique volcanic units and sedimentary units occur overlying these, including a tuffaceous, diatomaceous lacustrine deposit. Fox and others (1985a) placed these caldera units as a portion of the upper member of the Sonoma Volcanics at all ages of 3.8 to 3.4 m.y. Because of the unique nature of the MST area and the previous detailed studies, this report does examine the area in detail.

Upper Member – Tuffs and Rhyolites

The upper member of the Sonoma Volcanics is exposed north of Conn Creek on the east side of the valley and surrounds the upper valley extending northward to Mount St. Helena. In contrast to the lava-flow dominated lower member, the upper member is characterized by pyroclastic volcanic deposits formed by being explosively or aerially ejected from a volcanic vent. Depending upon the nature of the volcanic process and increasing size of the ejecta material, a variety of deposits can be formed, such as ash flow tuffs, tuffs, tuff breccias, and agglomerates (foot-sized ejecta). Ejecta material generally decreases in size away from the source vent and the bed thickness decreases. However, processes at the vent may change or multiple vents may lay down overlapping and intermingled deposits. Finally, surficial processes such as stream erosion

and mass movements, i.e., landsliding and mud flows, may ultimately modify pyroclastic deposits into sedimentary deposits.

Fox and others (1985a) termed the tuffaceous beds and interbedded minor andesitic lava flows as the Tuff of Petrified Forest. Radiometric age dates of tuffs west of the upper valley are about 3.3 – 3.2 m.y. Overlying the tuffaceous deposits is a sequence of rhyolite lava flows and flow breccias largely in the upper valley area and further north. Fox and others (1985a) termed these upper member deposits as the Rhyolite of Calistoga. A radiometric age near the top of these units on Mount Saint Helena is reported as about 2.9 m.y. Small, faulted bodies of rhyolite on the west side of the middle valley appear to be part of the upper member (Fox and others, 1985a); although like other isolated rhyolite exposures the relationship is not totally clear.

Tertiary Sedimentary Rocks – 'Huichica' Formation

Weaver (1949) termed relatively undeformed stratified gravel, sand, reworked tuff, clay and conglomerate in the Carneros area as the Huichica Formation. He mapped similar deposits as Huichica Formation near the mouth of Conn Creek. The third major exposure in the Napa Valley in the MST area, he termed the Montezuma Formation. Kunkel and Upson (1960) include these deposits in their Huichica Formation.

Weaver considered the Huichica Formation as Quaternary age, probably based on its undeformed nature and since it overlies the andesites of the Sonoma Volcanics. A tuff bed near the bottom of the Huichica Formation in the Carneros area has been radiometric age-dated at 3.9 m.y., which indicates a Pliocene Age. The detailed mapping by Sims and others (1973) retained the Huichica Formation nomenclature, but they reported them as Tertiary aged deposits. Fox (1985a) continued with the Huichica Formation nomenclature, and he placed the unit as stratigraphically younger than the andesitic-lower member of the Sonoma Volcanics. In the Conn Creek and Conn Valley areas, these sedimentary rocks appear to interfinger and interbed and are overlain by tuff beds of the upper member of the Sonoma Volcanics.

In the MST area, the Tertiary sedimentary rocks consist of sand, gravel, and clay beds with a tuffaceous component. Johnson (1977) and Farrar and Metzger (2003) show the sedimentary rocks overlying the tuff deposits and the diatomaceous beds. Again the stratigraphic relationships and age appear to be at least partially equivalent to the upper member of the Sonoma Volcanics.

To further complicate matters, the USGS authors Graymer and others (2002), Graymer and others (2007), and Farrar and Metzger (2003) have dropped the name Huichica Formation for the Conn Creek and MST areas. They have replaced it by a Tertiary Sonoma Volcanics sedimentary unit (Tss) described as volcanic sand and gravel. Graymer and others (2002)

retained the Huichica name for the Carneros area, but they modified the term to Huichica and Glen Ellen (found in the Sonoma Valley) Formations of early Pleistocene (?) and Pliocene age. The final complexity is that recent mapping efforts for the Napa Valley area by the CGS retain the nomenclature of Huichica Formation (Th) for the three main areas of exposures.

The implication of these various nomenclatures is that the same geologic exposure may be named and labeled differently on different maps. For example, in the MST area, the same geologic unit is shown as Huichica Formation (Th) on older USGS maps (Kunkel and Upson, 1960; Fox, 1985a) and newer CGS maps (Bezore and others, 2005 and Clahan and others, 2004). However, on recent USGS maps is shown as Tertiary Sonoma Volcanics sedimentary rocks (Tss) such as Graymer and others (2002), Farrar and Metzger (2003), and Graymer and others (2007).

While the term Huichica Formation is deeply embedded in the geologic and hydrogeologic studies of the Napa Valley, the term is somewhat misleading and obscures the nature of the deposits. The three main surface exposures are relatively small, isolated from one another, and exhibit somewhat different stratigraphic nature. The Conn Creek and Conn Valley area is interbedded and overlain by the tuffaceous upper member of the Sonoma Volcanics, and it is strongly deformed. In the Carneros area, the deposits are weakly deformed, overlie the lower member Sonoma Volcanics, have minor tuffaceous interbeds, and may range in age from Pliocene to early Pleistocene.

Because of these nomenclature conflicts, the complexity of the stratigraphic relationships, and the isolated nature of the main exposures, this Report applies a hybrid nomenclature for late Tertiary sedimentary rocks modified from Graymer and others (2002) and Bezore and others (2002). In the Carneros area, the Huichica Formation (QTh) will be used. In the Conn Creek/Conn Valley and MST areas, the Tertiary Sonoma Volcanics sedimentary rock (Tss/h) will be used.

Quaternary Sedimentary Deposits

Quaternary (post 2.5 m.y.) sedimentary deposits cover the Napa Valley Floor. They have been divided on surficial geologic maps into Holocene (post 100,000 years to present) deposits of present stream channels, terrace, floodplain, and alluvial fans. Older Pleistocene (2.5 m.y. to 100,000 years) deposits have been divided into terrace, alluvial fan, and older alluvium. South of Napa, Holocene Bay muds (Qh) of marshland and estuary origin extend and merge with similar deposits of San Pablo Bay.

The surficial deposits are separated by topographic expression, aerial photographs, and soil maps with older units exhibiting thicker well-developed soils. The deposits are

unconsolidated becoming weakly consolidated with increasing age and deformed only by faulting.

The Quaternary deposits are highly complex and variable in composition. Stream channel deposits are composed of thicker beds of sand and gravel, and they are lenticular and elongated in nature. They are interbedded with floodplain deposits of silt and clay with mixtures of sand and gravel, and flood-flow thin sheets of sand with gravel. Alluvial fans spreading out from the valley sides and tributaries tend to be broad, gravelly sandy silt and clay beds formed by flood flows with lenticular sand and gravel interbeds formed by the streams. The alluvial fan deposits tend to thin and become finer-grained towards the valley center merging into the floodplain deposits. The bay muds, as the name implies, are composed of fine-grained silts and clays; the bay muds tend to be blue or gray in color as a result of reducing conditions and constant saturation. Some interbedded lenses of finer sand beds occur formed by streams or estuary channels.

Faye (1973) examined the thickness of the Quaternary deposits (alluvium) in the northern Napa Valley. He found that the alluvium occurred as a relatively narrow band from over 200 feet thick in the south to less than 100 feet thick just north of St. Helena. Towards the valley edges, the alluvium thins progressively to zero. This Report re-examines the nature of the Quaternary deposits using some forty years of additional information from water well drillers' reports.

4 STRUCTURAL GEOLOGY

4.1 Structural Geology

The structural geology of the Napa Valley area is extremely complex. Deformational features and structures of the pre-Sonoma Volcanics geologic units are largely unimportant for this study, as these units occur outside the valley, or are at a great depth below the valley. The collapse caldera in the MST area, while fascinating and locally important, is more stratigraphically significant in its age relationship within the Sonoma Volcanics and the Napa Valley.

4.2 Napa Valley Graben

The simplest, generalization of the structure of the Napa Valley is to describe it as a graben, a fault-bound, down-dropped block relative to the adjacent uplifted blocks. The best visualization of this is the isostatic gravity map of Langenheim and others (2006). The northern gravity-low basin extends northwestward beneath the middle valley, indicating, thick low density Sonoma Volcanics over older geologic units. A higher gravity ridge occurs beneath the Yountville Narrows indicating thinner Sonoma Volcanics and the exposure of older rocks on the east side of the valley. The smaller southern, gravity-low basin extends south to the Suscol Narrows, where a narrow higher gravity ridge separates it from the larger, deeper gravity-low basin below San Pablo Bay.

4.3 West Boundary Fault Zone

The graben bounding faults have been mapped variously on the different geologic maps. The best depictions of the faults are Graymer and others (2007) and the more detailed CGS maps (see previous sections). The west boundary fault is the West Napa Fault Zone which separates the Mesozoic rocks to the west from the small Sonoma Volcanics exposures along the valley side. The main fault appears to be a steeply west-dipping reverse fault with movement up on the west side, but also right lateral movement, northwestward, strike-slip faulting reported.

The West Napa Fault Zone appears to be composed of a complex of multiple faults subparallel to one another, east of the main fault. A strand of faults (?) appears to diverge more northward just west of the City of Napa and trends east of the Sonoma Volcanics hills through Yountville and on the east side of the Yountville Hills.

4.4 East Valley Fault Zone

The east boundary fault has been more elusive to map. A concealed fault extending northward just east of or below the river from Suscol to the Soda Creek fault in the northwest MST area has some evidence from subsurface information and from the isostatic gravity map (Langenheim and

others, 2006). The study reported herein found some subsurface evidence that a concealed fault may extend northward below the trend of Napa River parallel to the valley side. This possible fault may extend further north on the east side of the Yountville Narrows as shown on the CGS map of the Yountville Quad (Bezore and others, 2005). A linear feature just south of the Yountville Narrows may be either a fault or possibly an erosional feature.

4.5 Strike and Dip of Bedding

An eastern boundary fault along the eastern part of the northern Yountville Narrows and northward to Conn Creek has not been discerned. Some subsurface information in the present study indicates some possible concealed fault traces west of the valley side. At the mouth of Conn Creek Canyon, complex parallel faults occur in the Sonoma Volcanics and Tertiary sedimentary rocks; these extend northward parallel to the valley.

The final structural element to consider is the strike and dip of beds, i.e., the geographic direction of the bed and the angle that the bed slopes into the subsurface. Around the middle valley in the north, Sonoma and Tertiary sedimentary beds trend parallel to the valley and dip steeply (greater than 45°) towards the valley center, giving a synclinal aspect to the gravity basin. In the Yountville Narrows area, strike and dips are more variable, but generally exhibit lower dip. Around the lower valley, strike and dips of the Sonoma Volcanics are poorly known. The strike and dip of the beds must be considered when evaluating the subsurface geology.

5 SUBSURFACE GEOLOGY

This section examines in greater detail the geology below the Napa Valley Floor in relation to groundwater. Previous hydrogeologic studies have focused on the Quaternary alluvium and did not attempt to subdivide the Sonoma Volcanics in the subsurface (**Figure 5-1a**). A representative cross section from Kunkel and Upson (1960) is shown in **Figure 5-1a** together with an annotated version of the cross section (**Figure 5-1b**) that shows geologic features identified during the recent work for this study. Previous geologic cross-sections were largely in the Napa area (Kunkel and Upson, 1960). Faye (1973) presented no cross-sections north of the City of Napa, but he mapped the thickness of the alluvium. In the MST area, Johnson (1977) and Farrar and Metzger (2003) subdivided the Sonoma Volcanics on their cross sections. Sweetkind and Taylor (2010) presented digital cross-sections, but the data used were pre-1952 drillers' reports from Kunkel and Upson (1960).

From a previous reconnaissance study of the entire County (LSCE, 2011a), it was known that several thousand water well drillers' reports existed on the Napa Valley Floor. A majority of these reports post-dated 1970 and apparently had not been used in published reports. A series of geologic cross-sections were recommended to examine the subsurface geology, including derivative maps of alluvium thickness and Sonoma Volcanics rock types. This Report summarizes the work conducted to implement these recommendations. The upper Napa Valley and the MST area were largely excluded from the present study because of the small size of the upper valley and the previous detailed studies of the MST.

5.1 Subsurface Information

Subsurface information for groundwater studies is largely based on water well drillers' reports. These reports have been mandated for the last 60 years to be filled out on a state form for all water well or borehole drilling activities performed by drilling companies and submitted to DWR. Information for some wells, which predated the mandated drillers' report, was collected by governmental agencies (e.g., USGS and DWR) and from well owners or drilling companies for older hydrologic studies.

5.1.1 Water Well Drillers' Reports

The water well drillers' report form has evolved over 60 years, but it has three main features that have been retained through all the form changes: a location element; a lithologic description of material encountered (more simply, lithologic log or log); and well construction details, including estimated water yield. Shortly after the form was introduced, sequential identification numbers were added to be able to differentiate reports. In theory, this well ID number was supposed to be unique to a particular report and therefore to a well. In reality, numbers were used several times during printing additional forms, or when new formats of forms were

introduced. With the dawn of the digital age, a prefix of 'e' and subsequently 'E', was added to the number to indicate an electronic version of the form. For further confusion, older well reports on a variety of forms, early water well drillers' reports without numbers, and some of the early numbered reports were given County identification numbers. For Napa County, this was in the form of 28-001, 28-002, etc.

5.1.2 Well Location

The most important information on a water well driller's report is the location of the well. Initially, a written description of the location was required, and distances to the grid-location by Township and Range and Section were to be shown. Unfortunately, only selected reports were located. Heat-exchange well reports were also ignored much of the Napa Valley Floor was not surveyed on topographic maps. Often, drillers did not fill out the form. Subsequently, DWR requested a map showing distances to roads or geographic features. This also proved relatively inadequate. Eventually, about 1970, DWR requested the assessor's parcel number. But parcel numbers can change or be misidentified. When the water well driller's report was submitted, DWR assigned a Township/Range/Section identifier with an alphabetic subdivision for each of sixteen unique 40 acres in the square mile section. The wells were then numbered in chronological order as drilled. This task proved to be impossible for the personnel and resources assigned, given the quantity of well reports and the quality of the location information. Most drillers' reports within the last 40 years tend to be assigned only to the Section square mile area. This problem was exacerbated in the last 30 years by hundreds of shallow monitoring wells installed at fuel stations and hazardous materials sites.

In summary, while the well location for the driller's report is the most important item, each report must generally be approached as though the location is unknown. Using the street address, any map descriptions, and parcel number, the location must be identified, if possible. The DWR location must be examined until confirmed. In many cases, the DWR location is wrong for various reasons, such as by being in an adjacent section; in some cases, the location may be off by miles by a misreading of the Township and/or Range.

During this study, over 1,300 wells were located by using the information on the reports. The parcel numbers on reports from the last 30 years proved fairly reliable. Older parcel numbers tended to be more difficult to confirm. Drillers' reports prior to 1970 were the most difficult to locate as information was lacking or could not be related to present conditions. A few critical deep well reports were traced by file search on parcel numbers or County permit numbers.

Shallow (less than 100 feet deep), hazardous-site monitoring wells were largely ignored. Shallow domestic well reports, located where deeper adjacent well drillers' reports also existed, were mostly ignored. In areas where a high density of wells occurred, only the deeper reports

were used. Most irrigation well reports were located, if possible, unless they were on small parcels with numerous adjacent wells. Well drillers' reports for wells located outside the Napa Valley Floor were also mostly not used for this study.

Because many drillers' reports are incorrectly located, or the report lacks a state-location identifier beyond the Section designator, a location identity was assigned to the 40 acre designator, followed by the year of the drillers' report. For example, a well report was designated as 20a-78 meaning location in Section 20, northeast-most 40 acre area, drilled in 1978. If several wells were drilled in 1978, a post script alphabetic designator was added, (i.e., -20A-78A; 20a-78b, etc.). The drillers' report is listed in the database with the report ID number listed. During the course of this study, about 1,300 water well drillers' reports were located and tabulated in the database.

5.1.3 Lithologic Logs

The second most important element on the water well drillers' report is the lithologic log, or description of the geologic material encountered in the borehole. Most drillers do not have geologic training, although they may have vast experience in drilling wells in their region. Most drillers can readily discern the differences between sand, gravel, and clay. However, mixtures of these materials are more difficult to describe. Generic terms such as 'rock' can describe many things such as boulders, hard sedimentary rock of any type, or volcanic rocks such as lava flows or tuffs. The driller is hindered by having to control the drilling operation and observe the nature of the material being drilled through and coming out of the borehole. Most drilling rigs use 20-foot long drill pipe sections, resulting in the 'rules of tens'. The driller observes the material coming out of the borehole (cuttings) at the bottom of the 20-foot drill pipe and describes what was drilled as either 10 or 20 feet thick.

Drilling through other geologic materials such as sedimentary rocks or volcanic rocks, the driller may describe the size of the fragments resulting from the drilling process, such as sand, gravel, or clay. Modifiers added to the description may help unravel the nature of the geologic material, such as 'hard', 'sticky', 'smooth', and colors.

Each lithologic log must be evaluated with recognition of the above limitations, and the log must also indicate the drilling method, the drilling date, the purpose of the well, the well location, and the drilling company. Review of numerous water well drillers' reports from the same drilling company generally shows evolving patterns in logging descriptions through time. If lithologic logs by other drilling companies are located nearby, comparison of the logs can lead to better evaluation of all of the logs. From such a review, a hierarchy of reliability of lithologic logs by different drillers can be defined based on the descriptions. In some instances, a lithologic log

may be deemed unusable because of the lack of detail or incompatibility of the log with other nearby wells.

5.1.4 Geophysical/Electrical Logs

A complement to the driller's lithologic log is the geophysical (or electric) log, or survey of a borehole, which measures the resistivity of the geologic material to an induced electric current. Evaluation of such electric logs with the lithologic log can aid identification of the geologic material and bedding thickness. However, in Napa Valley only a dozen or so such electric logs have been found in the area. A small cluster of such electric logs just north of the Yountville Narrows show that correlation of geologic units is possible in that area. However, the remaining available electric logs are too widely scattered across the valley to allow correlation. Some additional water well drillers' reports indicate an electric log was made in the borehole, but these were not available for review. South of the Yountville Narrows no electric logs were found.

5.1.5 Well Construction Details

The third major element on the water well driller's report is the well construction details. These consist of the borehole size, size of the installed well pipe, and the location of intake sections (i.e., perforations or screened pipe). Also, the thickness and nature of any surface sanitary seal installed is noted.

Most wells in the Napa Valley constructed post 1970 tend to have long intake or screened intervals that extend from the near surface alluvium, if present, and across the underlying Sonoma Volcanics or Tertiary sedimentary rocks to the total depth drilled. The final well construction information is the estimated yield of the well in gallons per minute (gpm). This is determined by test pumping the well; this tends to be more accurate and give possible aquifer characteristics derived from lowering of the water level corresponding with pumping (drawdown). This method was used on a minority of wells, and these were mostly large diameter irrigation wells or public water supply wells.

The vast majority of wells were tested by air-lift methods where an air compressor is used to remove water from the well and the quantity of outflow is estimated by the driller. Most wells in the valley tested by this method are reported to have a yield of a few gpm, to several tens of gpm, to in a few occasions a couple of hundred gpm. When the resulting water level in the well is reported at the end of the test (usually 2 to 3 hours), and water levels are near the bottom of the well, this indicates the specific capacity (gpm/foot of water level lowering) of the well is low, i.e., fractions of a gallon per minute for each foot of drawdown. This indicates poor aquifer characteristics or low permeability, i.e., the limited ability of water to flow through the geologic material into the well. Alternatively, low well yields may be a result of well inefficiency due to

the construction process. Because low well yields are generally widespread across the valley, and uniformly across the different well drilling companies, it is believed that poor aquifer characteristics are the cause. This is discussed in more detail in a later section.

5.2 Methodology

Geologic units described in Sections 5.2.1 Geologic Cross-Sections and 5.2.7 Structure Contours/Subcrop Map of Pre-Alluvium and depicted in **Figures 5-2 through 5-12**are compiled for reference in Appendix A.

5.2.1 Geologic Cross-Sections

As part of this study to update the hydrogeologic conceptualization and further evaluate the subsurface geology of the Napa Valley, a series of eight geologic cross-sections (**Figures 5-2 through 5-10**) have been prepared. The first step in cross-section construction was to review the water well drillers' reports along the general trend of the cross-sections. It was found that few reports were located on some initial cross section locations, so the locations were relocated to where more driller' reports occurred. This was particularly acute in the south, beneath the City of Napa to Suscol. Few drillers' reports in this area post-date 1960, exclusive of hazardous site monitoring wells.

The well locations from the drillers' reports were plotted on enlarged topographic base maps at a scale of 1 inch equals 1,000 feet with an overlay of parcel numbers. Wells which could be located were assigned a location number based on Township/Range/Section 40-acre subarea, and the date of construction, as described previously. The information for drillers' reports that could be located was tabulated into a database and the location was assigned digital coordinates.

Cross sections were constructed at a horizontal scale of 1 inch equals 500 feet, and a vertical scale of 1 inch equals 100 feet. The wells were located on the cross-section, and the lithologic log for each well was used to construct a profile of encountered geologic material. The initial cross-sections were made in the lower valley. It became apparent that the number and depths of well reports in this area were extremely limited. The location of cross-sections F and G were predicated on older deep wells drilled pre-1950. Beneath the City of Napa, deep well control was nearly non-existent. Cross-sections D and E were relocated from initially proposed locations due to a lack of drillers' reports for deep wells.

The following sections summarize the geologic observations on the cross sections by the various valley areas from south to north.

5.2.2 Lower Valley Cross Sections

In the lower valley, four geologic cross sections were constructed: Sections D; Section E; Section F; and Section G, from north to south (**Figures 5-6 through 5-9**). These cross sections show the general geologic patterns of the lower valley. Quaternary alluvium (Qa) grades southward into fine-grained Quaternary sedimentary basin deposits (Qsb). The alluvium overlies Tertiary sedimentary rocks (Tss/h) which declines southward and transitions into thick, fine-grained Tertiary and early Quaternary sedimentary basin deposits (TQsb). The sedimentary rocks and basin deposits overlie the lower member Sonoma Volcanics andesite flows with tuffs (Tsva, Tsvt), which descends to depths of 1,000 feet or more below the City of Napa. At the south end of the valley at the Suscol Narrows, faulting has brought the Sonoma Volcanics to shallower depths.

At the north end of the lower valley, Section D appears to show Quaternary alluvium of unconsolidated deposits, including lenses of thick sands and gravel beds, especially to the east, and more widespread fine-grained clays with thin beds of sand with gravels. The alluvium thins east and west towards the margins of the valley. Below the alluvium, a thin sequence of finer-grained deposits occurs with some thin sand and gravel beds and some volcanic ash beds. This unit was correlated to the Tertiary sedimentary rocks (Tss/h) exposed in the MST area.

Deeper boreholes encountered volcanic materials of the lower member Sonoma Volcanics, but these appeared to occur in bands or zones. To the east, andesite lava flows and breccias with tuffs (Tsva) occur. In this area, thin Tertiary sedimentary rocks occur overlying the andesite unit. In the center of Section D, between two possible faults, limited information indicates tuff beds (Tsct) occur, but whether these are of the lower or upper member is not clear. To the west, a mix of andesite lava flows or breccias (Tsvab?), and tuffs (Tsvt) occur; these are probably the lower member Sonoma Volcanics.

Cross-section E (**Figure 5-7**) shows a similar pattern for the Quaternary alluvium. The east side of Section E shows Tertiary sedimentary rocks above the Sonoma Volcanics in the MST area. Beneath the alluvium, the main valley area shows thick, fine-grained deposits with some sand and gravel beds. This unit is termed Tertiary Quaternary sedimentary basin deposits. Only one deep well (projected on to this section) encountered Sonoma Volcanics of uncertain correlation at great depth. On the west side of Section E, lower member Sonoma Volcanics (Tsva) are overlain by sedimentary deposits of uncertain correlation (TQsu) in a fault band block.

Cross-sections F and G (**Figures 5-8 and 5-9**) are located south of the City of Napa where little deep well control occurs. The locations of Sections F and G were predicated on the existence of a few deep old well logs from Kunkel and Upson (1960) along each cross section. These well

logs date from the first half of the 1900s. A few more recent drillers' reports were also used to construct the cross sections.

Cross-section F (**Figure 5-8**) shows Quaternary sedimentary basin deposits (Qsb) up to about 300 feet thick and largely composed of clays with thin interbeds of sand. These are believed to be floodplain (?), marshland, and estuary origin. These deposits are underlain by thick clay with sands deposits of the Tertiary-Quaternary sedimentary basin deposits (TQsb). Some thick sand or sandstone beds occur interbedded with fine-grained units. The TQsb units are believed to be marshland, estuary, and lacustrine (?) deposits. The unit may be equivalent, in part, to the diatomaceous lake beds in the MST area, and the Tertiary sedimentary rocks of the MST and Carneros areas. As such, the age of the unit would range from the Pliocene and possibly into the Quaternary (early (?) Pleistocene). Below these units, the lower member of the Sonoma Volcanics of andesite flows and tuffs rise from great depth below the center of the valley to surface exposures, or near surface, by faulting.

Cross-section G (**Figure 5-9**) occurs at the south end of the lower valley near the Suscol Narrows. The south gravity low basin rises to the Suscol Narrows and the gravity high ridge. The high ridge separates the Napa Valley from the deep gravity low basin below the San Pablo Bay to the south. At the Suscol Narrows, the Napa Valley drains through a narrow (~2,000 feet) gap between exposed lower member Sonoma Volcanics (Tsva) to the east and low hills and exposes an older Tertiary marine rocks (Td) to the west. Cross-section G shows the complexity of this area as these older units are overlain by Tertiary-Quaternary sedimentary basin deposits and Quaternary alluvium. The cause of this complexity may be the intersection of the East Napa and West Napa Fault Zones. The merged (?) fault zone may continue southeasterly across the San Pablo Bay area towards Vallejo.

5.2.3 Carneros Area – Cross-Section H

To the west of the Napa Valley in the Carneros area, the review and locating of drillers' reports for the present study indicated that few wells occur until near Cuttings Wharf Road. West of that road, drillers' reports indicated that wells tend to be relatively shallow and low yielding. Near the marshlands of San Pablo Bay, drillers' reports were essentially non-existent. The drillers' reports in the Carneros area appear to show the geologic unit as mostly clays with thin sand and gravel beds with poor correlation (cross-section H; **Figure 5-10**). The entire unit encountered in the wells is believed to be the Huichica Formation as defined by Weaver (1949), or more recently as Tertiary-Quaternary Huichica Formation (TQh) by Graymer and others (2002).

5.2.4 Yountville Narrows Area – Cross-Section C

Northward in the Napa Valley, the review of water well driller's reports in the Yountville Narrows area indicated limited available well control, especially along the Napa River floodplain. Even away from the river, well control was limited. Cross-section C (**Figure 5-5**) was located near the north end of the area where well control was sufficient to extend the cross section across the valley. This cross section shows the complex structural features of the Yountville Narrows area. To the east, a possible East Napa Fault Zone separates the valley from the Howell Mountains. Beneath the valley floor, westward thickening Quaternary alluvium overlies the lower member Sonoma Volcanics andesite flow breccias mapped by the CGS. This unit appears to overlie a harder, more massive andesite flow and breccias (Tsvab) unit with some tuffs more typical of the Tsva in the mountains to the east. Deep well control is limited to one well, but the reported well yield (480 gpm) was much higher than nearby wells. Dips of bedding in the small hills and in the mountains to the east are somewhat lower (less than 30°) to nearly flat (less than 10°). This portion of the cross section overlies a flat shoulder of higher gravity which extends northward from the gravity ridge seen below the Yountville Narrows (Langenheim, 2006).

In the center of the Section C, the Quaternary alluvium, bound by faults, thickens and contains thick beds of fluvial sand and gravel. The underlying unit is termed Sonoma Volcanics conglomerate/breccias (Tca/b). The nature of the unit is unclear; it is uncertain whether it is a sedimentary conglomerate or volcanic flow breccias, or possibly a combination. Drillers' reports tend to log it as 'hard' gravel and boulders with some clay or volcanic ash, either as intermingled or separate beds. Two geophysical logs on the central two wells indicate high resistivity values and similar characteristic responses, but it could not be distinguished whether the deposits in these wells are sedimentary or volcanic. The four wells on the cross section were constructed for groundwater intake both in the thick coarse alluvium and this lower unit. Reported well yields were some of the highest in the valley, ranging from 770 to 2,000 gpm. Short duration test pumping of the two central wells indicated specific capacities of 17.9 and 33.9 gpm per foot of drawdown. This is higher than most wells in the valley which tend to be less than 1gpm per foot of drawdown. However, it is unclear if the extracted groundwater originated from the alluvium, which is most likely, and/or from the underlying conglomerate/breccias. The conglomerate/breccias unit was traced to north of Section A (see later section).

Further west on Section C occurs a fault-bound block of lower member Sonoma Volcanics andesite flows (Tsva). This is a continuation of the Yountville Hills just to the south.

The western remainder of Section C shows Mesozoic Great Valley Sequence rocks west of the main strand of the west Napa Fault Zone. The intervening area of the cross section shows a syncline-like or fault band block underlain by lower member Sonoma Volcanics andesite (Tsva),

andesite and tuff (Tsva & t), and tuff (Tsvt). The actual configuration of these units is unclear due to limited information and possible complications of faulting. Overlying these units is a fine-grained sedimentary unit termed (Tertiary-Quaternary sedimentary basin deposits undivided (TQsbu), as it does not match with either the Tertiary sedimentary rocks or the Quaternary alluvium. The gravity map shows a small, low-gravity basin from just west of the northern Yountville Hills to about halfway to Section B. This may represent a small fault band block on which late Pliocene (?) and early (?) Quaternary fine-grained sediments are deposited in a marsh-like or lacustrine environment.

5.2.5 Middle Valley – Cross-Sections A and B

The northernmost cross section, Section A (**Figure 5-3**), shows a typical Quaternary alluvium configuration of thickest depths near the center of the valley. However, thick sand and gravel beds in the central area are largely lacking. Localized thick sand and gravel beds occur, but well yields are less than seen farther south. In general, the alluvium appears to be finer-grained than farther south in the middle valley and the Yountville Narrows.

Section A appears to show the disappearance of the lower member of the Sonoma Volcanics andesite units to depths not reached by boreholes. In the easternmost part of Section A, Tertiary sedimentary rocks (Tss/h) may overlie the lower member (Tsva?) in a fault block; farther west, they overlie Sonoma Volcanics of uncertain correlation (Tsv?), or do not reach the volcanics. A narrow, fault bound (?) block appears to contain the conglomerate/breccias (Tcg/b) overlying Sonoma Volcanics of uncertain correlation (Tsv?). However, well yields are only moderate (<150 gpm), and specific capacities are lower (less than 1 gpm per foot of drawdown). Overlying thick sand and gravel alluvium may not be either present or yielding little water. On the west side of Section A, upper member Sonoma Volcanics (Tsv?) and upper member (?) tuffs (Tst?) exhibit well yields across this entire western area that are low (a few tens of gpm) with specific capacities of much less than 1 gpm per foot of drawdown.

In the middle valley, the geologic units of the Sonoma Volcanics change in their surface exposure and in the subsurface. The lower member Sonoma Volcanics dominated by the andesite flows (Tsva) and flow breccias (Tsvab) with minor tuffs (Tsvt) seen in the Yountviille Narrows descend to depths northward, and they are replaced by upper member tuffs and Tertiary sedimentary rocks. This is the result of the northern low-gravity basin where the lower member and overlying upper member of the Sonoma Volcanics have been down-dropped in relation to the adjacent mountainous areas.

Section B (**Figure 5-4**) shows Quaternary alluvium overlying older units with the greatest thickness near the center of the valley. To the east on the Valley Floor, lower member Sonoma Volcanics andesite breccias (Tsvab) occur near the valley margin, which is overlain by the

Tertiary conglomerate/breccias (Tcg/b). Across the center of Section B, the conglomerate breccias occur similarly to what is seen on Section C to the south. The thickest part of the unit is overlain by thick Quaternary alluvium. The center area is bound by faults to the east and west. The four wells to the east in this area are similarly constructed with groundwater intake structures across both the alluvium and the conglomerate/breccias. Reported well yields by test pumping are high (between 1,000 to 2,400 gpm), and specific capacities are between 10.5 and 26.9 gpm per foot of drawdown (i.e., they are comparable to similar wells on Section C). It is unclear if the groundwater is sourced largely from the alluvium and/or from the conglomerate breccia.

Farther west on Section B, lower member andesite flows with tuffs (Tsva) are overlain by fine-grained beds of Tertiary sedimentary rocks, which may be in part tuff beds (Tss & t). This unit is believed to be possibly a portion of the upper member of the Sonoma Volcanics, although its exact correlation is unclear. To the west on the section, the lower member andesite appears to have been up-faulted by the west Napa Fault Zone.

5.2.6 Isopach/Facies Map of Alluvium

With the cross sections as a working conceptual model, the study involved locating water well drillers' reports which occurred outside of the cross-section areas. Besides the problems of locating wells, it became apparent that areas on the Napa Valley Floor were deficient in wells, especially south of cross-section E below the City of Napa.

In order to evaluate the Quaternary alluvium, each driller's report, was located and the thickness and nature of the alluvium were noted on base maps. Initially the net or total, thickness and number of the sand and gravel beds were annotated on the base maps. However, it became apparent that outside of a band of thick sand and gravel beds, representing previous Napa River channels, the remainder of the valley was characterized by thin bands outside the central band, These represent tributary stream channel beds found outside the central band, but they could not be traced due to lack of well control, or because the beds tend to thin away from the valley sides. For these reasons, the alluvium deposits are represented by the facies of the depositional environment which formed them. The thick sand and gravel bed areas were perceived as former Napa River stream channels, and these were termed the fluvial facies. The marginal areas towards the valley sides of thin sand and gravel beds were designated as the alluvial plain facies formed by alluvial fans of tributary channels. Near cross-section E, the alluvium was perceived to change in character. The deposits appear to be fine grained with some thicker sand and gravel beds interbedded. This area is believed to represent a broader flood plain to deltaic depositional environment grading further south into possible marshland or estuary environment. Well control south of cross-section E is very limited, so it is difficult to draw adequate conclusions. This finer-grained dominated area is termed the sedimentary basin facies. From the data collected on

the alluvium, an isopach/facies map (**Figure 5-11**) was estimated to show equal thickness of alluvium and the distribution of the perceived facies.

5.2.7 Structure Contour/Subcrop Map of Pre-Alluvium

Concurrent with the process to locate wells and identify the alluvium thickness, the nature of the underlying older Sonoma Volcanics-aged deposits was examined. The initial step was to subtract the alluvium thickness from the surface elevation to yield the elevation of the older deposits at each well site; these elevations were plotted on base maps. These elevations were then contoured to produce the structure contour, or elevation map, on the top of the Sonoma Volcanics-aged geologic units.

Classification of the Sonoma Volcanics-aged units was problematic due to the varied drillers' descriptions of these units. Correlation between wells tended to be poor, and characterization of the rock types was interpretive. For each water well driller's report, it was necessary to recognize the age of the report and the driller, as patterns in drillers' terminology could be seen both between drillers and time. In most areas, it was necessary to examine all of the located wells to interpret the rock type encountered. It became advantageous to construct working cross sections in different areas to show to scale the various rock types in numerous wells. From these broader patterns, rock types and relationships became apparent.

The subcrop map (**Figure 5-12**) shows fine-grained sedimentary basin deposits near and south of Section E to Sections F and G. These deposits are believed to have formed in a subsiding basin banded by the marginal faults in marshland and estuary environments. These deposits are poorly known due to lack of deep well control except at the cross section locations and from wells mostly drilled almost 100 years ago. Some of the fine-grained deposits may represent tuffaceous deposits, but this is unclear. There appear to be few sand beds within these deposits. For groundwater production, volcanic rocks of the Sonoma Volcanics are found only along the margin of the valley bound by faults, or possibly at great depths of 1,000 feet or more. There sedimentary basin deposits are believed to be at least in part equivalent to the diatomaceous beds found in the MST and may range in age up to the early Quaternary.

Northward, toward Section D, a band of Tertiary Sonoma Volcanics sedimentary rocks (Tss/h) occurs of fine-grained beds with few sand and gravel beds. These overlie volcanic lower member Sonoma Volcanics andesites and a tuff of unknown correlation. Again, Sonoma Volcanics occur on the margin valleys bound by the faults. On the east side of the valley to just north of Section D, thin Tertiary sedimentary rocks overlie irregular topography of Sonoma Volcanics andesites as shown by the small knobs on the surficial geologic map.

Working cross-sections between Sections D and E indicate that the Sonoma Volcanics in Section D decline southward into the southern low-gravity basin. The overlying Tertiary sedimentary rocks appear to in part underlie, interbed, and interfinger with the Tertiary sedimentary basin deposits to the south.

In the Yountville Narrows area, the central Napa Valley Floor has poor and limited well control. Many wells appear to be completed solely in thick alluvial sand and gravel deposits. A few deeper wells either did not penetrate the alluvium, or the underlying rock type was not identifiable. The subcrop map in this area along the valley margins appears to reflect the surficial geologic units exposed in the various knobs and hills.

The subcrop map at Section C shows a more complex pattern. To the east, the lower member andesite breccias occur. In the central part of the valley, a sequence of reported conglomerate or flow breccias (Tcg/ab?) underlying thick sand and gravel of the alluvium is reported in a number of wells. This unit appeared distinct enough to map it separately, although the nature of this unit is unclear. It was traced laterally northward as shown, and it seems to be confined to a central narrow band. To the east, south of the Tertiary sedimentary surficial exposures near Conn Creek to the exposed flow breccias to the south, the conglomerate/breccias appear to grade southward into the flow breccias to the south. Both of these units appear to be overlain by Tertiary sedimentary rocks which extend northward.

The western side of the subcrop map north of Section C is more enigmatic in that rock types are more indistinct and dominated by tuffs and tuffaceous sedimentary rocks. Upper member tuffs of the Petrified Forest exposed north of the City of St. Helena appear to transition southward into interbedded tuffs and sedimentary rocks. Well control across this area from Section A to B and just south of these sections is limited by both the number and depth of wells. The areas are complicated by faulting, and the contours were drawn on local marker beds which do not match the top of Sonoma Volcanics-aged deposits. Beneath the Tss/h area, the contours are drawn on the underlying Tsva unit. The alluvium thickness across this area is thin, 50 feet or less. In the Tsvt areas near Section C, the structure contours are drawn on the top of the volcanic tuff unit. These are overlain by thick fine-grained sedimentary deposits which are undivided Tertiary and Quaternary (?) beds. The overlying alluvium is thin, about 50 feet thick or less. These two areas show the contours drawn on deep local marker beds to illustrate the complexity exhibited by certain beds in complex structural areas.

In the middle of the valley, the subcrop map of the Sonoma Volcanics units appears to reflect the declining of units into the narrow synclinal, fault bound northern gravity basin. The lower member andesitic Sonoma Volcanics (Tsva, Tsvt) descends northward to be overlain by tuffaceous sediments (Tst/s) and sedimentary rocks. These units appear to interfinger and interbed with the upper member tuffs of the Petrified Forest (Tst pf). The conglomerate/breccias

unit appears to interbed with the tuffaceous sedimentary rocks. The subcrop map of the Sonoma Volcanics in the middle valley is complicated by structural deformation as shown by mapped perceived faults and the steeply dipping beds of the surficial geologic units. In addition, water well drillers' reports descriptions of thick tuffaceous deposits tend to be more difficult to interpret because of their fine-grained nature.

Cross-sections constructed in this study depict the interpreted subsurface shape and thickness of geologic units and movement of faults based on surface geologic mapping and subsurface lithology from well information. **Figure 5-13** illustrates how geologic interpretations from surface and subsurface geologic information can be visualized to understand the geologic setting and relate subsurface geologic features to surface geology and topography at a cross-section in the vicinity of the City of Napa. **Figure 5-14** provides a similar perspective, expanded to show the subsurface stratigraphic units mapped at each cross section throughout the Napa Valley study area.

6 HYDROGEOLOGY

Previously published hydrogeologic reports have largely focused on the Quaternary alluvium. This was probably a result of limited numbers of wells drilled into the underlying Sonoma Volcanics or sedimentary rocks. The Kunkel and Upson (1960) dataset consisted of wells drilled prior to the early 1950s. They mentioned only three areas where wells were completed in the Sonoma Volcanics: the MST area, the Suscol area, and the Calistoga area. The remainder of the valley was not mentioned; this was probably because few deep wells existed then. Faye (1973) also focused on the Quaternary alluvium from the City of Napa northward. His well dataset appeared to have been limited to pre-early 1970s. He mentions information for 140 wells tapping the Sonoma Volcanics, but their locations are unclear. Johnson (1977) and Farrar and Metzger (2003) examined the Sonoma Volcanics in the MST area, as Quaternary alluvium is largely absent in that area.

6.1 Alluvium

In this study, the Quaternary alluvium thickness was mapped, and three facies were defined: fluvial, alluvial plain, and sedimentary basin. The fluvial facies consists of a thin narrow band of stream channel sands and gravels deposited by the Napa River. The sand and gravel beds tend to be thicker and/or more numerous in the fluvial facies area. They are interbedded with finer-grained clay beds of probable floodplain origin. Wells constructed in the fluvial facies tend to be moderately high yielding (for the valley, roughly 50 to 200 gpm). Local areas where thicker sand and gravel beds are reported, the well yields are the highest in the valley, ranging from about 200 to 2,000 gpm.

These areas with thick sand and gravel beds occur in the Yountville Narrows area and extend northward. Local areas of relatively lower well yield values of 200 to 500 gpm occur to the north and south. Hydraulic properties of these deposits are recorded during airlift testing, and drawdown values are generally not reported. Only a few pump test results have been found, and these are in the high yielding area just north of the Yountville Narrows.

The alluvial plain facies of the Quaternary alluvium extends outward from the central fluvial facies and thins to zero at the edge of the valley sides. These deposits appear to have been deposited as tributary streams and alluvial fans. These deposits appear to consist of interbedded sandy clays with thin beds (less than 10 feet thick) of sand and gravel. Wells constructed in the alluvial plain facies tend to be low yielding, ranging from a few gpm to few tens of gpm. By at least 1970, most wells drilled on the alluvial plain facies were constructed to deeper depths into the underlying Sonoma Volcanics.

At the northern end of the lower valley, the sedimentary basin facies of the alluvium occurs. This facies is characterized by fine-grained silt, sand, and clays with thin to scattered thicker

beds of sand and gravel. The sedimentary facies is believed to be floodplain deposits that extend to the southern marshland/estuary deposits. As noted, the extent of this facies is poorly known due to lack of well control farther south. Limited information indicates low to moderate well yields of a few gpm to possibly up to 100 gpm. Again, the lack of pump test information makes hydraulic properties of the deposits difficult to assess.

6.2 Sonoma Volcanics and Tertiary Sediments

In previous studies, the Sonoma Volcanics and sedimentary rocks have been undifferentiated in the subsurface below the Napa Valley. For this study, numerous water well drillers' reports from the last 40 years were used, and a subcrop map of the distribution of rock types has been developed. The subcrop pattern has been interpreted into the stratigraphic and structural features. Wells drilled into the Sonoma Volcanics and sedimentary rocks tend to be low yielding. Typically, wells yield less than 16 gpm to less than 50 gpm. A few wells are reported to yield over 100 gpm. Nearly all of this data is from airlifted well tests, where water levels decline drastically. This indicates that the hydraulic characteristic of these geologic units is poor, probably as a result of their origin, the degree of consolidation and/or fine-grained nature of the units. Essentially, this means the Sonoma Volcanics typically exhibit relatively low permeability, or limited ability to yield water to wells.

The subcrop units of tuffs (Tst and Tsvt) and sediments (Tsvt/s) have similar low water yielding characteristics. The Tertiary sedimentary rocks (Tss/h) seem to have slightly higher, but still low, well yielding characteristics. The conglomerate/breccias unit (Tcg/ab) appears to have somewhat higher water yielding characteristics, but most wells are screened across overlying thick alluvium deposits.

The andesite flows and flow breccias (Tsva and Tsvab) are possibly the most variable in well yielding characteristics ranging from low yields to as high as several hundred gpm. The final Sonoma Volcanics unit is the Tertiary sedimentary basin deposits (TQsb) in the lower valley, which may have low to moderate well yields depending on whether thin sand and gravel interbeds are encountered in the generally fine-grained sedimentary deposits.

The final part of the subcrop map is the small area of Mesozoic Great Valley unit (KJgv) in the Yountville Narrows which has possibly the lowest well yields of the units beneath the Napa Valley Floor.

6.3 Recharge Areas

The distribution and quantity of groundwater recharge occurring in Napa County is primarily a function of the geologic units which precipitation encounters, either as rainfall or runoff. Johnson (1977) performed a series of seepage experiments on the major creeks and tributaries in and

around the MST Subarea to determine the primary mechanisms of groundwater recharge. A seepage experiment consists of several streamflow measurements taken along the length of a stream to quantify streamflow gains and losses. The stream is considered losing where streamflow decreases between measurements, and gaining where streamflow increases. He concluded that the infiltration rate from precipitation and runoff is greatest where tuffs are exposed or underlie shallow Quaternary deposits. Additionally, only a small percentage of groundwater recharge was found to come from direct precipitation, but instead it is greatest where streams and tributaries come in contact with tuffs. Farrar and Metzger (2003) similarly analyzed seepage gains/losses for various creeks and tributaries in the MST. They concluded that significant streambed infiltration also occurs where streamflow passes over unconsolidated, highly permeable, alluvial deposits. **Figure 6-1** is a conceptual illustration of the major surface and subsurface hydrologic processes occurring within a watershed and shows how the hydrogeology of the Napa Valley area relates to these processes. As illustrated in **Figure 6-1** and discussed in greater detail in Sections 7 and 8 of this report, precipitation falling within the watershed infiltrates the ground or becomes surface water outflow through surface runoff processes. Some fraction of infiltrated water is consumed through plant evapotranspiration and some water percolates deeper and into the aquifer system as recharge. The potential for water to recharge the groundwater system depends on many factors, including the nature of the geologic materials and topography.

Based on the findings of Johnson (1977) and Farrar and Metzger (2003), a map was created to locate areas of greatest recharge potential. This map shows the location of exposed tuffs throughout the county (**Figure 6-2**). Sonoma Volcanics sedimentary deposits and various alluvial units found countywide were also included in the map following findings by Farrar and Metzger (2003). Areas in which the slope of the land surface exceeds 30 degrees, beyond which recharge potential is significantly reduced, were also added to the map.

Two sizeable exposures of rhyolitic ash-flow tuff and related alluvium occur in the northern portion of the Eastern and Western Mountains near Calistoga. The eastern exposure covers roughly 30 square miles with tuff in the north and Sonoma Volcanics sedimentary deposits to the south. Following Johnson (1977), the greatest recharge would be expected along Bell Creek, which traverses much of the northern tuffs, and Conn Creek, which passes over large Sonoma Volcanic sedimentary deposits in Conn Valley, some of which are covered by younger alluvium. The Western Mountains exposure, which covers roughly 18 square miles, is almost entirely tuff, with a single Sonoma Volcanics sedimentary deposit in the north at Cyrus Creek. Again, following Johnson (1977), the greatest recharge potential would be expected along York, Mill, Richie, Nash, and Cyrus Creeks (Figure 6-2). Although concealed below the Napa Valley Floor, it is likely that the two exposures are connected at depth. It is expected that much of the water recharged through these two exposures eventually reaches the aquifer units of the Napa Valley Floor and flows to the south.

Another significant tuff exposure occurs to the east of the MST, which is discussed in depth in a later section. Other isolated exposures are found throughout the western portion of the county, including one in the Western Mountains along Redwood Creek, which may significantly influence local groundwater conditions. Additional local recharge occurs in the various alluvium filled valleys in the eastern portion of the county. The most significant area of groundwater recharge for the entire county occurs along the Napa Valley Floor in the Calistoga, St. Helena, Yountville, and Napa Subareas.

6.3.1 Napa Valley Floor

Groundwater recharge to the alluvium of the Napa Valley Floor (Calistoga, St. Helena, Yountville, and Napa Subareas) occurs by infiltration of precipitation, percolation from streams/rivers, and subsurface inflow from the surrounding subareas (**Figure 6-2**). The high permeability of the alluvial sediments permits precipitation and surface water to readily infiltrate and recharge groundwater throughout the majority of the valley. These high permeability soils combined with the large volume of water that flows through the Napa River create the potential for significant recharge to occur.

According to Faye (1973), this potential is restricted by high groundwater levels around the Napa River. According to the Napa Baseline Data Report (Jones and Stokes; and EDAW, 2005), recharge in the northern Napa Valley occurs primarily from direct infiltration of precipitation, and to a lesser extent, from irrigation and streambed percolation.

Data relating to groundwater inflow to the Napa Valley from surrounding subareas is limited to the MST. Johnson (1977) estimated that outflow from the MST into the Napa Valley was roughly 2,050 acre-feet per year (afy). Subsequently, Farrar and Metzger (2003) estimated that 600 acre-ft/yr of groundwater was entering the Napa Valley from the MST; they noted that the difference between their estimate and Johnson's closely matches the increase in groundwater pumping in the MST between 1975 and 2000.

6.3.2 Milliken-Sarco-Tulucay

To the east of the MST Subarea a series of tuff exposures occur along Milliken, Sarco, Hagan, and Tulucay Creeks. Milliken, Sarco and Hagan Creeks flow into the MST Subarea where each crosses a large body of Sonoma Volcanics sedimentary deposits. Farrar and Metzger (2003) measured the greatest stream losses (16.5 acre-feet per day (afd)) along Milliken Creek where alluvial fan and Sonoma Volcanics sedimentary deposits overlie a thick tuff deposit. Streambed infiltration was significantly lower in the Sarco and Tulucay Creeks (0.1-1.1 afd), where low permeability diatomaceous deposits are either found in place of or covering tuff deposits.

6.3.3 Carneros

The Carneros Subarea is predominantly low permeability Huichica Formation with only minor tuff and alluvial deposits. The tuff deposits, located along the eastern and westernmost borders of the area are not expected to be significant sources of groundwater recharge, primarily due to their limited size and lack of proximity to surface water. Recharge within alluvial deposits along the Huichica and Carneros Creeks, as well as other nameless tributaries, is a significant source of recharge (Jones & Stokes et al., 2005), although this is most likely restricted by the underlying low permeability Huichica Formation and Sonoma Volcanics. Other sources of recharge may include inflow from the Western Mountains, Napa Valley or infiltration through local concentrations of coarse-grained materials within the Huichica Formations. More data would be necessary to determine where and to what extent recharge is occurring within the Carneros Subarea.

7 SURFACE WATER GROUNDWATER INTERACTIONS

7.1 Napa Valley Groundwater Levels

The nature of interactions between groundwater and surface water depend largely on the gradient for water flow between groundwater and surface water systems. Water flows from higher elevations to lower elevations. Groundwater elevation contours represent lines of equal groundwater elevation and are independent of ground surface topography. Contours of groundwater elevation provide a snapshot of the direction and relative magnitude of the groundwater flow gradient. If the groundwater system depicted on a contour map exists in an unconfined condition (i.e., at atmospheric pressure), as is expected in the widely distributed shallower alluvial deposits in Napa Valley, the groundwater elevation contours also represent the water table elevation. Characterizing the relationship between surface water elevations and groundwater elevations is important for understanding the nature of groundwater-surface water interaction. In an unconfined groundwater setting, groundwater and surface water will interact and exchange water according to the elevation gradient between these water bodies. To evaluate this relationship, elevations along surface waterways in the Napa Valley area were compared with groundwater elevations.

Previously published groundwater elevation contour maps provide a visual representation of historical conditions covering approximately 60 years between 1949 and 2008. These historical interpretations serve as a basis for comparing flow directions and gradients over different time periods. The 1949/1950 contours represent conditions during the early era of groundwater development in Napa Valley, while subsequent contour maps represent periods of increasing groundwater development and extraction. This report includes groundwater elevation contours for Napa Valley in Spring 2010, as an update to previous LSCE efforts (LSCE, 2011a) and as the basis for initial comparisons of groundwater-surface water interactions.

In addition to providing updated groundwater elevation contours, this report also evaluates available information about the construction of wells where groundwater level measurements were recorded in Spring 2010. This evaluation is important to ensure that groundwater elevations represent the conditions within a single unit of the aquifer system.

7.1.1 Groundwater Elevation Contours

Groundwater elevation contours are derived from available water level measurements made in wells. As a result, the accuracy of interpretations in groundwater elevation contours depends on the spatial distribution and accuracy of water level control data points. Spring 2010 groundwater level measurements were available from 30 monitored wells in Napa Valley, excluding the MST subarea. Sixteen of the measured wells are in the current Napa County groundwater monitoring

network, which is monitored semi-annually while four additional wells are monitored monthly by DWR. Water level data for the remaining 10 wells are from regulated groundwater monitoring sites included in the SWRCB GeoTracker network. The total number of wells with available groundwater level data for Spring 2010 was down from 45 in 2008. **Figure 7-1** shows the locations of groundwater elevation data points used in generating the Spring 2010 groundwater elevation contours.

Groundwater elevation contours are developed from the available depth to water records from the 30 available wells. Prior to interpolating groundwater elevations across the valley, depth to water values were converted to groundwater elevation values by subtracting the measured depth to water from the reference point elevation at each monitored well. In this way the depth to water measurements were related to mean sea level as a standard point of reference. The resulting groundwater elevation values at each well were used to interpolate groundwater elevation contours throughout the Napa Valley Floor. Measured groundwater levels used in contouring generally represent conditions in the Napa Valley alluvium; therefore, mapped bedrock outcrop areas were excluded from the contouring process.

Interpreted groundwater elevation contours for Spring 2010 and Spring 2008 are shown in **Figures 7-1 and 7-2**, respectively. The direction of groundwater flow is perpendicular to the contour lines. Groundwater elevation contours for Spring 2010 appear similar to those developed by LSCE for Spring 2008. Contours during both time periods show a generally southeasterly to east-southeasterly groundwater gradient paralleling the valley axis from Calistoga to Yountville with similar groundwater elevation ranges. Groundwater elevations in Spring 2008 and 2010 ranged from above 300 feet near Calistoga to less than ten feet along the Napa River in southern areas of the City of Napa. In the southwestern quadrants of the St. Helena and Yountville Subareas and eastern portions of the Napa Subarea, Spring 2010 contours show a gradient for groundwater flow that is more perpendicular to the valley axis generally from the valley edges towards the Napa River. These areas have a greater density of groundwater elevation data, which improves the accuracy of interpreted groundwater elevation contours in the area. Both the accuracy and extent of the groundwater elevation contours could be improved with an expanded groundwater monitoring network of aquifer-specific wells, as previously recommended (LSCE, 2011a). Consistent with those recommendations, Napa County is embarking on activities to expand the countywide groundwater monitoring network (LSCE, 2013).

Some form of well construction information is available for 18 of the 19 non-regulated monitored wells used to create the Spring 2010 groundwater elevation contours. Of these wells, eight include sufficient information to determine the aquifer unit in which the well is completed. Of those eight, only three are completed in the Quaternary alluvium only. The other five monitored, non-regulated wells with a known well completion report all have well screen intervals extending into stratigraphic units below the alluvium, most often into underlying

Sonoma Volcanic units. The regulated monitoring wells used for the contour map are assumed to be completed only in the alluvium, since the purpose of such wells is generally to monitor shallow groundwater at soil and groundwater contamination sites.

7.1.2 Groundwater Elevations Northeastern Napa Subarea

Historical groundwater levels and trends through 2009 are comprehensively discussed in the report on Napa County Groundwater Conditions and groundwater Monitoring Recommendations (LSCE, 2011a). Historical groundwater level declines are described for the MST area and are also noted for the northeastern Napa Subarea, where there has been a 10 to 30 foot decline in water levels over the past 10 years. The geologic cross sections presented in this Report, along with the work described in Section 9, help to identify factors contributing to the observed groundwater level decline in the northeastern Napa Subarea. As shown in LSCE (2011a), there are four pumping depressions that have developed in the northern, central, southern, and northwestern parts of the MST subarea. The latter pumping depression (which is also shown on **Figure 7-1**) extends west of the Soda Creek fault. The currently monitored well located just east of the Napa River and west of Soda Creek fault (i.e., the well that shows a Spring 2010 groundwater elevation of – 7.6 msl) is constructed to a depth of 205 feet and is completed in the Sonoma Volcanics formation. The three nearest monitoring wells located west of the Napa River in the northeastern Napa Subarea constructed to depths of 120 feet or less and are completed in the alluvium. These well have shown stable groundwater level trends. The monitoring well in the alluvium that is closest to the well constructed in the Sonoma Volcanics has shown stable water levels since the 1960s.

As shown in Section 5, **Figure 5.7**, there is an offset of the Sonoma Volcanics in the west side of the Napa River where a possible fault is identified. It appears that the extent of the pumping depression beyond the MST subarea may be limited to the northeastern Napa Subarea east of the Napa River. However, there are no currently monitored wells west of the Napa River which are completed in the deeper Tertiary Quaternary sedimentary basin deposits. As described in Section 9 (and LSCE, 2013) additional monitoring locations are recommended in the Napa Subarea.

7.2 Stream Thalweg Mapping

Academic and resource management studies increasingly recognize the importance of groundwater-surface water interactions on the availability and quality of water resources (Winter et al., 1998; Alley et al., 1999; Sophocleous, 2002). As discussed above, water flows from high elevation potential to low elevation potential. The nature of interaction between groundwater and surface water depends largely on the hydraulic gradient between these water bodies. Previous hydrogeologic investigations of Napa Valley, beginning with Faye (1973), identified direct

infiltration of precipitation and percolation of surface water as the primary mechanisms for groundwater recharge in the Napa Valley. Faye concluded that groundwater recharge from percolating surface water was greatest where tributaries overly alluvium along the valley margins. In 1972, Faye interpreted that groundwater was discharging to the Napa River and that the river was under net gaining conditions for the study area upstream of Oak Knoll Avenue, at least regionally and on an annual basis. Later, Farrar and Metzger (2003) noted that subsurface inflow to the southern Napa Valley had been significantly decreased by groundwater pumping within the MST.

These previous studies suggest that a strong relationship between groundwater and surface water systems exists in the Napa Valley. Consequently, characterizing the nature of these interactions and responses to hydrologic changes (including variations in annual precipitation and increasing surface water and groundwater use) warrant further attention. The hydrogeologic synthesis and groundwater elevation contours presented previously in this Report provide the foundation for better understanding this component of the Napa Valley hydrologic system.

The stream thalweg represents the path of lowest elevation along the length of a stream or other surface waterway. Determining stream thalweg elevations along waterways in the Napa Valley is an important element in understanding the relationship between surface water and groundwater resources in the area. Comparison of the elevations along the stream thalweg with groundwater elevations provides a general representation with which to evaluate the hydraulic gradient between the groundwater and surface water bodies. This analysis identifies approximate stream elevations based on available elevation data. These stream elevations are referred to as "estimated stream thalweg" throughout this Report.

Mapping of stream alignments and analyses of thalweg elevations were performed for the main stem of the Napa River and 28 tributaries using GIS analyses. Resulting estimated stream thalweg elevations and locations were checked against other readily available data and deemed adequate for characterizing the vertical relationship between groundwater and surface water bodies. However, the thalweg alignment and elevations are approximate and may not be accurate for all purposes. It is important to recognize the limitations of the approach and in the developed data. This approach was developed to estimate stream thalweg elevations across the entire Napa Valley area at reasonable expense. Conducting field surveys of stream thalweg elevation, which would verify the accuracy of this approach, were beyond the scope of this study.

Outputs from this mapping effort included GIS files containing polylines, with points and elevations representing the Napa River and its tributaries. The following description is provided as background on the development of these files and to explain and demonstrate the quality control and checks performed.

7.3 Elevation Data and Stream Alignments

GIS analyses relied on two primary pieces of data: ground surface elevation data for the Napa Valley area and stream alignments for the Napa River and tributaries. During the course of the analysis multiple elevation data sets were utilized and initial stream alignments were refined to produce a final set of stream alignment points with associated elevations.

Initial stream alignments for the Napa River Basin were extracted from an existing data set of stream alignments developed at the former Teague Data Center (TDC) based on USGS 1:100,000-scale topographic maps. TDC stream alignment data contain both named and unnamed streams in Napa County. Only named streams in the Napa Valley area were analyzed in this study. **Table 7-1** lists the named streams included in the estimated stream thalweg analysis. The locations of streams are shown in **Figure 7-3**.

Table 7-1: Napa River Tributaries Included in Estimated Stream Thalweg Analysis

Westside Tributary Streams	Eastside Tributary Streams
Blossom Creek	Garnett Creek
Cyrus Creek	Biter Creek
Ritchie Creek	Bell Canyon Creek
Mill Creek	Moore Creek
York Creek	Chiles Creek
Sulphur Creek	Sage Creek
Bale Slough	Conn Creek
Bear Canyon Creek	Rector Creek
Dry Creek	Soda Creek
Redwood Creek	Milliken Creek
Browns Creek	Sarco Creek
Napa Creek	Murphy Creek
Carneros Creek	Kreuse Creek
	Tulucay Creek
	Suscol Creek

TDC stream alignment data were acquired as geo-referenced polylines. Points were added to the polylines to develop discrete locations for sampling elevation data. A preliminary analysis was done using TDC stream alignments and 30-meter and then 10-meter resolution digital elevation model (DEM) data from the National Elevation Dataset (NED). Thalweg elevations derived from NED DEM data provided reasonable, but very coarse estimates. Comparison of these data with surveyed stream thalweg data for the Napa River obtained from the Napa County Resource Conservation District (RCD) showed reasonable results in some reaches and considerable

differences in other reaches. Therefore, other sources of readily available elevation data were reviewed.

Light Detection and Ranging (LiDAR) elevation data collected on February 1, 2003 and available from the National Center for Airborne Laser Mapping (NCALM) were used to refine stream thalweg elevation estimates. These LiDAR data were processed to provide last return data representing bare ground elevation measurements. The resolution of LiDAR points was approximately 1.45 points per square meter, much finer than the 10-meter NED DEM data. The LiDAR survey was not identified as water penetrating and is therefore assumed to represent the water surface where water exits.

TDC stream alignments were used to sample point LiDAR elevation data at approximately 3-foot intervals along stream polylines. Review of resulting stream elevations showed considerable variation in elevation moving from upstream to downstream. Water surface elevation should generally decrease from upstream to downstream; however, initial results based on LiDAR data showed numerous sudden increases and decreases in elevation that were clearly in error. Further review of TDC stream alignments using aerial photographs showed that in many areas, stream alignments were outside stream corridors. Therefore, TDC stream alignments for the Napa River and tributaries were reviewed and redefined. The Napa River alignment was redrawn using a combination of shaded relief maps developed from LiDAR data and aerial photographs (Bing Maps Aerial imagery from www.esri.com). In this way, a polyline more closely following the current Napa River alignment was developed.

Tributaries of the Napa River were re-drawn by analysis of LiDAR data in GIS. This analysis processed the LiDAR data to automatically create a polyline along waterways based on the number of LiDAR data points that contribute to a drainage area. Computational limitations for processing the entire Napa River watershed with the high density LiDAR data prevented using this approach to re-draw the Napa River alignment.

All of the revised stream alignments were used to resample the LiDAR data at approximately 3-foot intervals along stream polylines to create final representations of the estimated thalweg elevation along the length of each stream thalweg.

7.4 Validation of Estimated Stream Thalweg Elevation

Final stream elevation points, based on revised stream alignments and LiDAR data, were reviewed for quality control and compared with surveyed stream thalweg data and other data sources. Direct comparisons of Napa River estimated thalweg elevations were made with surveyed stream thalweg data from the NCRCD. Stream thalweg surveys performed by the Napa County RCD were conducted with a rod and level in May and June of 2007. Survey data

included thalweg distance and elevation and cover approximately 13.7 river miles of the Napa River between St. Helena and Napa, from just downstream of Zinfandel Lane Bridge and continuing downstream to Oak Knoll Avenue. Comparisons of surveyed data from Napa County RCD and estimated stream thalweg elevation points developed in this analysis are presented in **Figure 7-4**.

Figure 7-4 illustrates the generally similar trends in estimated stream thalweg elevations based on LiDAR data and digitized Napa River alignment and surveyed thalweg elevations from Napa County RCD. Differences between estimated stream thalweg elevation and survey data were quantified separately for the reach upstream of Oakville Cross Road and downstream of Oakville Cross Road. The average absolute difference upstream of Oakville Cross Road is 3.2 feet. Differences between estimated stream thalweg elevation and surveyed data are greatest at the upstream end of this reach, starting at approximately Zinfandel Lane. Differences in this section average approximately 6 feet. The estimated stream thalweg elevation is consistently higher than surveyed elevation upstream of Oakville Cross Road, perhaps due to LiDAR data measuring water surface instead of stream channel bottom. However, the estimated stream thalweg elevation is not consistently representing Napa River water surface as evidenced by frequent spikes and dips in elevation.

Average absolute difference between the estimated and surveyed stream thalweg elevations downstream of Oakville Cross Road is 2.3 feet. Estimated stream thalweg elevations are generally variable and are higher than surveyed elevations in some sections and lower than surveyed elevation in other parts of this reach. Estimated stream thalweg elevations are higher than surveyed data between Oakville Cross and Cook roads, approximately equal to surveyed data for several thousand feet downstream of Cook Road, and below surveyed data starting approximately 5,000 feet upstream of Oak Knoll Avenue

The variability in elevation of estimated stream thalweg elevations likely indicates LiDAR data are not always representative of water or ground surface. LiDAR data may include riparian canopy elevations, bridges, and other errors. An adjustment to estimated stream thalweg elevations was considered to partially account for these differences and potential errors. However, adjustments were not made because differences were not consistent and adjustments could potentially introduce additional error. Some component of these differences is likely caused by error in the stream alignment.

Estimated stream thalweg elevations for tributaries and other Napa River reaches were reviewed and spot checked with 1:24,000-scale USGS topographic maps to determine if estimated stream thalweg elevations are consistent with topography. The following figures are three examples of estimated stream thalweg elevation for tributaries throughout the Napa Valley area.

Figure 7-5 illustrates estimated stream thalweg elevations for Mill Creek, a small tributary on the west side and northern end of the Napa River. Mill Creek joins the Napa River at an elevation of approximately 250 feet and shows a steep section at approximately 16,000 feet of stream length upstream from the Napa River. The estimated stream thalweg elevations presented in **Figure 7-5** appear smooth compared to those presented above for the Napa River. However, this is a function of the large range of elevations illustrated (y-axis range). Closer review of data show that the same type of variability evident in estimated stream thalweg elevation data along the Napa River also exists in estimates for Mill Creek and other tributaries. This variability is likely caused by LiDAR data that represent canopy returns instead of ground surface or stream water surface.

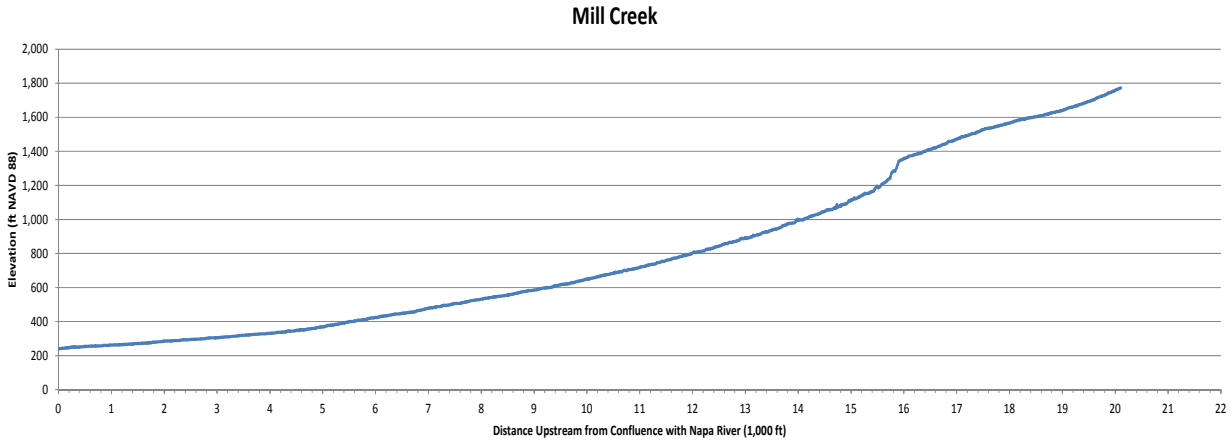


Figure 7-5. Estimated Stream Thalweg Elevations for Mill Creek

Figure 7-6 illustrates estimated stream thalweg elevations for Rector Creek, a tributary on the east side of the Napa River near Yountville. Rector Creek is dammed to create Rector Reservoir. Both the dam and reservoir water surface are clearly illustrated in the estimated stream thalweg elevations. The dam is located at approximately 9,500 feet of stream length and the reservoir water surface is shown from approximately 10,000 to 15,000 feet of stream length.

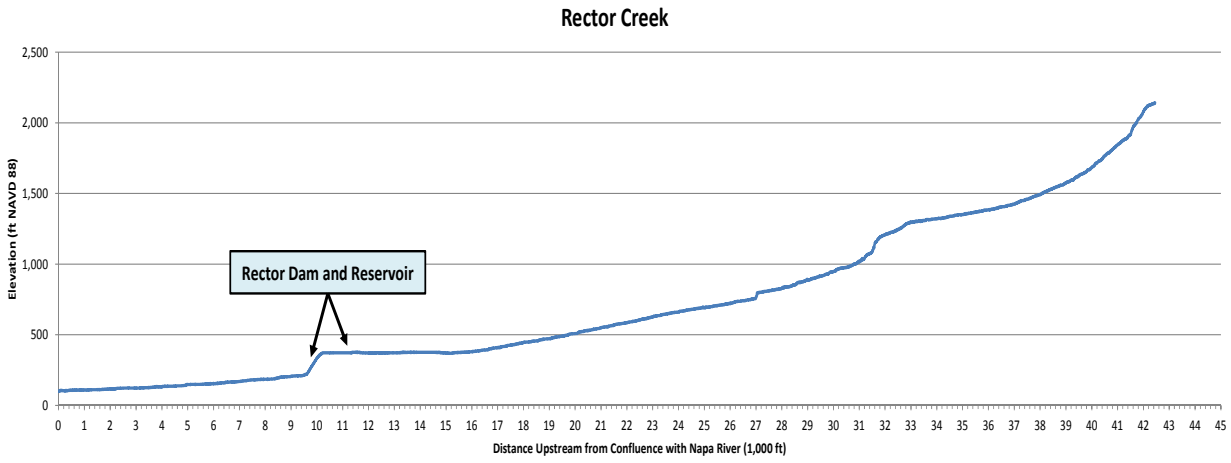


Figure 7-6. Estimated Stream Thalweg Elevations for Rector Creek

Figure 7-7 illustrates estimated stream thalweg elevations for Tulucay Creek, a tributary on the east side of the Napa River near Napa. This is the lower portion of Tulucay Creek only, with the upper portions represented as Murphy and Kreuse Creeks. The variability in estimated stream thalweg elevations evident along Tulucay Creek in **Figure 7-7** is representative of the variability for all tributaries; however, this pattern is more apparent in the profile for Tulucay Creek because of the narrower elevation range shown in the figure.

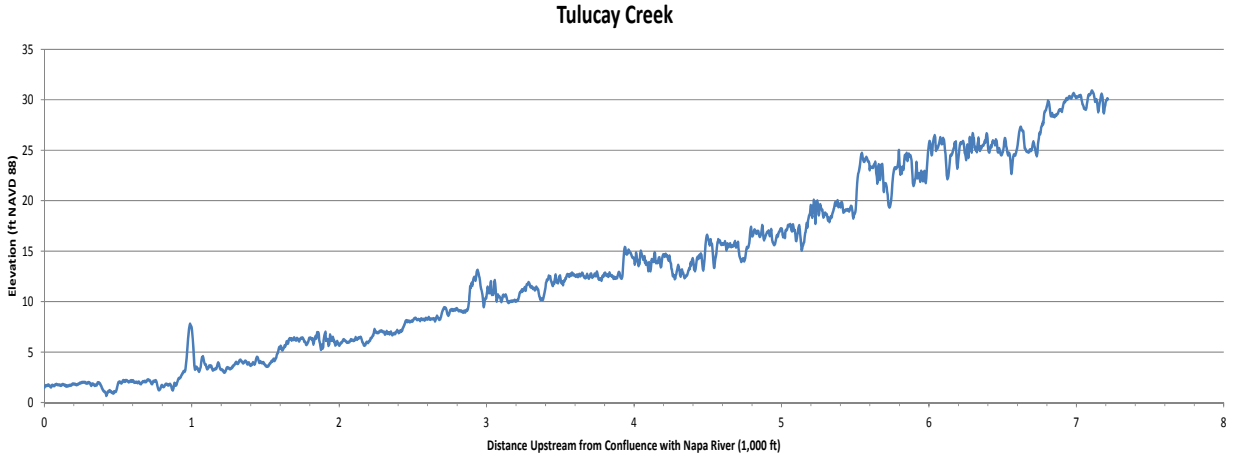


Figure 7-7. Estimated Stream Thalweg Elevations for Tulucay Creek

Based on review of all tributaries, checks against USGS topographic maps, and comparisons presented in **Figure 7-4**, estimated stream thalweg elevations are generally in agreement with surveyed data and topography and provide data useful for evaluating the vertical relationship between the groundwater surface and stream thalweg, which can be used to characterize groundwater-surface water interactions in the Napa Valley area. Estimated stream thalweg elevations show considerable variability over short distances, likely due to canopy returns in the LiDAR data used in the analysis or because of misalignment of the mapped stream with the actual channel.

7.5 Preliminary Evaluation of Groundwater-Surface Water Relationship

The groundwater surface elevation and the estimated stream thalweg elevation data are important components for characterizing the groundwater-surface water relationship in the Napa Valley area. The Spring 2010 groundwater elevation contours provide a snapshot representation of groundwater conditions with which to compare the vertical relationship between the groundwater and surface water. This spatial relationship will assist in developing an understanding of the nature of water exchange between the groundwater and surface water systems. When and where the groundwater surface is higher than the surface water elevation then groundwater is expected to discharge to the surface body. Conversely, when surface water elevation is higher than the groundwater elevation surface water is expected to flow into the groundwater system providing recharge. This analysis focuses specifically on the degree of connectivity between the Napa

River thalweg, as estimated above, and the elevation of the regional groundwater surface of the unconfined alluvial aquifer system of the Napa Valley in Spring 2010. Future expansion of this evaluation using more refined spatial representations of the groundwater surface and at different time periods will greatly improve the understanding of the dynamics in this relationship.

7.5.1 Methods and Limitations

This analysis is based on interpreted groundwater elevation contours for the alluvial aquifer system in Napa Valley for Spring 2010. As discussed above, the Spring 2010 groundwater elevation contour map was produced from 30 monitored wells in the Napa Valley area. The interpreted groundwater elevation has considerable uncertainty and limitations because of the sparse distribution of monitored sites over the mapped area. Furthermore, some of the monitored wells used to interpret the groundwater elevation contours may not be completed exclusively in the alluvial aquifer system.

The estimated Napa River thalweg alignment and elevations, described above, are used here to define the lowest point in the valley for evaluation of the vertical relationship between groundwater and surface water along the valley floor. Before performing this analysis, the estimated stream thalweg elevation data were filtered in order to minimize the variability in estimated stream thalweg elevation data and consistently represent the lowest estimated stream thalweg elevation. This was done by selecting the minimum stream thalweg elevation values within every approximately 60-foot segment of river. This process successfully provides a stream thalweg elevation representation that follows the elevation trends of the original data while consistently representing the lowest thalweg elevation along the river without the larger variability contained in the original data. This data filtering process was also conducted using smaller and larger sample intervals; however, the 60-foot sample interval appeared to best reduce the variability in the data without excessive generalization. The location of each minimum value was preserved along the thalweg alignment and assigned to a thalweg segment extending to the midpoint between each minimum value. The difference between the groundwater elevation and the estimated stream thalweg elevation was calculated for each stream thalweg segment to evaluate the vertical relationship between the groundwater surface and the thalweg bottom.

A similar depth to water value was calculated using valley-wide LiDAR data for 2003 from NCALM and the Spring 2010 groundwater elevation contours. In this case, the depth to groundwater below the ground surface was calculated throughout the extent of the interpreted groundwater elevation contours for the Napa Valley area.

7.5.2 Results and Interpretations

Figure 7-8 shows the calculated depth to groundwater below the estimated thalweg elevation along the Napa River as interpreted for Spring 2010. Only the calculated depth to groundwater values for portions of the Napa River thalweg located within one mile of a monitored well are symbolized on **Figure 7-8**. Confidence in the calculated depth to groundwater in these segments is greater because the groundwater elevation contours in these areas are more constrained by measured water levels at monitoring sites. The degree of confidence in the interpreted groundwater elevation is less in areas farther from monitoring locations.

Calculated depths to groundwater below the estimated thalweg alignment in **Figure 7-8** are commonly "negative" for Spring 2010 indicating that the interpreted groundwater elevation was above the bottom of the Napa River thalweg. These negative values suggest areas where a direct connection between the water table and the river may have existed in Spring 2010 and where groundwater has the potential to discharge into the stream channel. Positive values suggest areas where groundwater is below the bottom of the Napa River thalweg and where surface flows in the river have the potential to percolate and recharge the groundwater system. These results provide an insight into reaches where a direct connection between the Napa River and the alluvial aquifer are not likely under the conditions documented in Spring 2010. These areas include reaches along the northern boundary of the Napa and MST subareas at the Soda Creek Fault, adjacent to a previously documented area of lower groundwater elevations.

A definitive evaluation of the relationship between the river and groundwater would require accurate data for the river stage (i.e., elevation of water in the river) and more data about depth to groundwater in areas adjacent to the river at the time for which the depth to groundwater is represented. The product of such an evaluation depends greatly on the ability to accurately interpret groundwater levels throughout the valley. As discussed above, an expanded groundwater monitoring network would provide data for a more refined interpretation of the groundwater surface. Compiling and analyzing the necessary data for more detailed evaluations is beyond the scope of the current study but could be addressed in future water resource investigations in the Napa Valley.

Figure 7-9 shows the calculated depth of groundwater below the ground surface in the Napa Valley for Spring 2010. As with the calculated depth to groundwater values along the Napa River thalweg, the groundwater elevation contours in Spring 2010 were interpreted with limited well control (wells in the groundwater level monitoring program with known well construction information) and, therefore, calculated values in many areas of the valley have great uncertainty. Calculated depth to groundwater values are negative in parts of the valley (i.e., the computed groundwater depth is above the ground surface). Generally, these values occur in areas where the interpreted groundwater elevation contours are not constrained by actual water level

measurements (no well control). Although negative depth to groundwater values are possible, such widespread shallow water table conditions (water table at or above the ground) have not been reported in the area. Because of the uncertainty of the interpreted groundwater elevation contours the negative depth to water values are not shown in **Figure 7-9**.

A review of depth to water values in the LiDAR-derived data set and the measured depth to water values in monitored wells shows consistent values between the two data sets. This suggests that these data represent actual conditions in areas where measured data exist; however, beyond these control points the data are more uncertain. Consequently, the calculated depth to groundwater values shown in **Figure 7-9** should be interpreted with consideration of the degree of confidence in the calculated values throughout the area. The degree of confidence in these calculated values is highest near monitoring well locations and decreases with distance away from such well control. Despite the great uncertainty in the data in parts of the valley, depths to groundwater (both measured and calculated) show generally shallow groundwater throughout much of the valley, particularly in the northern end of the valley. Areas where calculated depth to water is negative generally coincide with areas of the valley lacking sufficient monitoring site density. The calculated depths to groundwater appear to be reasonably represented in the Napa Subarea because this area has the greatest density of monitored sites, particularly along the lower elevation eastern edge.

8 GROUNDWATER RECHARGE

8.1 Estimating Groundwater Recharge (With Root-Zone Water Balance)

8.1.1 Overview

Updating the hydrogeologic conceptualization and characterization of conditions in Napa County involves refining understanding of the hydrologic processes for groundwater storage and movement, particularly in the aquifer system underlying the main Napa Valley Floor. These processes involve many complex pathways at many different time scales. A key County General Plan goal (Napa County, 2008) is to "Conserve, enhance and manage water resources on a sustainable basis to attempt to ensure that sufficient amounts of water will be available for the uses allowed by this General Plan, for the natural environment, and for future generations." Construction of a water budget, also known as a water balance, is a tool scientists can employ to assess the quantity of groundwater in storage. A conceptual illustration of the components of a water balance in a watershed is shown in **Figure 8-1** (figure from Healy et al., 2007).

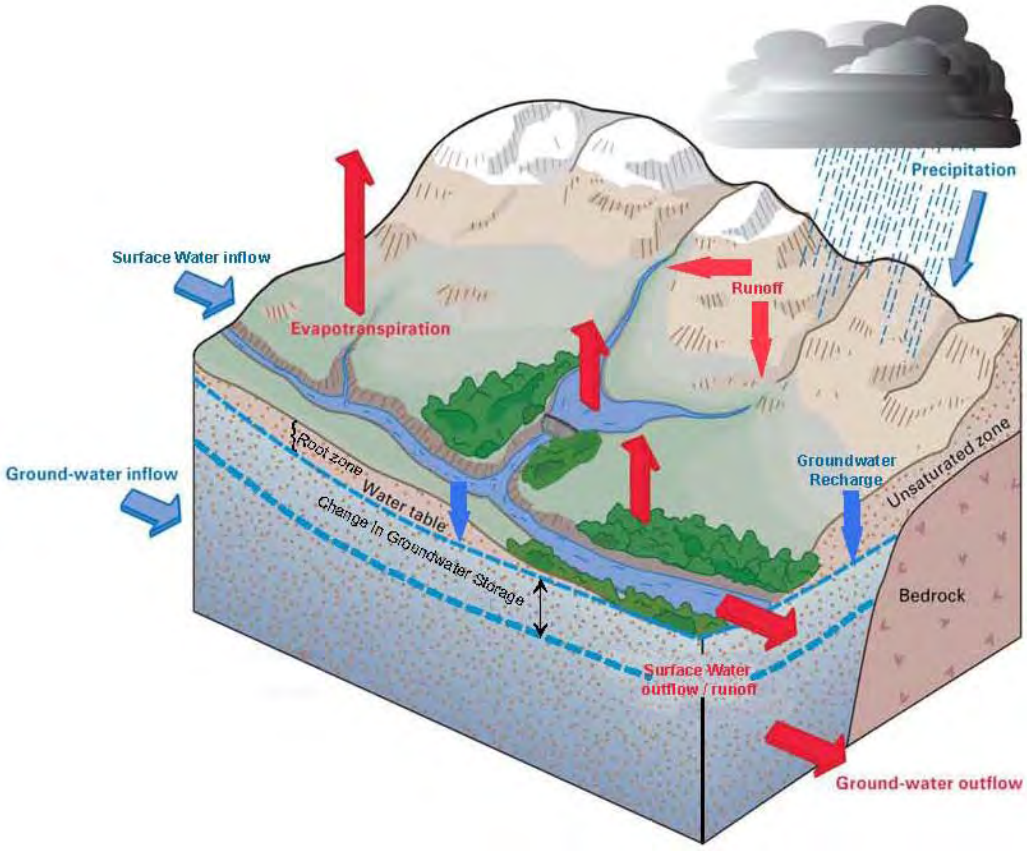


Figure 8-1. Conceptual Diagram of a Watershed Water Balance

A water balance can be used to observe how the quantity of groundwater in storage may vary over time. This tool relies upon a defined accounting unit of volume, for example a groundwater basin or other hydrologic unit of analysis. Measurements of water flowing into and out of the defined unit are used to determine the change in water storage. In the simplest form, the equation for this is:

Inflows – Outflows = Change in Storage

Typical Inflows and Outflows are summarized below (DWR, 2003):

Inflows

- Natural recharge from precipitation;
- Seepage from surface water channels;
- Intentional recharge via ponds, ditches, and injection wells;
- Net recharge of applied water for agricultural and other irrigation uses;
- Unintentional recharge from leaky conveyance pipelines; and
- Subsurface inflows from outside basin boundaries.

Outflows

- Groundwater extraction by wells;
- Groundwater discharge to surface water bodies and springs;
- Evapotranspiration; and
- Subsurface outflow across basin or subbasin boundaries.

Calculating change in storage using data for each inflow and outflow component provides the best approximation of the change in storage. A simple way of estimating the change in storage in a basin is through the determination of the average change in groundwater elevations over the groundwater basin for a period of time. This change in water levels is then multiplied by the area overlying the basin and the average specific yield (in the case of an unconfined aquifer system, or storativity in the case of a confined aquifer system). Change in groundwater levels is best determined over a specific study period that considers different water year types (wet, normal, dry, multiple dry years), but it is common for shorter time periods (e.g., one year's spring to spring groundwater elevations) to be used. This simplistic approach to calculating a change in storage does not provide an indication of the total volume of groundwater storage or the storage available for use. Rather, this computation provides a "snapshot" perspective of short-term trends. The quick calculation should only be considered as an indicator; a more complete groundwater balance evaluation is much preferred (e.g., groundwater flow model). For example, if stresses on the aquifer system induce additional surface water infiltration, the change in groundwater storage may not be apparent (DWR, 2003).

Groundwater recharge is a key component when assessing the water budget of a groundwater basin. Understanding recharge and other fluxes is important in evaluating groundwater conditions and understanding the effects of land development on groundwater resources. This study included characterizing groundwater recharge with an emphasis on the Napa Valley Floor. The groundwater recharge process begins in the shallow soil column when precipitation or applied water infiltrates below the ground surface. At shallow depths within the plant root zone water is consumed by plant evapotranspiration and can also be stored as soil moisture. When soil moisture exceeds its holding capacity, water percolates below the root zone as groundwater recharge. If plant consumptive needs are met and soil moisture storage is below its holding capacity, infiltrated water is stored within the root zone.

8.2 Root-Zone Water Balance

Groundwater recharge can be estimated based on a mass balance analysis of the root zone to estimate the amount of groundwater recharge occurring below the root zone. Flux terms for the root-zone water balance include precipitation (P), runoff (RO), evapotranspiration (ET), recharge (R), and change in soil moisture storage (ΔS). The root-zone water balance expression can be written as:

$$P - RO - ET - R = \Delta S \qquad [1]$$

Figure 8-2 illustrates the components of the root-zone water balance.

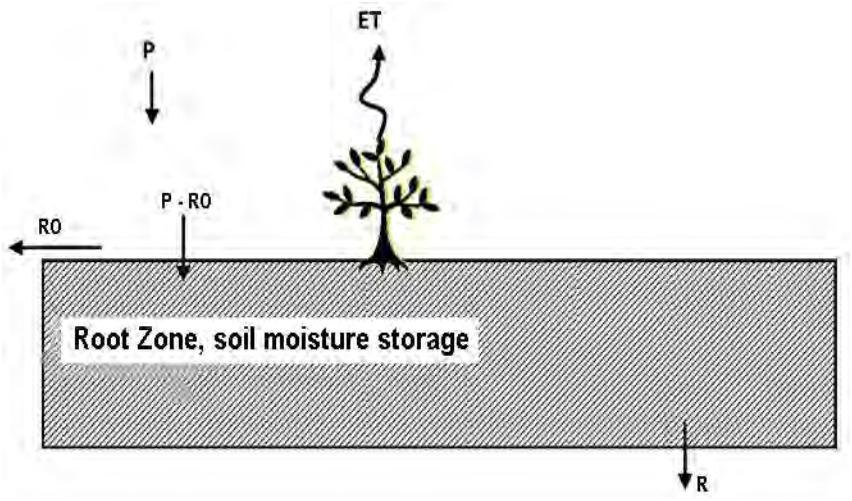


Figure 8-2. Conceptual Diagram of the Water Balance within the Root Zone

Infiltration is defined as precipitation minus runoff and is implicit in the root-zone water balance expression [1]. The root-zone water balance can also be expressed to solve for recharge as R = P – RO – ET – ΔS. Although this expression shows a solution for groundwater recharge with

respect to the root-zone water balance, the estimations of groundwater recharge derived as part of this study are based on methods of calculating recharge from physical processes within the root zone. Instead, this analysis calculates groundwater recharge using three physical processes models as a function of ending soil moisture storage and soil texture parameters. Change in soil moisture storage (ΔS) becomes the closing term. A spreadsheet, hereinafter referred to as the root-zone water balance model, was developed on monthly time-steps to calculate this root-zone water balance in the Napa Valley area and is described in detail in the following sections.

8.3 Root-Zone Water Balance Model

The root-zone water balance model uses data from various sources described below to solve the water balance expression [1] within the root zone on a monthly time-step for each of nine gaged watersheds within the Napa Valley area. Land use is an important component in the model and is used to derive a number of the model parameters. Therefore, the root-zone water balance model performs most calculations by land use category within a watershed. However, infiltration is calculated as the difference between precipitation and runoff. Streamflow gage data are a valuable resource for quantifying runoff and were used in this analysis to represent the runoff component of the root-zone water balance. The limited availability of data from gaged streamflow locations precludes developing a more spatially distributed estimate of recharge using this method. Because streamflow as measured at a gage is an aggregate for the upstream drainage area, infiltration is assumed to be uniform throughout each gaged watershed and across all land use categories.

Water balance calculations in the model are made by land use category on a volumetric basis for the acreage of each land use. Calculations are made monthly in the following sequence:

1) Infiltration is added to the end of previous month soil moisture storage
2) ET is calculated based relationship between potential evapotranspiration (PET) and soil moisture storage from Step 1
3) ET is subtracted from soil moisture storage from Step 1
4) Recharge is calculated using soil moisture storage from Step 3
5) Recharge is subtracted from soil moisture storage from Step 3
6) End of month soil moisture storage is soil moisture storage from Step 3 minus recharge and becomes starting soil moisture storage for the next month.

Results in the root-zone water balance model are summed by land use category within a watershed to develop monthly values of groundwater recharge, ET, and change in soil moisture storage. This method estimates monthly groundwater recharge by accounting for changing hydrologic processes within the root zone as they occur at a monthly time step and root-zone soil moisture storage conditions are carried over from month to month. However, precipitation,

runoff, and infiltration are calculated at the watershed level only. Because of this limitation in the spatially explicit nature of the model inputs, the resulting groundwater recharge estimates are aggregated at the watershed level.

Modeling groundwater recharge in the Napa Valley using a root-zone water balance method, where hydrologic processes are aggregated at a watershed level, provides a way to estimate groundwater recharge without as great a need to quantify other hydrologic components. The root-zone water balance model explicitly represents many of the physical processes occurring within a given watershed, including precipitation, runoff, evapotranspiration, storage in the root zone, and outflow. Implicit in the root-zone water balance model is a representation of surface water diversions for irrigation. Surface water diversions reduce watershed outflow at the outflow stream gage. Infiltration into the root zone is calculated as the difference between precipitation and outflow. Therefore, reductions in outflow tend to increase infiltration, producing the same effect as diversion and application of surface water for irrigation.

The root-zone water balance model does not correctly account for the location of the applied water in that it assumes infiltration is constant throughout the watershed. The root-zone water balance model likely overestimates infiltration in native vegetation areas in some months, resulting in increased ET from those areas, while underestimating infiltration in agricultural areas and decreasing ET. These errors help to offset each other at the watershed level, but are not expected to completely balance out.

Groundwater pumping and ET of applied groundwater are not represented in the root-zone water balance model. The root-zone water balance model was developed to estimate recharge at the watershed level and is not applicable for estimating demand for total applied water or groundwater pumping.

Although streamflow gage data were used to represent runoff in this study, it is important to recognize that streamflow gage data represent outflow from a watershed as a composite of surface runoff processes and subsurface flows discharging to the stream. Streamflow measured at watershed gages was not differentiated into surface runoff and subsurface discharge components in this analysis. Consequently, the groundwater recharge estimates developed in this study represent groundwater recharge values in excess of outflowing surface and subsurface discharges. In this study, runoff within a gaged watershed is represented by the total outflow past a streamflow gage located at the bottom of the watershed.

The root-zone water balance model applied in this study includes several assumptions. Two of the primary assumptions are that land use data used are representative of the time period being analyzed, and surface water used for irrigation is diverted and reapplied within the same gaged watershed.

8.4 Physical Processes

Time-series of flux terms identified in the water balance expression [1] are necessary to estimate recharge. Flux terms can be either observed data or calculated values based on mathematical representations of physical processes. Steps taken in the development of each model input term are discussed in sections that follow:

Precipitation (P)

Precipitation is a prepared input to the root-zone water balance model based on spatially distributed data from Parametric-elevation Regression on Independent Slopes Model (PRISM). The methods for preparing these data are further discussed in the Data Development section.

Runoff (RO)

The root-zone water balance expression represents fluxes within a defined area where inputs and outputs can be evaluated. For this analysis, the Napa County study area is divided into contributing areas or watersheds above measured streamflow gages within the County. In the water balance expression [1], runoff is the amount of precipitation that does not infiltrate below the ground surface and flows over the ground surface and out of the watershed. Streamflow gage data from the USGS were used in this analysis to represent watershed outflow which comprises the process of surface runoff and subsurface discharges to the stream.

Infiltration (I)

Infiltration is equal to the difference between precipitation and runoff (I = P - RO).

Evapotranspiration (ET)

Evapotranspiration is water loss through the combination of land surface evaporation and plant transpiration. Potential evapotranspiration (PET) represents the maximum volume loss when sufficient moisture is available in the soil column. PET is estimated in this analysis using a crop coefficient to relate PET to a reference evapotranspiration (ETo). Water stress reduces the PET for a given crop when plants are unable to extract enough moisture from the soil to fully meet PET. The water balance model incorporates water stress with the use of a water stress coefficient. A water stress coefficient is calculated each month as a function of available soil moisture. When the previous month's soil moisture storage plus infiltration exceeds 50% of field capacity (field capacity is the amount of water held in the soil that does not drain under gravitational forces), full land use PET is used in the root-zone water balance (DWR, 2012). Otherwise, a reduced PET is computed and used in the root-zone water balance.

Groundwater Recharge (R)

For comparison, three different physically based methods were used to estimate groundwater recharge: Van-Genuchten Mualem model (VGM), Campbell's model, and percent over field capacity. All three methods calculate groundwater recharge as a function of soil moisture storage and soil textural properties.

In terms of soil characteristics, the VGM model calculates groundwater recharge as a function of saturated hydraulic conductivity (ks), total soil porosity (η), soil moisture storage (θt), and pore-size distribution index (λ). Campbell's model calculates groundwater recharge as a function of saturated hydraulic conductivity (ks), total soil porosity (η), and residual water content. Details of the VGM and Campbell's model for calculating groundwater recharge are described in DWR's theoretical model documentation for the Integrated Water Flow Model (IWFM) demand calculator. This documentation is available on DWR's website at:

http://baydeltaoffice.water.ca.gov/modeling/hydrology/IWFM/IDC/IDCv4_0_226/downloadables/IDCv4.0_Documentation.pdf

The percent over field capacity method calculates groundwater recharge as a function of field capacity and soil moisture storage. Field capacity is defined as the amount of water held by capillary forces in the soil that does not drain under gravitational forces (Charbeneau, 2000). Field capacity is typically defined in units of length per unit of soil depth. Specifically, at any time-step when soil moisture storage exceeds field capacity, groundwater recharge equal to the difference between soil moisture storage and field capacity occurs.

8.5 Data Development

8.5.1 Precipitation

Daily precipitation gage records were collected from National Climatic Data Center (NCDC) CD-ROM product (NCDC, 2010). Daily records were aggregated into monthly depths and quality-control checked by comparison with other available sources such as DWR's California Data Exchange Center (CDEC) records. Available precipitation records and their period of record are summarized in **Table 8-1**. Values for "Data Completeness" quantify the percent of daily data available from NCDC for the period of record. Most missing data are during summer months when precipitation is likely zero. **Figure 8-3** identifies the locations of precipitation gages in Napa County with available NCDC data.

Table 8-1. Available Precipitation Gage Data

Gage Name	Elevation (feet)	Start Date	End Date	Number of Years	Data Completeness
Napa State Hospital	35	1-Feb-1917	31-Dec-2009	93	99.6%
St Helena	225	10-Feb-1931	31-Dec-2009	79	94.2%
Angwin Pacific Union	1715	1-Jul-1948	31-Dec-2009	61	97.2%
Calistoga	400	1-Jul-1948	31-Oct-2009	61	98.0%
Oakville 1 WNW	161	1-Jul-1948	30-Jun-1981	33	89.6%
Dutton's Landing	20	1-Nov-1955	30-Jun-1977	22	99.9%
Napa	20	1-Jul-1948	31-Dec-1965	17	98.7%
Napa Co Ap	14	1-Oct-2000	31-Dec-2009	9	100.0%
St Helena 4 WSW	1780	1-Jul-1948	16-Nov-1956	8	99.9%
Yountville	95	1-Nov-2002	31-Dec-2009	7	87.0%
Atlas Road	1742	1-Jul-1948	30-Sep-1951	3	97.8%
Oakville 4 SW	1470	1-Jul-1948	30-Sep-1951	3	97.2%
St Helena 6 NE	1001	3-Jul-1948	30-Sep-1951	3	98.3%

The root-zone water balance model requires precipitation data on a monthly basis distributed across the study area. The variability in the available period of record for precipitation gage data and limited spatial distribution of these data points present limitations for use in the model. Methods such as Thiessen Polygon or Isohyetal mapping can be used to create areal distribution and contour maps of precipitation depth. However, the relatively small number of discrete precipitation gages (13) combined with the limited overlap of precipitation records would produce spatially and temporally coarse precipitation contours of the basin. Additionally, these approaches do not capture, in great detail, orographic effects on precipitation. Therefore, an alternate method was used.

Spatially distributed precipitation data developed by the Oregon State PRISM Climate Group incorporates digital elevation models, point measurements of precipitation, and other climatic factors to map precipitation trends. PRISM monthly normal precipitation data for the period 1971 to 2000 at a cell size of 800 meters (30-arcsec) were acquired and used as the basis for developing the temporally distributed precipitation inputs to the water balance model. **Figure 8-4** illustrates the 800 meter (30-arcsec) grid system for the Napa County PRISM data. The

PRISM dataset contains only monthly precipitation depths for a normal year, whereas the water balance model requires a time-series of precipitation.

To accomplish this, the monthly normal precipitation depth for each cell in the PRISM dataset was translated into a time-series of precipitation for each grid cell. The Napa State Hospital precipitation gage contains records from 1917 to 2009 and the PRISM grid cell encompassing this gage was selected as a reference cell. A monthly multiplier was developed for each grid cell in the County by dividing the monthly normal precipitation for the reference cell by each grid cell. Using the precipitation data at the Napa State Hospital, these cell multipliers were used to estimate precipitation for all grid cells in the County. This approach will be referred to hereinafter as the PRISM scaling method. As described, the PRISM scaling method produced monthly time-series data for precipitation from 1917 through 2009 for the entire county at an 800 m (30-arcsecond) grid resolution. The PRISM scaling method is similar to producing monthly isohyetal maps for this period, but at a grid resolution of 800 meters.

8.5.2 PRISM Scaling Method Validation

The PRISM scaling method provided time-series of precipitation for grid cells across the county based on established relationships to the Napa State Hospital precipitation gage. Because of reliance on only one gage, measures were taken to assure the validity and applicability of this approach for other parts of the county.

The PRISM scaling method was validated by comparing NCDC records (observed data) with precipitation estimated using the PRISM scaling method at four different locations: Angwin Pacific Union, Calistoga, St. Helena, and Oakville for the periods of available data between 1971 and 2000. **Figures 8-5 and 8-6** illustrate comparisons of the observed and estimated data conducted for the Angwin Pacific Union and St. Helena precipitation gages. The Angwin Pacific Union gage is located in the northeastern portion of the Napa River Basin at an elevation of approximately 1,715 feet. The St. Helena gage is located in the northern portion of the Napa River Basin with an elevation of approximately 225 feet.

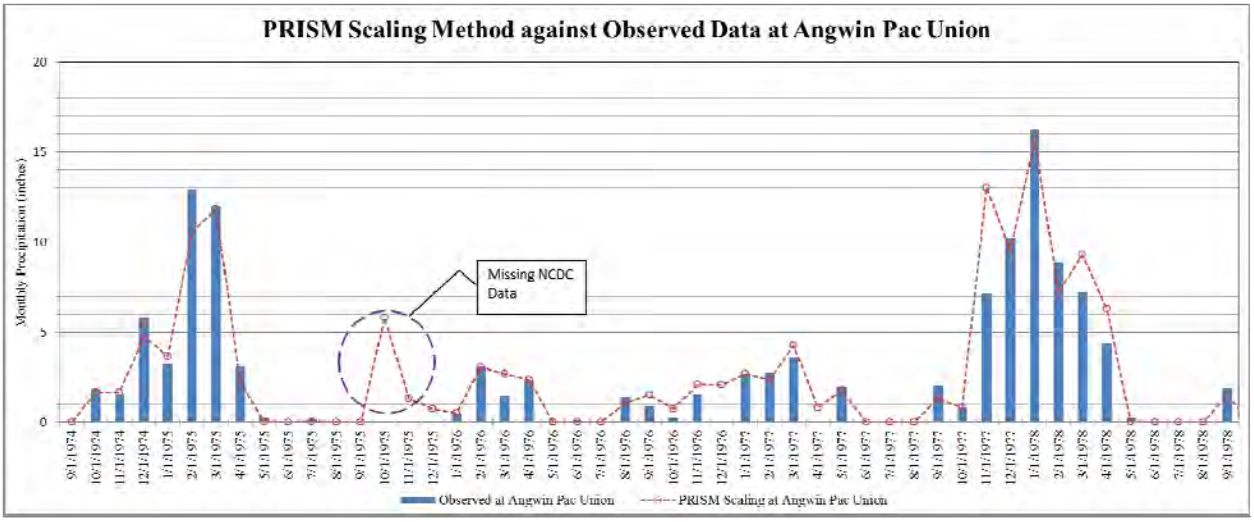


Figure 8-5. PRISM Validation (Angwin Pacific Union Gage - Higher Elevation)

Figure 8-5 illustrates PRISM scaled precipitation plotted against Angwin Pacific Union observed monthly precipitation during a four-year period that includes both wet (1975 and 1978) and dry (1976 and 1977) years. In general, the PRISM scaling method estimates precipitation time-series that are similar to observed data. At the Angwin Pacific Union gage, the PRISM scaled precipitation method tended to slightly overestimate precipitation. The average annual PRISM scaled precipitation at the Angwin Pacific Union gage was seven percent above the observed precipitation for all years with full precipitation data records.

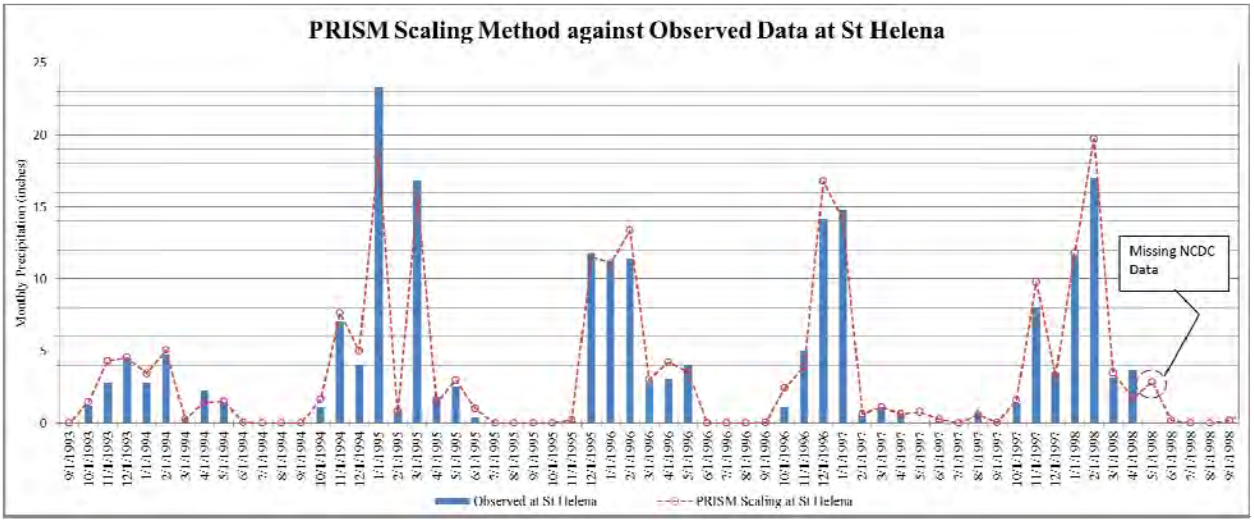


Figure 8-6: PRISM Validation (St. Helena - Valley Floor)

Figure 8-6 illustrates the PRISM scaling method precipitation compared with St. Helena observed monthly precipitation during a five-year period that includes both wet (1995 through

1998) and dry (1994) years. The PRISM scaled precipitation method tended to slightly underestimate precipitation. The average annual PRISM scaled precipitation was three percent below the observed precipitation for all years with full precipitation data records.

Comparisons between the PRISM scaling method and observed data at the other two locations were similar to those at Angwin Pacific Union and St. Helena. These comparisons indicate the PRISM scaled precipitation is a reasonable approximation for precipitation depths across the Napa River Basin.

8.5.3 Streamflow

Streamflow gage data are a valuable resource for quantifying runoff and were used in this analysis to represent the runoff component of the root-zone water balance. However, it is important to note that raw streamflow gage data represent outflow from a watershed as a composite of surface runoff processes and subsurface flows discharging to the stream. Measured streamflow data were not separated into surface runoff and subsurface discharge components in this analysis. Consequently, the runoff component in the water balance model may be overestimated. It is important to recognize this when interpreting the results of this analysis. There are nine streamflow gages identified in the Napa Valley area (**see Figure 8-4**). The upstream contributing areas for each streamflow gage define the watersheds for which the water balance model is applied. The periods of record for the nine streamflow gages are tabulated in **Table 8-2**. Several gaged watersheds are sub-watersheds of other larger, gaged watersheds. For example, the Napa River at Calistoga watershed is a part of both the Napa River near St Helena and the Napa River near Napa watersheds. Sub-watersheds are listed and indented below the encompassing watershed.

Table 8-2. Available Streamflow Gage Data

Stream-flow Gage Name	USGS #	Start	End	# of Years	Watershed Size (mi^2)
Napa River near Napa	11458000	1960	2011	52	218
- Conn Creek near Oakville	11456500	1930	1959	30	55.4
		1971	1975	5	
- Dry Creek near Napa	11457000	1952	1966	15	17.4
- Napa River Near St Helena	11456000	1940	1995	56	78.8
		2001	2011	11	
- Napa River at Calistoga	11455900	1976	1983	8	21.9
Milliken Creek Near Napa	11458100	1971	1983	13	17.3
Tulucay Creek at Napa	11458350	1972	1983	12	12.6
Redwood Creek Near Napa	11458200	1959	1973	15	9.79
Napa Creek at Napa	11458300	1971	1983	13	14.9

8.5.4 Land Use

Land use throughout each watershed where a water balance is calculated is important for several reasons. A primary reason is that different plants use water at different times and rates. Therefore, an estimation of the plant types growing throughout the county is necessary when performing a root-zone water budget. Land use data from DWR, representing surveyed conditions in 1999, were initially used to classify land uses by land cover and crop type (DWR 1999). However, the DWR land use survey data do not differentiate land cover in undeveloped areas, which represent much of the county. To address this limitation, additional land use data were incorporated from the Natural Resources Conservation Services (NRCS). The NRCS data were developed from analysis of satellite imagery and classifying undeveloped areas as forest, shrubland, grassland, and other native categories. Land use data used in the root-zone water balance model were an aggregation of both DWR and NRCS data.

Each of the nine gaged watersheds, outlined according to streamflow gage locations, is partitioned by land use type. A summary of land uses for each watershed is presented in **Table 8-3**. Native vegetation (NV) represents a majority of the land cover in Napa County and is categorized into three types: grasslands (NV Type 1), shrubland and brush (NV Type 2), and forests (NV Type 3). Vineyards are the predominant agricultural crop with typically less than 10 percent of agricultural areas planted in other crops as noted in **Table 8-3**. Therefore, agricultural land uses were categorized into two types for the root-zone water balance model analysis: vineyards and crops, which include all other agriculture.

Table 8-3. Land Use Acreages by Gaged Watershed

	Gaged Watershed								
Land Use	**Conn Creek (ac.)**	**Dry Creek (ac.)**	**Napa Creek at Napa (ac.)**	**Tulucay Creek (ac.)**	**Redwood Creek (ac.)**	**Milliken Creek (ac.)**	**Napa River at Calistoga (ac.)**	**Napa River at St. Helena (ac.)**	**Napa River near Napa (ac.)**
Evergreen Forest	10,700	6,365	2,505	492	2,351	426	4,529	19,390	42,568
Shrubland	11,445	2,345	1,311	1,597	1,055	6,935	3,775	11,820	34,718
Vineyard	3,392	303	1,106	449	826	332	1,376	7,217	27,064
Mixed Forest	4,059	1,056	1,606	1,771	1,114	948	1,195	4,284	12,101
Grassland Herbaceous	3,127	412	1,291	1,405	487	1,070	1,493	3,156	10,416
Developed or Open Space	993	313	375	782	165	434	667	2,378	4,359
Urban	268	62	1,138	1,042	50	639	667	1,904	4,353
Deciduous Forest	362	264	521	111	368	168	144	434	1,309
Open Water	753	0	3	11	2	51	12	121	1,016
Idle	171	24	6	206	6	14	22	124	1,162
Deciduous Fruits	9	7	14	13	4	0	44	87	157
Pasture	102	0	0	37	0	23	0	0	109
Grain and Hay Crops	25	0	1	20	0	4	0	17	180
Woody Wetlands	43	1	5	2	0	9	4	21	151
Herbaceous Wetlands	41	0	0	4	0	1	0	7	85
Almonds	1	0	0	77	0	37	0	0	1
Fallow/Idle Cropland	6	0	1	26	1	12	1	9	45
Citrus and Subtropical	5	0	0	5	0	9	0	5	10

8.5.5 Rooting Depth

Plant rooting depths are associated with the plant's potential to reach infiltrated water in the root zone. The water balance model in this analysis represents processes within the root zone, where water can be stored within soil pores, consumed by plant evapotranspiration, or become recharge to the groundwater system below. These rooting depth values are used to represent root-zone

thickness or soil thickness. Soil thickness, in combination with other parameters such as field capacity, porosity, and pore-size distribution determines the soils' ability to hold water and the physical processes of drainage below the soil via groundwater recharge.

The rooting depth for plants is variable and these differences in rooting depth affect the water balance. Land use data were used to interpret rooting depth. Plant rooting depths range from 5 to 10 feet. Root-zone depths for different land uses were obtained from Chapter 11, of the NRCS National Engineering Handbook (NRCS, 1983) and are tabulated in **Table 8-4**.

Table 8-4. Root-Zone Depths

Land Use	Root-Zone Depth (ft)
Water	10
Wetlands	10
Vineyards	5
Idle Lands	5
Developed	5
Crops	5
NV Type 1	8
NV Type 2	8
NV Type 3	10

8.5.6 Soil Textural Parameters

Field capacities were selected for each land use based on values from the University of California's Drought Management website (UC, 2012). Assigned field capacities range from 1.5 to 2.5 inches of water holding capacity per foot of rooting depth and represent values for medium to fine textured soils. **Table 8-5** tabulates the field capacity with their corresponding land use.

Table 8-5. Field Capacities

Land Use	Field Capacity (ft/ft)
Water	0.2
Wetlands	0.2
Vineyards	0.15
Idle Lands	0.2
Developed	0.2
Crops	0.2
NV Type 1	0.2
NV Type 2	0.2
NV Type 3	0.25

An area-weighted approach was applied to soil parameters of porosity (η) and pore-size distribution index values (λ). Parameters were selected from Groundwater Hydraulics and Pollutant Transport (Charbeneau, 2000) and the NRCS SSURGO database (USDA, 2007). Four hydrologic soils groups (HSG) A, B, C, and D were identified in SSURGO. Bookend porosity and pore-size distribution index values from Charbeneau were selected and assigned to HSG A and D. The intermediate HSGs of B and C were assigned an equal increment between the bookend values selected for HSG A and D. The soil textural parameters for each HSG as used in the root-zone water balance model are shown in **Table 8-6**. Porosity and pore-size distribution indices were weighted with HSG percentages for each gaged watershed. The resulting area-weighted soil parameters are tabulated in **Table 8-7**.

Table 8-6. HSG Textural Parameters

HSG	Porosity (η)	Pore Size Distribution Index (λ)	Soil Texture Description
[1]A	0.43	1.68	Sand – Silty Clay Loam
B	0.41	1.15	Sandy Loam
C	0.39	0.62	Sandy Clay Loam
[1]D	0.37	0.09	Clay – Silty Clay

[1]Bookend Values

Table 8-7. Percentage Breakdown of Hydrologic Soils Groups

Gaged Watershed	Hydrologic Soils Group				Weighted Porosity (η)	Weighted Pore Size Distribution Index (λ)
	A	B	C	D		
Tributaries						
Conn Creek	0%	11%	61%	28%	0.39	0.53
Dry Creek	0%	10%	52%	38%	0.38	0.48
Napa Creek at Napa	0%	15%	77%	8%	0.39	0.66
Tulucay Creek	0%	9%	46%	45%	0.38	0.43
Redwood Creek	0%	18%	73%	9%	0.39	0.67
Milliken Creek	0%	30%	21%	49%	0.39	0.52
Napa River						
Napa River at Calistoga	0%	33%	54%	13%	0.39	0.73
Napa River at St. Helena	2%	26%	56%	16%	0.39	0.69
Napa River near Napa	2%	19%	57%	23%	0.39	0.62

8.5.7 Evapotranspiration

Evapotranspiration is collectively the processes of evaporation from ground surfaces and transpiration from plants. The root-zone water balance represents ET as a flux out of the root zone. In this study ET is represented by monthly depth estimates for different land uses. Average monthly reference ET values (ETo) from the California Irrigation Management Information System (CIMIS) Oakville station were used as a basis for calculating PET for each land use. The ETo values from the CIMIS Oakville station appear similar to and representative of monthly and annual values for Zone 8 of the CIMIS reference ETo map for California. Zone 8 encompasses most of Lake and Napa Counties. Average monthly ETo values were multiplied by crop coefficient (kc) for various land uses to determine PET.

Vineyards represent the greatest non-native land use in the Napa Valley area. Deficit irrigation methods are commonly used in growing wine grapes, which are the dominant vineyard type in the Valley. This irrigation method reduces water application in specified periods to control the characteristics of grapes. As a result, the annual ET pattern for deficit-irrigated wine grapes does not follow typical patterns of table grape vineyards. SEBAL (2009) described the effects of deficit irrigation on the ET of wine grapes in the adjacent Russian River Basin. The PET pattern for vineyards used in this study was derived following crop coefficient patterns identified in the SEBAL. Additionally, the SEBAL report also provides estimates of ET for different native vegetation types in the area. These estimates were used to develop PET estimates for the three native vegetation land uses in the root-zone water balance model.

Agricultural land uses other than vineyards represent only a small part of the Napa Valley. Crop coefficients for non-vineyard agriculture and idle lands were obtained from the Irrigation Training and Research Center's (ITRC) Report 03-001 (ITRC, 2003). Crops including deciduous fruit trees, pasture, grain, hay, almonds, walnuts, citrus, and other subtropical trees were identified in the land use survey and were grouped as a single "crops" land use in the model.

The monthly and annual reference ET (ETo) and PET for land uses in the model are summarized in **Table 8-8**.

Table 8-8. Reference Evapotranspiration and Potential Evapotranspiration

Units:	Jan (in)	Feb (in)	Mar (in)	Apr (in)	May (in)	Jun (in)	Jul (in)	Aug (in)	Sep (in)	Oct (in)	Nov (in)	Dec (in)	Ann[1] (in)
ET_O	1.3	1.7	3.5	5.1	6.3	6.8	7.0	6.4	5.1	3.4	1.8	1.3	**49.8**
PET_{Water}	1.1	1.5	2.7	4.1	6.2	7.7	9.3	8.4	6.1	4.0	1.7	1.2	**53.9**
$PET_{Wetlands}$	1.1	1.5	2.7	4.1	6.2	7.7	9.3	8.4	6.1	4.0	1.7	1.2	**53.9**
$PET_{Vineyards}$	0.9	1.0	1.5	1.1	3.0	2.4	1.7	3.3	2.6	2.5	1.1	1.6	**22.5**
$PET_{Idle\ Lands}$	0.1	0.2	0.5	1.0	3.1	2.0	1.4	1.0	0.5	0.3	0.2	0.1	**10.6**
$PET_{Developed}$	0.3	0.4	0.9	1.3	1.6	1.7	1.8	1.6	1.3	0.9	0.5	0.3	**12.4**
PET_{Crops}	0.9	1.6	2.6	4.0	5.5	5.6	5.2	4.8	3.9	3.0	0.9	1.2	**39.2**
$PET_{NV\ Type\ 1}$	0.1	0.2	0.5	1.0	3.1	2.0	1.4	1.0	0.5	0.3	0.2	0.1	**10.6**
$PET_{NV\ Type\ 2}$	0.4	0.5	1.0	1.5	1.9	2.0	2.1	1.9	1.5	1.0	0.6	0.4	**14.9**
$PET_{NV\ Type\ 3}$	0.5	0.7	1.4	2.0	2.5	2.7	2.8	2.6	2.1	1.4	0.7	0.5	**19.9**

[1]Annual totals

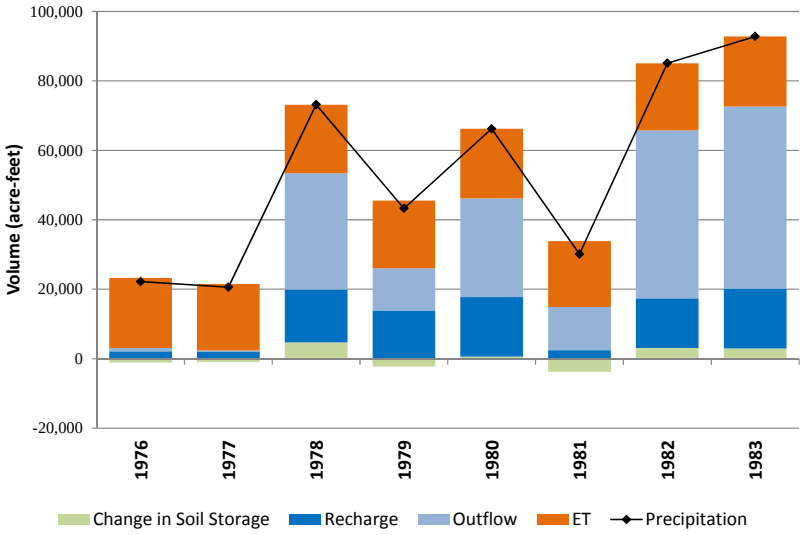
8.6 Results and Summary for Root-Zone Water Balance

The following figures illustrate annual water year results for several watersheds for the period of available streamflow gage data. Because streamflow is a necessary input in the root-zone water balance model, the model was applied to each watershed for the period of record of available streamflow data. Most watersheds were analyzed for a period of approximately 10 to 15 years. Two sub-watersheds of the Napa River, upstream of gages near St. Helena and near Napa, were analyzed for 67 and 52 years, respectively.

Annual figures illustrate the values for root-zone water balance terms. Stacked bar charts illustrate how the root-zone water balance model allocates precipitation between all terms, i.e., precipitation = recharge + outflow + ET + change in soil moisture storage. Annual precipitation is illustrated as a line and provides an indication of the relative wetness for any given year. Outflow (surface runoff plus subsurface discharges to stream) is measured as the annual surface flow at the streamflow gage; infiltration is precipitation minus outflow. Fluxes out of the root zone include ET and groundwater recharge with soil moisture changing in response to the balance of water into and out of the root zone. Change in soil moisture storage can be positive or negative. Positive soil moisture storage values indicate that soil moisture storage was greater at the end of the water year than at the beginning because precipitation exceeded outflow, recharge, and ET. Conversely, negative values indicate soil moisture storage decreased during the water year because outflow, recharge, and ET exceeded precipitation. Such years are illustrated in the following figures when the total height of the stacked bars exceeds the precipitation line. This occurs most often during dry years following wet years because existing soil moisture storage is high following a wet year and is depleted over the course of a dry year. Conversely, larger

increases in soil moisture storage occur most often during wet years that follow a dry year when soil moisture storage is low and is replenished by precipitation during a wet year. Annual figures illustrate the year-to-year variability in root-zone water balances, including considerable variability in groundwater recharge.

Annual root-zone water balance values represent the sum of monthly results from the root-zone water balance model for each water year (October through September). Results presented in this report are based on root-zone water balance model results using Campbell's method for calculating groundwater recharge, although the results were similar for the three methods of calculating recharge.



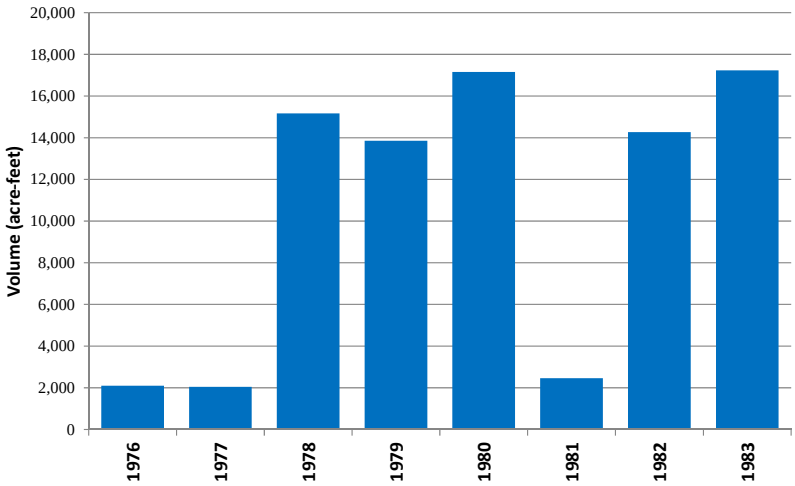


Figure 8-7. Annual Results for Napa River near Calistoga Watershed

Figure 8-7 illustrates annual root-zone water balance model results for the Napa River near Calistoga watershed. This watershed is located at the north end of the Napa Valley and includes developed and undeveloped lands. The streamflow gage near Calistoga was only in operation for eight years, but the period included considerable hydrologic variability, including a very wet year (1983) and very dry year (1977). This variability is evident in the root-zone water balance model results. Measured data and model results indicate large variations in precipitation, outflow, and recharge over this period. However, ET remains fairly constant because land use in the model does not change through time and PET represents typical year conditions. However, PET can be reduced due to water stress in years with low precipitation. In dry years such as 1976 and 1977, measured outflow from the watershed is low and estimated groundwater recharge is also low. In wetter years, groundwater recharge is estimated to be approximately 15,000 acre-feet.

Figure 8-8 illustrates annual root-zone water balance model results for the Napa River near St. Helena. This watershed is also in the northern portion of the Napa River Basin and includes the Napa River near Calistoga watershed. The streamflow gage near St Helena began operation in 1930. **Figure 8-8** illustrates the root-zone water balance for this watershed for the period from 1940 through 1994. **Figure 8-8** also illustrates the annual variability in root-zone water balance terms. During this period, the volume of precipitation varied greatly from less than 100,000 acre-feet to more than 300,000 acre-feet. Similarly, outflow and groundwater recharge vary considerably while ET again remains relatively constant at an annual average of approximately 70,000 acre-feet. Groundwater recharge generally increases and decreases with precipitation. However, although the highest annual precipitation occurred in 1983, the greatest annual groundwater recharge occurred in 1980. Interactions among the timing of precipitation, outflow, soil moisture conditions, and other factors affect the timing and magnitude of groundwater recharge.

Annual root-zone water balance model results for Dry Creek, a watershed located on the west side of the Napa Valley, are shown in **Figure 8-9**. The USGS streamflow gage on Dry Creek has a 15-year period of record and measures outflow from a mostly undeveloped watershed with an area of approximately 11,000 acres. Results from the root-zone water balance model for the Dry Creek watershed show the trends in the annual values for each water balance term and illustrate the dynamic relationship between the root-zone water balance components. For example, during each of the water years 1956, 1958, and 1963 the annual precipitation in the Dry Creek watershed was approximately 50,000 acre-feet; however, the timing and intensity of this precipitation varied. In 1956, approximately 35,000 acre-feet of precipitation were recorded in December and January and much of the precipitation left the watershed as outflow so estimated groundwater recharge for this period was relatively low. In contrast, during water year 1963 considerable early precipitation occurred in October with much less of the water leaving the watershed as outflow, presumably because soils were drier and able to absorb more precipitation

during this time. This early precipitation replenished soil moisture storage, which resulted in greater groundwater recharge throughout the remainder of the winter season. The watershed experienced similar precipitation during water year 1958 and the estimated annual groundwater recharge was approximately twice that of 1956 and two-thirds that of 1963.

Figure 8-10 illustrates annual root-zone water balance model results for Tulucay Creek, a watershed encompassing approximately 8,000 acres in the southern end of the Napa Valley. Based on the land use data, Tulucay Creek watershed is the most developed of the watersheds analyzed. The USGS streamflow gage on Tulucay Creek was in operation for 12 years during a period of great hydrologic variability. Results from the root-zone water balance model for the Tulucay Creek watershed resemble trends in results for other watersheds. Recharge was highest in 1978, following two extremely dry years despite precipitation values below those for 1982 and 1983. In 1978, approximately 56 percent of precipitation was classified as infiltration and 44 percent was outflow from the watershed. By comparison, infiltration was calculated to be 32 and 36 percent of precipitation in 1982 and 1983, respectively. The higher infiltration in 1978 resulted in high groundwater recharge in this year.

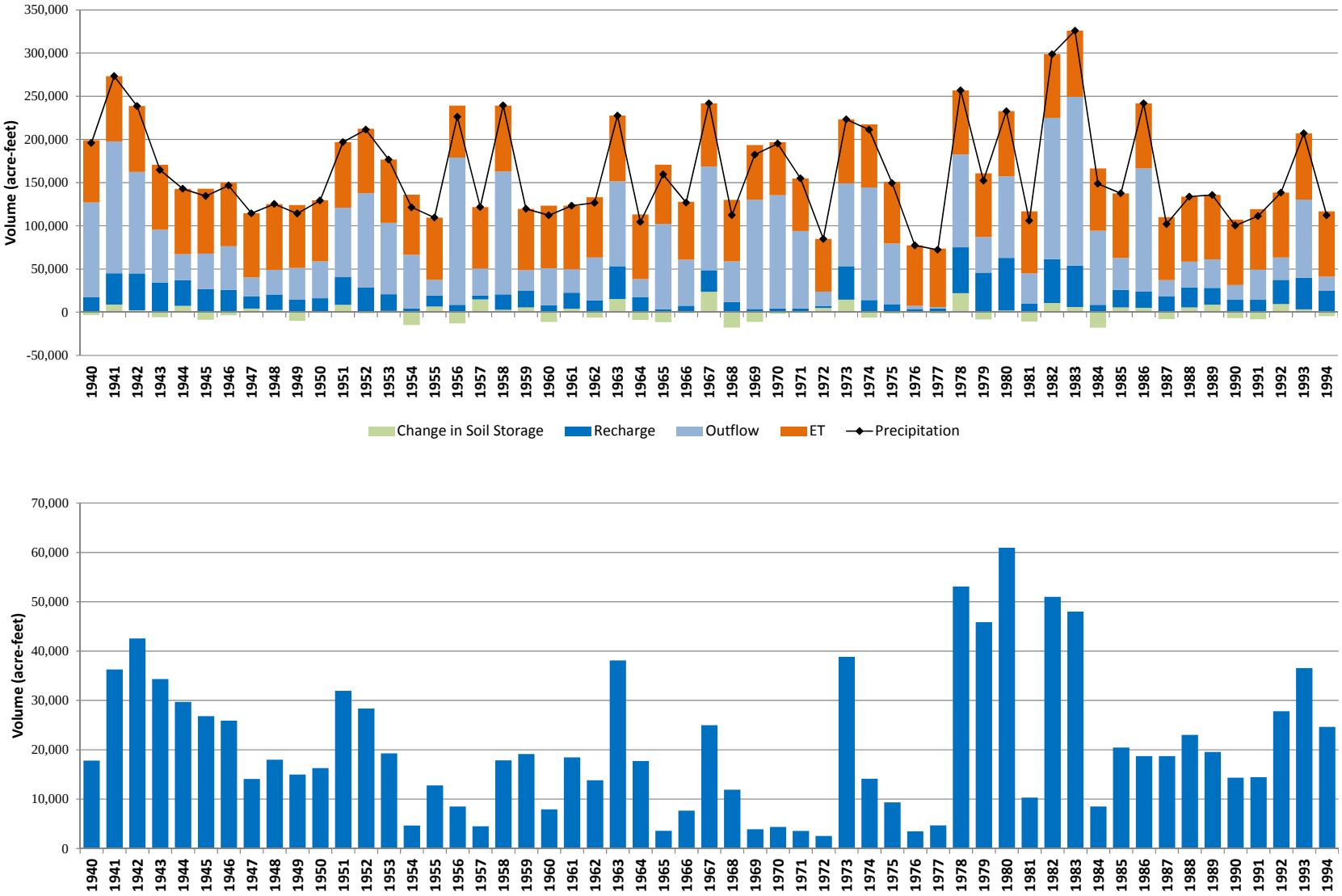


Figure 8-8. Annual Results for Napa River near St Helena Watershed

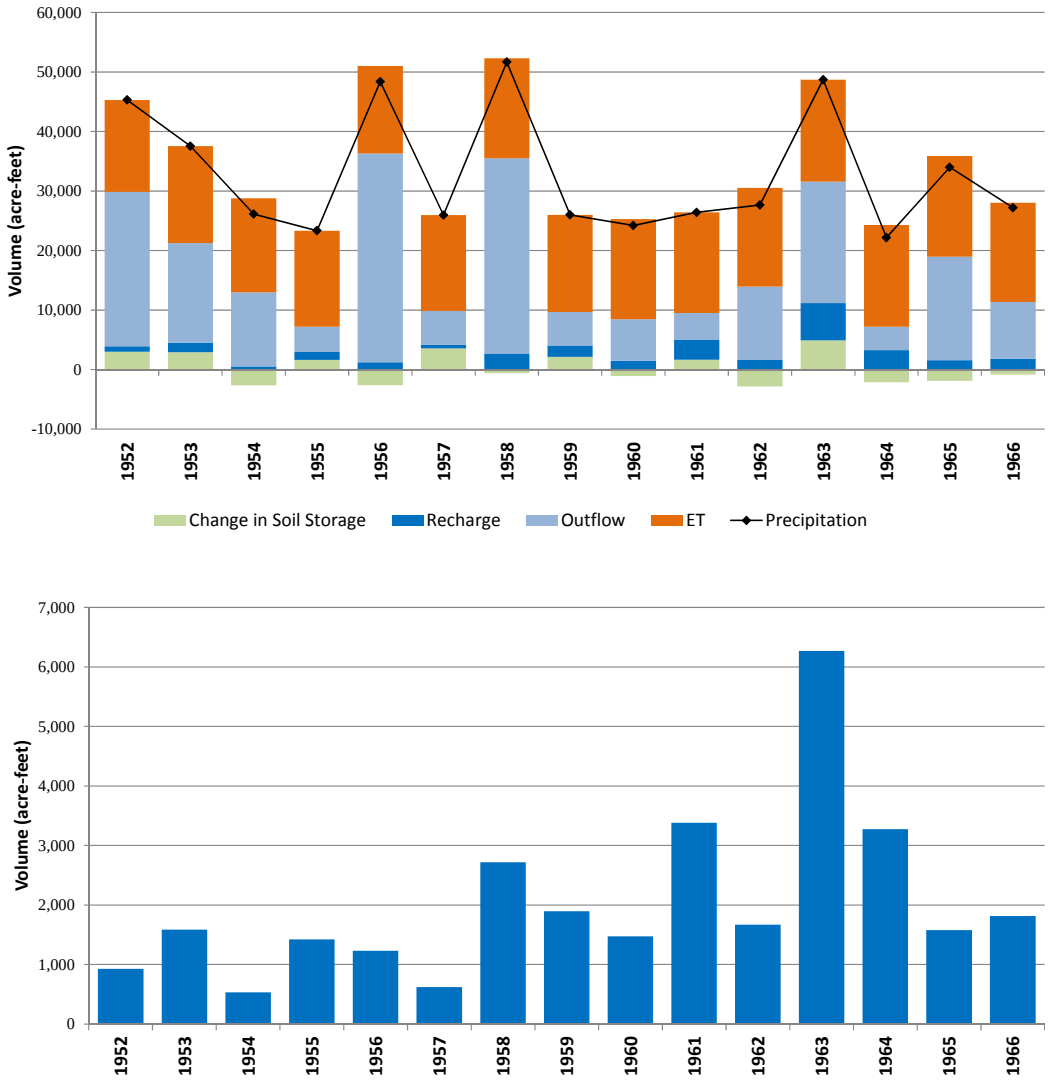


Figure 8-9. Annual Results for Dry Creek Watershed

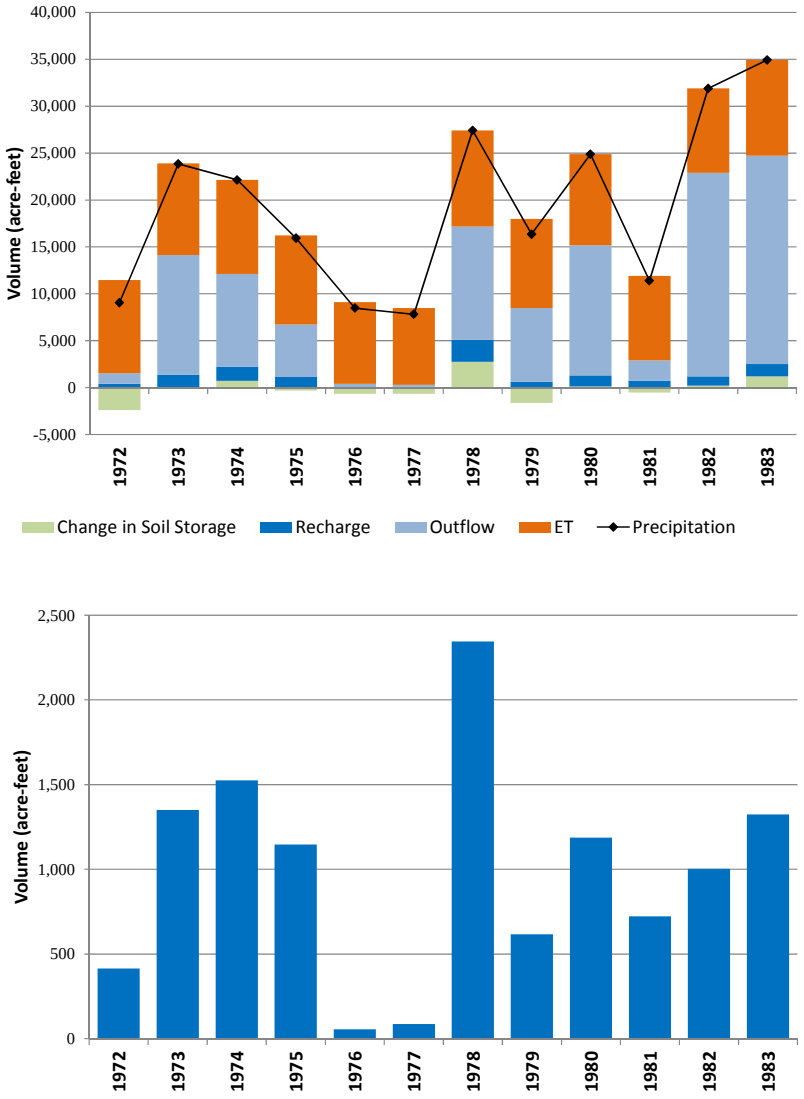


Figure 8-10. Annual Results for Tulucay Creek Watershed

Figure 8-11 illustrates annual root-zone water balance model results for the Napa River near Napa. This watershed is approximately 140,000 acres and includes the Dry Creek, Napa River at St. Helena, Napa River at Calistoga, and Conn Creek watersheds. The Napa River near Napa watershed accounts for approximately 60 percent of the entire Napa River drainage basin. Annual trends in soil moisture storage change and the relationship between years with high precipitation, high infiltration, and high recharge seen in other watersheds are also evident in this watershed.

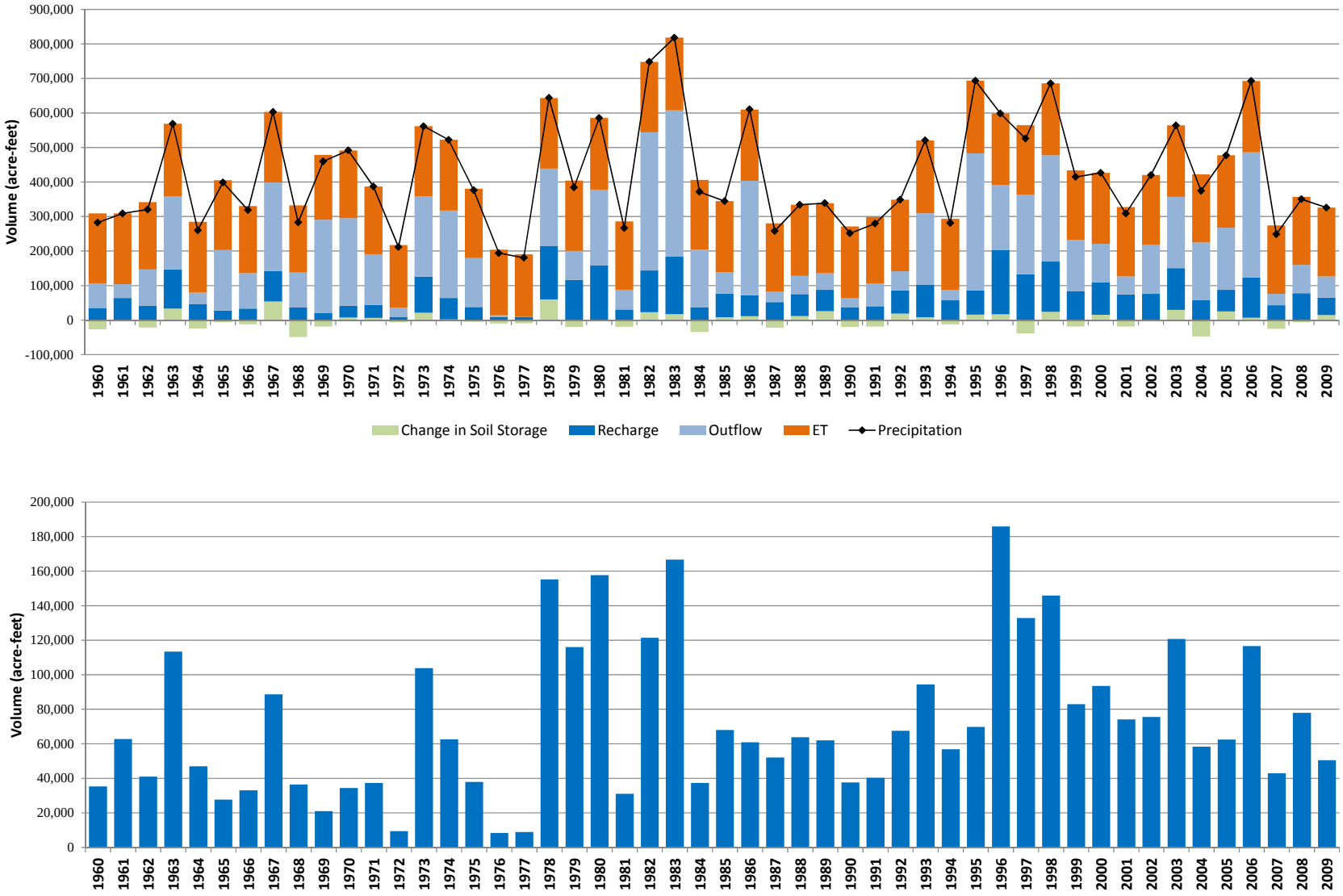


Figure 8-11. Annual Results for Napa River near Napa Watershed

In addition to annual results, monthly results from the water balance model indicate seasonal patterns including increased recharge from November through March when precipitation is higher, increased ET during the spring and summer months, increasing soil moisture storage from October through March and decreasing soil moisture storage from April through September. **Figure 8-12** illustrates the average monthly patterns for the Napa River near Napa watershed. This figure is provided as an example of monthly results of the water balance model to demonstrate that monthly results follow expected seasonal trends.

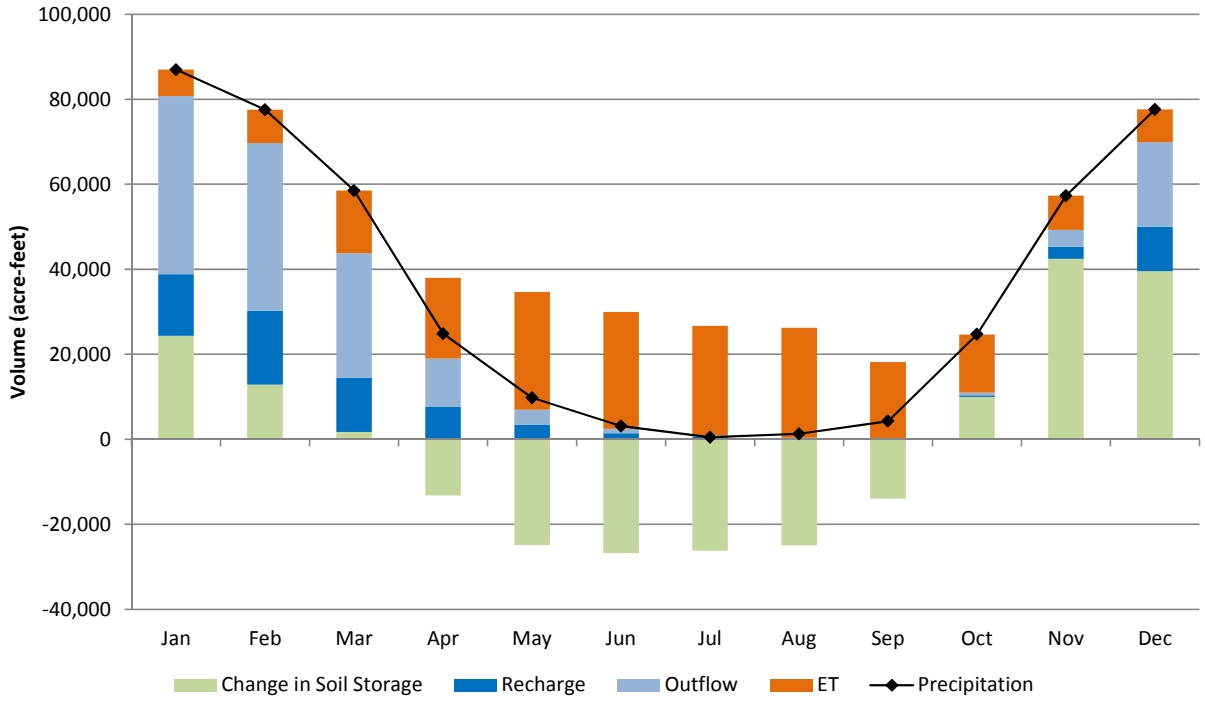


Figure 8-12. Example Average Monthly Root-Zone Water Balance Model Summary for Napa River near Napa Watershed

The average annual root-zone water balance for each watershed is summarized and tabulated in **Table 8-8**. **Table 8-8** is organized by watershed with each watershed listed and indented below encompassing watersheds. For example, Conn Creek, Dry Creek, and Napa River at St. Helena are all contributing watersheds contained within the Napa River near Napa watershed. As illustrated in the preceding figures, groundwater recharge estimates varied considerably from year-to-year and depended largely on timing and magnitude of precipitation. The variability in annual groundwater recharge estimates for the period of analysis are presented in **Table 8-8** as a range of minimum and maximum values. Annual groundwater recharge as a percent of annual precipitation is calculated for each watershed during the root-zone water balance analysis time period. Average annual groundwater recharge as a percent of average annual precipitation is included in **Table 8-8** to represent how recharge fits into the overall annual root-zone water

balance for each watershed and provide a means to compare groundwater recharge between watersheds. Estimated groundwater recharge as a percent of precipitation ranges from 5 to 21% in the analyzed watersheds.

Average annual recharge values in **Table 8-9** reflect both the spatial variability of groundwater recharge within the Napa Valley area and the hydrologic variability of the period analyzed. Because of limitations in available streamflow gage data, each watershed was analyzed only for the time period for which streamflow records were available. Because of these unique aspects of each watershed analysis, direct comparisons of average annual recharge between watersheds in terms of absolute volumes are less meaningful. For example, the Napa River at Calistoga watershed analysis was based on eight years of available stream gage data. These eight years include two extreme dry years and four very wet years. Therefore, the average annual recharge for this watershed may appear higher when compared to other watersheds in the basin, but this is at least partially due to the wetter period of analysis. Comparisons of groundwater recharge as a percent of precipitation better account for hydrologic variability that occurs through time.

Note that several watersheds include dams and reservoirs on tributary streams. The largest reservoir is Lake Hennessey on Conn Creek. Results presented in **Table 8-9** for Conn Creek are for only the period prior to construction of Lake Hennessey in 1945. Regulation on other streams was considered insignificant due to the size of the reservoir and because the water budget was summarized on an annual time-step.

Table 8-9. Summary of Water Balance Model Results

	Average Annual (acre-feet)					Range (acre-feet)	Recharge (% of Precip.)
Watershed	**Precip.**	**Outflow**	**Infilt.**	**ET**	**Recharge**	**Recharge**	**Recharge**
Napa River near Napa	**418,500**	**146,800**	**271,700**	**201,900**	**70,600**	**8,300 - 185,900**	**17%**
- Conn Creek	98,200	24,600	73,600	52,200	21,100	4,300 - 40,700	21%
- Dry Creek	33,000	14,200	18,700	16,400	2,000	500 - 6,300	6%
- Napa River at St. Helena	161,400	67,000	94,400	72,500	22,000	2,500 - 60,900	14%
- Napa River at Calistoga	54,200	23,600	30,600	19,700	10,500	2,000 - 17,200	19%
Milliken Creek	**33,000**	**16,800**	**16,200**	**13,500**	**2,500**	**100 - 7,100**	**8%**
Tulucay Creek	**19,500**	**9,100**	**10,400**	**9,500**	**1,000**	**100 - 2,300**	**5%**
Redwood Creek	**19,300**	**7,800**	**11,500**	**9,500**	**1,900**	**400 - 5,000**	**10%**
Napa Creek at Napa	**32,100**	**14,800**	**17,300**	**13,700**	**3,600**	**600 - 6,900**	**11%**

Results presented in **Table 8-9** indicate that within the Napa River near Napa watershed groundwater recharge is higher in the Conn Creek watershed and in the northern portion of the watershed above Calistoga. Less recharge occurs in the Dry Creek watershed and the portion of the watershed between Calistoga and St. Helena. The Tulucay Creek watershed has the lowest estimated groundwater recharge equal to only 5% of precipitation.

A method for comparing absolute groundwater recharge between watersheds involves comparing groundwater recharge results as depth (normalized by area) for common hydrologic periods. Groundwater recharge can be expressed as depth by dividing average annual recharge volume by the watershed area. To facilitate such a comparison, three common hydrologic periods of eight years each were selected for comparisons of at least two different watersheds for each period. Common periods of record included water years 1952 through 1959, 1959 through 1966, and 1976 through 1983. Average annual groundwater recharge depths were calculated for each watershed during these periods. Average annual precipitation as depth over the watershed was also calculated to provide an indication of the relative wetness of the three common periods. These results are presented in **Figure 8-13**. The Conn Creek watershed was considered in this analysis for the period after construction of Lake Hennessey.

Results presented in **Figure 8-13** illustrate similar trends as seen in **Table 8-9**. The period from 1959 through 1966 was the driest of the three periods while the 1976 through 1983 period was the wettest. Based on absolute groundwater recharge depth, recharge was generally highest in

the Conn Creek and Napa River at Calistoga watersheds. Precipitation also is higher in these areas, which may contribute to higher groundwater recharge amounts in this area. Estimates from the root-zone water balance model indicate that the Tulucay Creek watershed has the lowest amount of groundwater recharge. This may be because approximately 23 percent of the Tulucay Creek watershed is represented by urban land uses, the highest of all watersheds analyzed.

Potential explanations for the spatial variability of recharge presented in **Table 8-9** and **Figure 8-13** include differences in watershed soils and geology, slope, and land uses. Previous work by LSCE (2011a) analyzed geology and slope in Napa County and developed a map showing areas of highest recharge potential. This map is presented as **Figure 6-1** in this report and illustrates identified geologic units with the greatest recharge potential and areas where ground surface slopes exceed 30 degrees. **Table 8-10** summarizes the land area for the geologic units of greatest recharge potential by watershed.

The extent of high recharge potential geologic units as summarized in **Table 8-10** may explain some of the variability in groundwater recharge between different watersheds. The Dry Creek watershed has the lowest percent of area underlain by units of greatest potential recharge and the estimated groundwater recharge in this watershed is also low relative to other watersheds. Similarly, the areal extents of units of high recharge potential in Milliken, Redwood, and Napa Creeks are also relatively small and estimated groundwater recharge in these watersheds is relatively low. However, this relationship is not consistent throughout the Napa Valley area and extent of land covered by units of greatest potential recharge does not explain all the variability in the groundwater recharge estimates from the root-zone water balance model. Results presented in **Table 8-9** and **Figure 8-13** suggest that the Conn Creek watershed has the highest groundwater recharge of all watersheds analyzed, but the percent of this watershed underlain by geologic units of high recharge potential is relatively low. Likewise, the Napa River above Calistoga watershed has more groundwater recharge than the Napa River above St. Helena watershed, but the areal extent of geologic units of high recharge potential is relatively lower. These trends suggest that other factors such as topography, land use, and soils also affect recharge estimates.

Table 8-10. Areas of Greatest Potential Recharge by Watershed

	Area of Units of Greatest Potential Recharge (acres)										
Watershed	**Alluvial Fan Deposits**	**Channel Deposits (Holocene)**	**Napa Valley Alluvium (Undiff.)**	**Quaternary Alluvium**	**Quaternary Alluvium (Holocene)**	**Sonoma Volcanic Sediment**	**Sonoma Volcanics Tuff**	**Total Recharge Area**	**Percent of Watershed**	**Total Watershed Area (acres)**	**Recharge (% of Precip.)**
Napa River near Napa	**6,406**	**1,212**	**22,152**	**1,040**	**3,955**	**3,952**	**21,093**	**59,809**	**43%**	**139,819**	**17%**
- Conn Creek	1,223	125	950	487	402	1,997	3,154	8,338	23%	35,502	21%
- Dry Creek	0	78	7	112	0	0	91	288	3%	11,155	6%
- Napa River at St. Helena	834	455	6,135	148	2,772	827	17,150	28,321	56%	50,984	14%
-- Napa River at Calistoga	178	138	1,398	0	1,484	664	2,006	5,867	42%	13,937	19%
Milliken Creek	**170**	**23**	**46**	**105**	**216**	**640**	**1,747**	**2,947**	**27%**	**11,112**	**8%**
Tulucay Creek	**0**	**44**	**2,507**	**771**	**125**	**0**	**438**	**3,886**	**48%**	**8,052**	**5%**
Redwood Creek	**0**	**25**	**75**	**0**	**69**	**0**	**1,056**	**1,224**	**19%**	**6,434**	**10%**
Napa Creek at Napa	**622**	**110**	**571**	**7**	**302**	**0**	**1,190**	**2,802**	**28%**	**9,886**	**11%**

8.7 Comparisons with Other Studies

Several other studies conducted on watersheds within the Napa Valley area or on nearby watersheds such as Sonoma Creek have developed water budgets and estimated recharge. A groundwater resources investigation was conducted by the USGS in the lower Milliken, Sarco, and Tulucay Creeks (MST) area. As part of this investigation, the USGS estimated 6,000 acre-feet of groundwater recharge in this area. This value is derived using an estimated average annual precipitation of 69,000 acre-feet, runoff out of the watershed of 29,000 acre-feet, and ET of approximately 34,000 acre-feet (Farrar and Metzger, 2003). This estimate equates to an annual groundwater recharge of approximately 9 percent of precipitation, which is similar to results from the root-zone water balance model used in this study. Combined average annual recharge for Milliken and Tulucay Creek watersheds from the root-zone water balance model is approximately 3,500 acre-feet, or 7 percent of average annual precipitation. This is for an area of approximately 19,000 acres while the USGS study covered an area of approximately 10,000 acres. The rot-zone water balance model estimate is calculated from more detailed estimates of individual terms and from a monthly analysis that considers root-zone storage and physical processes. However, the hydrologic period used in the USGS study of the MST area is not provided so potential differences in hydrology during the periods of analysis should be considered when comparing results from this study.

Another USGS study was completed on Sonoma Creek in the Sonoma Valley, just west of the Napa River Basin. As part of this study the USGS calculated an annual recharge estimate using a water balance between precipitation, runoff, and ET (Farrar et al., 2006). USGS estimated between 28,000 and 48,000 acre-feet of groundwater recharge for the Sonoma Creek watershed based on precipitation of 269,000 acre-feet, runoff of 101,000 acre-feet, and 120,000 to 140,000 acre-feet of ET. A range of groundwater recharge was calculated because ET was calculated using two different methods. The USGS estimate for Sonoma Creek equates to annual groundwater recharge equal to between 10 and 18 percent of precipitation. These percentages are comparable to the root-zone water balance model results from this study presented in **Table 8-9**. Again, the hydrologic period used in the USGS study of Sonoma Creek is not provided so potential differences in hydrology during the periods of analysis should be considered when comparing results from this study.

The Baseline Data report (Napa County, 2005) and information on the Napa County Surface Water model and Napa County Groundwater model were reviewed for comparisons to estimated recharge. The Final Baseline Data Report Technical Appendix includes summaries of the annual water balance for both models as **Table 2-16** and **2-19**, respectively (DHI, 2006b). These tables summarize components of the water balance as expressed as average annual depths per year. However, these tables do not include a specific term for recharge, and it is unclear exactly what terms such as “infiltration” represent. Therefore, it is not possible to make a comparison

between information from the Baseline Data Report or Napa County models and results from this analysis.

8.8 Sensitivity Analysis

The sensitivity of the root-zone water balance model to changes in select input parameters and processes was tested. This sensitivity analysis was performed to evaluate which parameters the model is most sensitive to and to understand how uncertainty in inputs creates uncertainty in recharge estimates. Input parameters with relatively larger uncertainties (i.e., soil parameters and evapotranspiration for native forests) were the main focus of the sensitivity analysis. These sensitivity analyses provide helpful guidance for considering approaches to improving recharge estimates in the Napa Valley area.

Results of sensitivity analyses are presented as the percent change in average annual recharge estimate for the Napa River near Napa watershed. This watershed was used for the sensitivity analyses because it is the largest watershed and most representative of the Napa Valley study area. Results for individual watersheds can be more or less sensitive to individual parameters, depending on the watershed. For example, watersheds with more native forests are more sensitive to changes in PET for native forests. Each sensitivity scenario was simulated for all three methods of calculating recharge: VGM, Campbell's model, and percent over field capacity. Percent change is the average for all three methods, except as noted.

8.8.1 Scenarios and Results

Five sensitivity scenarios were evaluated in the root-zone water balance model. The sensitivity of the model results to changes in the following model components were evaluated: root-zone depth, soil field capacity, porosity and pore-size distribution index, ET of native forest vegetation, and the sequence of operations for groundwater recharge and ET demand processes. The following sections summarize the results of each sensitivity scenario.

1. Root-zone depth

   Root-zone depths for native vegetation plants are not well documented in the literature and can vary for agricultural crops. Root-zone depth affects recharge estimates because increased root-zone depth increases soil storage capacity. When more water is stored in root-zone soils it is available for plant evapotranspiration. Therefore, increases in root-zone depth are expected to increase evapotranspiration and decrease recharge estimates in the water balance model.

   Sensitivity analysis results presented in **Table 8-11** illustrate the inverse relationship between root-zone depth and estimated groundwater recharge. Reducing the root-

zone depths used in the model (**Table 8-4**) results in increases in estimated recharge and increasing the root-zone depths decreases estimated groundwater recharge, but recharge is more sensitive to decreasing the root-zone depths. This is because greater root-zone depth equates to a greater soil moisture storage capacity makes it available to meet PET for the overlying land use. However, once PET is fully satisfied, water in the root zone will eventually drain. Increasing the root-zone depths in the model allows PET to be fully satisfied for some land use types, resulting in less reduction in estimated groundwater recharge.

Table 8-11. Sensitivity of Recharge Estimate to Change in Root-Zone Depth

Percent Change in Root-Zone Depth	Percent Change in Average Annual Recharge for Napa River near Napa
-20%	+12%
-10%	+5%
+10%	-3%
+20%	-6%

2. Field capacity

Field capacity, or water that remains in the soil and does not drain under gravitational forces, is not well known. Increases in field capacity increase soil moisture storage capacity and make more water available for plant evapotranspiration. Adjusting the model values for field capacity as shown in **Table 8-5** would be expected to reduce groundwater recharge estimates in the root-zone water balance model.

Sensitivity analysis results presented in **Table 8-12** show change in recharge estimates vary between different methods of calculating recharge for a change in field capacity. As expected, decreases in field capacity result in increases in calculated groundwater recharge using the percent over field capacity method. However, in the VGM and Campbell's model, decreases in field capacity tend to decrease recharge. Unlike percent over field capacity method, field capacity is not directly used to calculate recharge using VGM and Campbell methods. Recharge in VGM and Campbell methods are calculated as a fractional product of saturated hydraulic conductivity and corresponding land use area. That fractional product is a function of porosity and soil moisture storage, not field capacity. Field capacity indirectly affects recharge estimates in these two methods in the calculation of ET. Field capacity is used to determine the fraction of PET that becomes actual ET. As field capacity increases, evapotranspiration increases and moves closer to PET decreasing groundwater recharge.

Table 8-12. Sensitivity of Recharge Estimate to Change in Field Capacity

Percent Change in Field Capacity	Percent over Field Capacity Method	Average of VGM and Campbell's Method
	Percent Change in Average Annual Recharge for Napa River near Napa	
-20%	+10%	-3%
+20%	-7%	+4%

3. Porosity and pore-size distribution index

Soil porosity in the root-zone water balance model characterizes the amount of soil void space. Clayey soils tend to have higher porosities because of the many small pores, whereas sandy soils tend to have lower porosities. Increases in soil porosities from values used in the model (**Table 8-6**) would be expected to reduce recharge estimates from the root-zone water balance model because the capacity of the soil to store water decreases groundwater recharge below the root zone. Conversely, decreases in soil porosities would be expected to increase groundwater recharge estimates from the root-zone water balance model.

Pore-size distribution index "characterizes the range of pore sizes within the soil, with larger values corresponding to a narrow size range and small values corresponding to a wide distribution of pore sizes" (Charbeneau, 2000). The pore-size distribution index was varied to better understand its influence on the VGM and Campbell's recharge models.

Sensitivity analysis results presented in **Table 8-13** indicate that recharge estimates in the root-zone water balance model are relatively insensitive to changes in both porosity and pore size distribution index used in the model, but the results are more sensitive to porosity changes. Additionally, groundwater recharge estimates in the root-zone water balance model are more sensitive to decreasing soil porosity than increasing soil porosity.

Table 8-13: Sensitivity of Recharge Estimate to Change in Soil Porosity and Pore Size Distribution Index

Percent Change in Soil Parameter	Porosity (η)	Pore Size Distribution Index (λ)
	Percent Change in Average Annual Recharge for Napa River near Napa	
-10%	+5%	-1%
+10%	-3%	+1%

4. Evapotranspiration by native forests vegetation

Evapotranspiration by native forests is not well documented in the literature. While PET inputs to the water balance model were based on an energy budget calculation in the neighboring watershed, there is still considerable uncertainty in these inputs. As discussed in previous sections, native forests are the predominant land use in the Napa Valley area. Therefore, it is expected that changes in PET inputs for native forests from values used in the model (**Table 8-7**) will result in changes in recharge estimates. As PET increases, more water is consumed through ET and less water recharges to the groundwater.

Sensitivity analysis results presented in **Table 8-14** indicate that changes in PET values for native forests used in the root-zone water balance model inversely affect groundwater recharge estimates by roughly an equal percentage. In other words, increases to PET values for native forests result in approximately equal and opposite reductions in estimated groundwater recharge. However, these sensitivity results vary by watershed depending on the percentage of the watershed covered by native forest vegetation.

Table 8-14. Sensitivity of Recharge Estimate to Change in Potential Evapotranspiration of Native Forest

Percent Change in PET of Native Forests	Percent Change in Average Annual Recharge for Napa River near Napa
-20%	+27%
+20%	-17%

5. Prioritize recharge process before ET in root-zone water balance model calculations

The root-zone water balance model simulates the root-zone water balance on a monthly time-step. The sequence of operations within the model is as follows: 1) infiltration in the current month is added to the previous month's ending soil moisture storage, 2) evapotranspiration is subtracted from soil moisture storage, and 3) recharge is calculated and subtracted from soil moisture storage. This sensitivity scenario evaluates the change in groundwater recharge estimates if the recharge processes occurs prior to evapotranspiration during calculations within the root-zone water balance model. In reality, the ET and recharge processes occur simultaneously.

Prioritizing recharge before ET in the root-zone water balance model increases the average annual groundwater recharge estimate for the Napa River near Napa watershed by an average of 7%. This provides an upper estimate of groundwater

recharge for comparison with root-zone water balance model results presented in **Table 8-9**.

Results of the sensitivity analysis indicate that groundwater recharge estimates are most sensitive to ET and rooting depths of forests. Rooting depths and ET data for California native forests are not well documented and root-zone water balance model ET values were determined using professional judgment and sources outside California such as an evapotranspiration study of Douglas Fir in British Columbia and the Pacific Northwest (Elsevier, 2009). Approximately 42% of the Napa Valley area is classified as native forests. Refining the estimate of ET for native forests would improve groundwater recharge estimates from the root-zone water balance model. Alternatively, a measurement study of ET for the Napa River Basin, including the foothills and undeveloped areas, could be performed. This study would improve estimates of actual ET for undeveloped areas that could improve PET inputs to the water balance model. An understanding of the root-zone soil moisture storage potentials of native forests could be gained by further studying their root depths and examining underlying soil textures.

Results of the sensitivity scenarios also indicate that groundwater recharge estimates calculated in the root-zone water balance model are subject to uncertainty of approximately +/-20%. Sensitivity scenarios attempted to bound uncertainty in input parameters within expected ranges. Ranges for parameters such as porosity and pore size distribution index exist in the literature and can be constrained based on published values. Parameters such as root-depth and PET are less well known and were tested over a wider range of potential values.

8.9 Extrapolation to Remaining Areas

An effort was made to extrapolate results from gaged watersheds within the Napa Valley area to other watersheds of Napa County outside the Valley. The root-zone water balance model was configured for the Napa Valley area only because this was the primary area of interest in this study and because of the lack of streamflow gages in watersheds outside the Napa Valley area. Because of these limitations, an alternate approach was required to estimate recharge in other parts of the county. Other major watersheds in the county are Putah Creek, Napa-Sonoma Marshes, and Suisun Creek with watershed areas listed in **Table 8-15**.

Table 8-15: Areas of Major Watersheds outside of Napa River Basin and the Napa River Basin

Watershed	Acreage
Putah Creek	231,357
Napa-Sonoma Marshes	11,530
Suisun Creek	30,386
Napa River Basin	232,193

Land use and precipitation data required for input to the water balance model were collected while processing data for the Napa Valley area. To supplement for the lack of measured streamflow gage data, an alternate approach involving using the streamflow record of a physically similar watershed and applying the unit discharge (streamflow discharge per unit of watershed area) to scale these data and produce stream flow time-series for watersheds outside of the Napa Valley area. Evaluating physical similarities in watersheds involve physical characteristics of precipitation, elevation, topography, land use, and other factors. None of the watersheds used in the root-zone water balance analysis for the Napa Valley area ideal for extrapolation to watersheds outside of the Valley. However, The Napa River near Napa watershed and was selected as the physically similar watershed to perform this extrapolation. The Napa River near Napa watershed was selected because it is similar in size to the Putah Creek watershed and has a long record of outflow gage data. Smaller gaged watersheds were considered to represent Napa-Sonoma Marshes and Suisun Creek, but none were similar. The areas of major watersheds outside of the Napa Valley area are tabulated in **Table 8-15**.

This approach to extrapolating results beyond the Napa Valley area produced groundwater recharge estimates of less than 10 percent of precipitation for Putah Creek, Napa-Sonoma Marshes, and Suisun Creek. For the Napa-Sonoma Marshes watershed, average annual calculated groundwater recharge was approximately zero for all three recharge methods. This may be because the Napa-Sonoma Marshes are low-elevation and flatter watersheds, and the Napa River watershed contains significant mountain areas that may generate more surface runoff and outflow. Scaling this outflow to a much smaller watershed that is physically different may produce overly high outflow estimates resulting in minimal infiltration and minimal recharge. These recharge estimates are low when compared to recharge estimates for watersheds in the Napa Valley area. This is not surprising because the hydrologic responses in these watersheds are likely to vary considerably as a result of the great differences in watershed land use and size between the Napa River near Napa watershed and the three watersheds listed in **Table 8-15**. Therefore, these results should be considered very rough approximations and are reported here to describe the nature of attempts that were made to estimate recharge outside of the Napa Valley area.

8.10 Future Considerations

Analyses conducted to estimate groundwater recharge in the Napa Valley area were based primarily on available data and were made at a coarse spatial scale. However, results appear reasonable and provide foundational building blocks to better understand groundwater resources in Napa County. Improvements in data used in the root-zone water balance model will reduce uncertainty in groundwater recharge estimates.

PRISM precipitation data are generally accepted as a good estimate of spatially disaggregated precipitation. Historical precipitation time-series at 30 arc-second (800 meter) grid cells are available for purchase from Oregon State University's PRISM Climate Group. Using historical PRISM calculated precipitation time-series, as opposed to the PRISM scaled time-series, would improve infiltration estimates.

Better understanding of ET of native vegetation would reduce the uncertainty in groundwater recharge estimates. The sensitivity analysis indicated that assumptions for ET of native forests can greatly affect recharge estimates. Techniques for quantifying actual ET across large areas using multispectral satellite imagery and modeling the energy balance are methods that could be used to improve estimates of ET throughout Napa County. It is possible that these types of methods have been employed for vineyards and other parts of the County.

One of the major limitations in this study is the spatial and temporal availability of streamflow gage data. In order to estimate streamflow from ungaged watersheds, a rainfall-runoff model could be developed and calibrated with records from gaged watersheds. A rainfall-runoff model may also help improve the spatial resolution of infiltration within gaged watersheds. Several different platforms are available for these types of models.

The Putah Creek watershed represents approximately 46 percent of Napa County and is an ungaged watershed; however, it may be possible to estimate runoff from this watershed by calculating inflow to Lake Berryessa. Reservoir inflow calculations require close quality control of inputs and may not be possible if flood control releases from Monticello Dam are not accurate. If it is possible to calculate inflow to Lake Berryessa, this time-series could be used as the outflow component in the water balance model to estimate groundwater recharge for this area of the county.

Lastly more detailed characterization and modeling of the root-zone hydrologic processes, including spatial variability in soil properties that might be developed from the NRCS SSURGO database, could considerably improve estimates of groundwater recharge throughout the county. Data and results from this study would aid in the development and calibration of a more detailed root-zone water balance model.

8.10.1 Considerations Related to Overall Water Balance

The root-zone water balance has resulted in recharge estimates for the Napa River Basin Watershed and sub-watersheds. As noted in the discussion of the root-zone water balance components, this model does not include groundwater pumping or subsurface groundwater outflow from the underlying aquifer system. One other component not quantified with the root-zone water balance method is direct streamflow infiltration (seepage). At this time, insufficient data are available to quantify the stream seepage rate and volume within the applicable watershed and sub-watershed root-zone water balance analyses. As discussed in Section 7, groundwater may be connected to surface water in locations along the main stem Napa River such that groundwater discharge occurs to the River and groundwater levels are high enough such that seepage may not occur. This may be a temporal condition, depending on location, climate, and other factors. As discussed in the next section, additional groundwater monitoring and interrelated surface water monitoring are recommended. This monitoring will improve the understanding of groundwater/surface water interrelationships and will help quantify: 1) seepage from and/or groundwater discharge to the River and 2) subsurface groundwater outflow.

The overall watershed water balance, which can be used to observe how the quantity of groundwater flowing into and out of the groundwater basin and the change in groundwater storage, can be estimated with the addition of the above components (e.g., stream seepage, groundwater pumping, and subsurface outflow). Previous studies have estimated groundwater pumpage for the main Napa-Sonoma Valley Groundwater Basin (WYA, 2005). It would be beneficial to update these pumpage estimates based on more recent land cover information. Such an effort would necessarily need to be accompanied by an analysis of the sources of water (surface water, groundwater, and/or recycled water) used to meet agricultural, rural residential, municipal, and other water requirements.

9 SUPPLEMENTAL GROUNDWATER MONITORING IN HIGH PRIORITY SUBAREAS

An important element in Napa County's Comprehensive Groundwater Monitoring Program is an evaluation of construction information for wells with water level monitoring data. Understanding the exposure of monitored wells to aquifers in their vicinity is critical to analyzing the data collected from those wells. The two most important pieces of construction information for monitored wells, in addition to accurate location information, are information about the geologic materials encountered when the well was drilled and a record of the depth of the well screens. These well construction details allow data collected from a well to be understood in a larger hydrogeologic context, enabling more accurate quantification of aquifer conditions. This section presents the results of an inventory of wells in Napa County with water level monitoring data. The goals of this inventory are to assess the extent of aquifer specific construction information for currently monitored wells and identify wells with historic data that may be suitable for inclusion into the Napa County monitoring network. Findings from the inventory are presented in light of results from the updated hydrogeologic characterization contained in this report.

Monitored wells records included in this inventory include those from federal, state, county, and municipal groundwater level monitoring networks. Federal, state, and county records have been reviewed and compiled from the California State Water Resources Control Board's GeoTracker Database, the DWR Water Data Library, and the Data Management System (DMS) previously constructed for Napa County (LSCE, 2010). Records for wells monitored by municipalities were collected for this inventory from direct outreach to Public Works Directors and staff in each of the four incorporated municipalities within Napa Valley as well as the City of American Canyon.

Due to the large proportion of wells lacking complete construction information, efforts to locate construction information for monitored wells focused on the high priority subareas in the Napa Valley Floor and the Carneros Subarea. Additional efforts were made to identify monitored wells adjacent to the Napa River to evaluate potential groundwater/surface water monitoring sites.

Currently monitored sites referred to in this report are sites where data have been collected through at least 2011. No restriction has been placed on the number of years of accumulated monitoring data. This definition is distinct from the definition for current monitoring wells applied for the Comprehensive Groundwater Management Program, where wells with periods of record extending to at least 2005 were designated as current (LSCE, 2011a). The more narrow definition used here enables a more precise evaluation of current monitoring activities, particularly in the context of wells monitored by entities other than Napa County that may be suitable candidates for inclusion in the Napa County monitoring network. The definition of currently monitored sites used here is also reflected in the Napa County Groundwater Monitoring Plan (LSCE, 2013).

9.1 Available Location and Construction Information for Groundwater Level Monitoring Sites

The DMS served as the initial source of reference for location and construction information about groundwater level monitoring sites. Wells with current and historic groundwater level data were initially selected from the DMS without regard to the availability of construction information. However, wells with records indicating that the well has been destroyed or abandoned were omitted. The distinction between wells with current and historic data was made based on communication with the monitoring entity, or, in the case of regulated monitoring sites in the GeoTracker database, an electronic search for all wells with monitoring data reported since 2011. The DMS was modified to incorporate the results of this review with a record for each well to indicate whether or not it is currently monitored.

Often, DMS records for monitored wells include only some form of location information and a value for total well depth, without specifying the depth of well screens or a Well Completion Report (also called a driller's report) with borehole lithology records that could enable a definitive linkage with the well's completion relative to aquifer units in the area. As part of this inventory of monitored wells, an effort was made to locate Well Completion Reports (or equivalent information) for all current and historic non-regulated monitoring sites in the study area for this report.

Well Completion Reports were linked with the selected wells by comparing the location information available in the "Well" table of the DMS with township/range/section, parcel number, and well address contained in the "WellMa" DMS table. In cases where more than one record was found in a given location, the range of data collected at each well relative to the recorded well completion date, type of well, and intended use were all used to determine the correct match. Separate searches for Well Completion Reports were also performed by individually reviewing available Well Completion Reports on a township/range/section basis with the available location information for wells of interest. For wells with a DMS record for completion date predating the DWR standardized Well Completion Report form, well construction records compiled by Kunkel and Upson (1960) were reviewed.

Table 9-1 provides a summary of the groundwater level monitoring well inventory in the county. As with all results reported here, the determination of whether or not aquifer specific information is available was made based on two independent criteria. First, well records were checked for a well completion report that included sufficient lithologic detail and information regarding well screen depth intervals. Separately, wells constructed within the hydrogeologic characterization study area considered for this report were reviewed for records of well screen intervals and total well depth in the DMS. In the latter case, where either well screen interval or total well depth

information was available in the DMS, wells were reviewed with reference to their location relative to the mapped alluvium isopach contours and geologic subcrop units to make a determination, if possible, regarding the applicable aquifer unit(s) for each well.

Table 9-1 shows that a 54% of the currently monitored sites countywide are located in the Napa and MST subareas with in the Napa Valley Floor. The 87 currently monitored sites comprise only 15% of the total groundwater level monitoring sites that are not known to have been destroyed or abandoned. However, among wells for which aquifer specific construction information is available, currently monitored sites account for 61% of the total known sites.

Table 9-1
Summary of Sites[1,2] with Groundwater Level Data and Well Construction Information in Napa County

Napa County Subarea	Current and Historic Sites with WL Data[1,2]	Current and Historic Sites with WL Data and Any Construction Info	Current and Historic Sites w/ Aquifer Specific Construction Information	Current WL Sites	Current Sites w/ Aquifer Specific Construction Information
Napa Valley Floor-Calistoga	46	45	1	6	1
Napa Valley Floor-St. Helena	71	65	11	12	6
Napa Valley Floor-Yountville	51	50	13	9	7
Napa Valley Floor-Napa	79	75	13	18	9
Napa Valley Floor-MST	281	189	20	29	11
Carneros	18	17	4	5	4
Jameson/American Canyon	12	9	0	1	0
Napa River Marshes	2	2	0	1	0
Angwin	1	1	0	0	0
Berryessa	6	5	0	3	0
Central Interior Valleys	2	2	0	1	0
Eastern Mountains	8	4	0	0	0
Knoxville	1	0	0	1	0
Livermore Ranch	0	0	0	0	0
Pope Valley	2	2	0	1	0
Southern Interior Valleys	0	0	0	0	0
Western Mountains	0	0	0	0	0
Totals	**580**	**466**	**62**	**87**	**38**

[1] Regulated groundwater monitoring sites in the GeoTracker network with multiple monitoring wells are counted only once, while non-regulated monitoring wells with shared state well numbers are counted separately.

[2] Omits sites identified as abandoned or destroyed in Napa DMS water level records.

9.1.1 Voluntary and Non-Regulated Monitoring Sites

Napa County's existing groundwater monitoring program includes data currently collected at 47 non-regulated sites. The median and arithmetic mean periods of record for these sites are 13 years and 21.8 years, respectively, with the earliest record dated 2/14/1930.

Groundwater level monitoring data are also currently collected at twelve additional non-regulated sites in the county. These include monitoring at six sites by DWR, at four sites by the City of Napa, and at one site by the Town of Yountville.

Table 9-2 summarizes the construction and period of record information for all currently monitored non-regulated groundwater level monitoring sites with any available construction information. Of the 41 sites for which any construction information is available, 27 include sufficient information to determine the aquifer(s) in which the well is completed. Of these, 13 are completed in a single aquifer unit, with 9 wells completed solely in the Quaternary alluvium aquifer. The other 4 wells with a single aquifer completion are in a variety of Tertiary Sonoma Volcanic units, Tertiary sedimentary units.

Table 9-2
Current, Non-regulated Groundwater Level Sites with Any Construction Information

Napa County Subarea	Monitoring Network	Well ID	Construction Date (yyymmdd)	Water Level Period of Record	Well Depth (feet, bgs)	Screened Interval[1] (feet bgs)	Aquifer Designation[2,3,4]
Napa Valley Floor-Calistoga	NapaCounty	NapaCounty-127	19580310	1962 - 2012	149	unk	unk
	NapaCounty	NapaCounty-129	19620719	1962 - 2012	253	unk	unk
	NapaCounty	NapaCounty-128	19620719	1962 - 2012	50	unk	Qa
	DWR	08N06W10Q001M		1949 - 2009	200	unk	unk
Napa Valley Floor-St. Helena	NapaCounty	NapaCounty-131	193907	1963 - 2012	221	7 - sections	Qa
	NapaCounty	NapaCounty-132		1962 - 2012	265	25 - 265	Qa, Tsvab?
	NapaCounty	NapaCounty-138		1949 - 2012	321	unk	Qa?, Tsv?
	DWR	07N05W09Q002M		1949 - 2009	232	unk	unk

Table 9-2
Current, Non-regulated Groundwater Level Sites with Any Construction Information

Napa County Subarea	Monitoring Network	Well ID	Construction Date (yyyymmdd)	Water Level Period of Record	Well Depth (feet, bgs)	Screened Interval[1] (feet bgs)	Aquifer Designation[2,3,4]
Napa Valley Floor-Yountville	NapaCounty	NapaCounty-133	19720415	1978 - 2012	120	20 - 120	Qa
	NapaCounty	NapaCounty-135	19620720	1979 - 2012	125	unk	Qa
	NapaCounty	NapaCounty-125	19710823	1979 - 2012	160	63 - 160	Tsva
	NapaCounty	NapaCounty-126	19711116	1984 - 2012	345	140 - 345	Tsva
	NapaCounty	NapaCounty-134	19550801	1963 - 2012	260	160 - 260	Qa
	NapaCounty	NapaCounty-139	19770125	1978 - 2012	120	40 - 120	Qa
	DWR	06N04W17A001M		1949 - 2008	250	unk	unk
	Townof Yountville	TownofYountville-MW1	20041103	unk	300	105 - 300	Qa
Napa Valley Floor-Napa	NapaCounty	NapaCounty-75	19710719	1978 - 2012	205	45 - 205	Qa, Tss/h
	NapaCounty	NapaCounty-136	19620720	1979 - 2012	120	unk	Qa
	DWR	06N04W27L002M	19660609	1966 - 2009	120	60 - 120	Qa
	DWR	05N04W15E001M		1949 - 1978	158	unk	unk
Napa Valley Floor-MST	NapaCounty	NapaCounty-18	19760714	2000 - 2012	189	unk	Tsv?
	NapaCounty	NapaCounty-22	19680416	2000 - 2012	135	unk	unk
	NapaCounty	NapaCounty-4	19890913	2000 - 2011	385	unk	unk
	NapaCounty	NapaCounty-72	19971007	2000 - 2012	245	unk	unk
	NapaCounty	NapaCounty-81	19880725	2000 - 2012	290	unk	unk
	NapaCounty	NapaCounty-10		1979 - 2012	320	unk	unk
	NapaCounty	NapaCounty-2		1979 - 2012	700	unk	unk
	NapaCounty	NapaCounty-20	19771208	1978 - 2012	208	130 - 207	Tsvt?
	NapaCounty	NapaCounty-56	19760828	1978 - 2012	210	30 - 210	Tss/h
	NapaCounty	NapaCounty-95	19770110	1979 - 2012	195	155 - 185	Tsv?
	NapaCounty	NapaCounty-137	19620716	1979 - 2012	364	unk	Qa?,Tsv?
	NapaCounty	NapaCounty-43		1978 - 2012	310	unk	Unk
	NapaCounty	NapaCounty-49		1989 - 2012	399	unk	Qa, Tsv
	NapaCounty	NapaCounty-74	19880818	1999 - 2012	300	unk	Qa?, Tsv?
	NapaCounty	NapaCounty-91	19860815	1992 - 2012	415	315 - 415	Tsvt?
	NapaCounty	NapaCounty-92		1999 - 2012	368	unk	Qa, Tsv?
Carneros	NapaCounty	NapaCounty-150		2011 - 2012	155	unk	Qa?
	NapaCounty	NapaCounty-153	19780508	2012 - 2012	200	60 - 200	QTh
	NapaCounty	NapaCounty-154	19900828	2012 - 2012	300	60 - 295	QTh?
	NapaCounty	NapaCounty-155	20030813	2012 - 2012	220	80 - 220	QTh?
	DWR	04N04W05D002M		1951 - 1978	60	unk	unk

[1] Screen intervals reported here are overall intervals for a given well and are not always representative of a continuous length of screen.

[2] Aquifer designations are made based on interpretation of driller's log and/or well location relative to the mapped alluvium isopach and subcrop geology.

[3] Aquifer Designations: Qa = Quaternary alluvium, Qsb = Quaternary sedimentary basin deposits, QTh = Quaternary and Tertiary Huichica formation, TQsb = Tertiary and early Quaternary sedimentary basin deposits, Tsv = Tertiary Sonoma Volcanic undifferentiated, Tsva = Tertiary Sonoma volcanic andesite flow, Tsvt = Tertiary Sonoma Volcanic tuff, Tsva&t = Tertiary Sonoma volcanic andesite and tuff, Tsvt/s = Tertiary Sonoma Volcanic tuff and sediments, Tsvab = Tertiary Sonoma Volcanic andesite flow or breccia, Tss/h = Tertiary sedimentary rock, Tcg/ab = Tertiary Sonoma Volcanic Conglomerate/breccia, Td = Tertiary marine rock

[4] "?" indicates uncertainty in aquifer designation due to the lithogic descriptions provided in driller's log, or, if driller's log is not available, uncertainty due to a well's location outside of mapped extents of subcrop alluvium isopach and subcrop geology.

Based on this inventory, opportunities do exist within the Napa Valley Floor subareas to incorporate previously monitored wells with aquifer specific construction data. **Table 9-3** summarizes the construction and period of record information for these wells.

It is possible that some of the wells listed in **Table 9-3** are actually duplicates representing cases where wells have been monitored by more than one entity. Although each well has unique location data, in some cases the location data vary only slightly and may be attributable one of several sources of variation, including differences in survey methods used by monitoring entities. Distinguishing between such duplicates should involve field visits to resolve the location data provided for the potentially duplicate wells.

Table 9-3
Historic, Non-regulated Groundwater Level Sites with Aquifer Specific Construction Information

Napa County Subarea	Monitoring Network	Well ID	Construction Date (yyyymmdd)	Water Level Period of Record	Well Depth (feet, bgs)	Screened Interval[1] (feet bgs)	Aquifer Designation[2,3,4]
Napa Valley Floor-St. Helena	NapaCounty	NapaCounty-130	19740309	1978 - 2001	207	50 - 207	Qa, Tss/h
	DWR	07N05W04E001M	19740309	1978 - 2001	207	50 - 207	Qa, Tss/h
	DWR	07N05W14B002M		1963 - 2008	265	25 - 265	Qa, Tsvab?
	DWR	08N06W26B004M	19720511	1979 - 1991	280	30 - 280	Qa, Tst
	USGS	383746122254001	19740309	1979 - 1983	207	50 - 207	Qa, Tss/h
Napa Valley Floor-Yountville	DWR	06N04W06L002M	19550801	1963 - 2008	260	160 - 260	Qa
	DWR	06N04W09Q001M	19710823	1984 - 2008	160	63 - 160	Tsva
	DWR	06N04W09Q002M	19711116	1984 - 2008	345	140 - 345	Tsva
	DWR	06N04W17R002M	19770125	1978 - 2008	120	40 - 120	Qa
	DWR	07N04W31M001M	19720415	1978 - 2008	120	20 - 120	Qa
	USGS	382442122210501	19720415	1978 - 1983	120	20 - 120	Qa
Napa Valley Floor-Napa	DWR	05N04W15C002M		1951 - 1978	66	20 - 66	Qa
	DWR	06N04W22R001M		1959 - 2008	205	45 - 205	Qa, Tss/h
	DWR	06N04W27N001M	19290729	1930 - 2008	125	32 - 125	Qa
	USGS	381953122175401	19290729	1962 - 2002	125	32 - 125	Qa
Napa Valley Floor-MST	DWR	05N03W06B002M	19860815	1992 - 2008	415	315 - 415	Tsvt?
	DWR	05N03W07C003M	19771208	1978 - 2008	208	130 - 207	Tsvt?
	DWR	06N04W26G001M	19760828	1978 - 2008	210	30 - 210	Tss/h
	DWR	06N04W36G001M	19770110	1978 - 2008	195	155 - 185	Tsv?
	USGS	381648122151501	19761030	2000 - 2002	210	105 - 126	Tsv?
	USGS	381710122162501b		1962 - 1983	220	30 - 220	Qa, TQsb?
	USGS	381831122140501	19860815	2001 - 2002	415	315 - 415	Tsvt?

[1] Screen intervals reported here are overall intervals for a given well and are not always representative of a continuous length of screen.

[2] Aquifer designations are made based on interpretation of driller's log and/or well location relative to the mapped alluvium isopach and subcrop geology.

[3] Aquifer Designations: Qa = Quaternary alluvium, Qsb = Quaternary sedimentary basin deposits, QTh = Quaternary and Tertiary Huichica formation, TQsb = Tertiary and early Quaternary sedimentary basin deposits Tsv = Tertiary Sonoma Volcanic undifferentiated, Tsva = Tertiary Sonoma volcanic andesite flow, Tsvt = Tertiary Sonoma Volcanic tuff, Tsva&t = Tertiary Sonoma volcanic andesite and tuff, Tsvt/s = Tertiary Sonoma Volcanic tuff and sediments, Tsvab = Tertiary Sonoma Volcanic andesite flow or breccia, Tss/h = Tertiary sedimentary rock, Tcg/ab = Tertiary Sonoma Volcanic Conglomerate/breccia, Td = Tertiary marine rock

[4] "?" indicates uncertainty in aquifer designation due to the lithogic descriptions provided in driller's log, or, if driller's log is not available, uncertainty due to a well's location outside of mapped extents of subcrop alluvium isopach and subcrop geology.

9.1.2 Regulated Monitoring Sites

Regulated groundwater monitoring sites provide data collected at regular intervals, often quarterly or semi-annually, from multiple wells in close proximity to the contamination source. Data from these regulated facilities usually consist of data from groundwater monitoring wells (typically shallow) and remediation wells. Although the wells constructed at these facilities should have a corresponding Well Completion Report on file with DWR, the most efficient means for determining the construction details associated with these wells is often by accessing the well construction data uploaded to the GeoTracker database and corresponding reports of well construction uploaded in PDF format to the GeoTracker database.

The well inventory results presented here are limited to currently monitored sites. Although over 500 monitoring wells have been constructed at regulated facilities in Napa County, official correspondence between regulators and site owners available in the GeoTracker database indicate that wells are frequently destroyed by the well owner once the requirement of monitoring is lifted. However, these destruction records are not represented with a record in the GeoTracker database that would enable efficient updating of the Napa DMS. Currently monitored wells, therefore, present the best opportunity for identifying wells for possible inclusion into the Napa County monitoring network.

The GeoTracker database contains 60 open, active sites in Napa County. Of those, 28 sites include water level monitoring data uploaded in the previous 12 months. **Table 9-4** shows the distribution of those currently monitored sites throughout the county. In addition to the GeoTracker sites, **Table 9-4** includes records for two regulated sites monitored by Napa County. Although some of the current GeoTracker sites do not have sufficient construction information available to determine the appropriate aquifer completion, such information should be available from the site owner or responsible authority should the County wish to pursue adding any of

these sites to the current groundwater level monitoring network. However, since the status of monitored wells in the GeoTracker network tend to change more rapidly than those of wells in other monitoring networks, these correspondences should be reviewed prior to contacting a well owner regarding inclusion of a particular well in the Napa County monitoring network.

Table 9-4
Current, Regulated Groundwater Level Sites

Napa County Subarea	Monitoring Network	Well ID	Construction Date (yyyymmdd)	Water Level Period of Record	Well Depth (feet, bgs)	Screened Interval[1] (feet bgs)	Aquifer Designation [2,3,4]
Napa Valley Floor-Calistoga	Geotracker	T0605500250MW-1		2005 - 2009	24.83	10 - 25	Qa?
	Geotracker	T0605500272MW-1		2008 - 2009	0	unk	unk
Napa Valley Floor-St. Helena	Geotracker	T0605500061MW-8		2005 - 2009	20	6 - 20	Qa
	Geotracker	T0605500168MW-6		1998 - 2009	18	3 - 18	Qa
	Geotracker	T0605500190MW-1		2001 - 2009	22.5	7.5 - 22.5	Qa
Napa Valley Floor-Napa	Geotracker	SL0605536682MW-1		2005 - 2009	24	unk	Qa?
	Geotracker	T0605500008MW-3	20050721	2005 - 2009	15	3 - 15	Qa
	Geotracker	T0605500009MW1	19920301	2005 - 2009	14	3 - 14	Qa
	Geotracker	T0605500044C-4		2002 - 2009	12.63	10 - 30	Qa
	Geotracker	T0605500110KMW-1	19900815	2003 - 2006	19.65	9.5 - 24.5	Qa
	Geotracker	T0605500124MW-1		2002 - 2008	25	unk	Qa?
	Geotracker	T0605500164EX-1	2002112	2003 - 2009	37	10 - 35	Qa
	Geotracker	T0605500212MW-1		2003 - 2009	20	4 - 20	Qa
	Geotracker	T0605514064MW1		2005 - 2009	0	unk	unk
	Geotracker	T0605547200MW-1		2008 - 2009	0	unk	unk
	Geotracker	T0605575085MW-1		2009 - 2009	0	unk	unk
	Geotracker	T0605598080MW-1		2005 - 2009	0	unk	unk
Napa Valley Floor-MST	Geotracker	L10002804480DW-1		2005 - 2009	0	unk	unk
	Geotracker	T0605500138S-3	20030428	2003 - 2009	30	4 - 15	Qa
	Geotracker	T0605500140MW-1	19910119	2000 - 2009	24.86	11 - 26	Qa
Jameson/American Canyon	Geotracker	T0605500240MW-4		2007 - 2009	14.5	unk	Qa?
Napa River Marshes	Geotracker	L10002804480DW-2		2005 - 2009	0	unk	unk
Berryessa	NapaCounty	NBRID_MW2		2007 - 2009	0	unk	unk
	Geotracker	T0605500304MW-1		2002 - 2004	0	unk	unk
	Geotracker	T0605591908MW-1		2006 - 2009	34	unk	unk

Table 9-4
Current, Regulated Groundwater Level Sites

Napa County Subarea	Monitoring Network	Well ID	Construction Date (yyyymmdd)	Water Level Period of Record	Well Depth (feet, bgs)	Screened Interval[1] (feet bgs)	Aquifer Designation [2,3,4]
Central Interior Valleys	Geotracker	T0605500279MW1		2002 - 2009	0	unk	unk
Knoxville	NapaCounty	LBRID_MW1		2006 - 2009	0	unk	unk
Pope Valley	Geotracker	T0605593602MW-1		2002 - 2006	0	unk	unk

[1] Screen intervals reported here are overall intervals for a given well and are not always representative of a continuous length of screen.

[2] Aquifer designations are made based on interpretation of driller's log and/or well location relative to the mapped alluvium isopach and subcrop geology.

[3] Aquifer Designations: Qa = Quaternary alluvium, Qsb = Quaternary sedimentary basin deposits, QTh = Quaternary and Tertiary Huichica formation, TQsb = Tertiary and early Quaternary sedimentary basin deposits, Tsv = Tertiary Sonoma Volcanic undifferentiated, Tsva = Tertiary Sonoma volcanic andesite flow, Tsvt = Tertiary Sonoma Volcanic tuff, Tsva&t = Tertiary Sonoma volcanic andesite and tuff, Tsvt/s = Tertiary Sonoma Volcanic tuff and sediments, Tsvab = Tertiary Sonoma Volcanic andesite flow or breccia, Tss/h = Tertiary sedimentary rock, Tcg/ab = Tertiary Sonoma Volcanic Conglomerate/breccia, Td = Tertiary marine rock

[4] "?" indicates uncertainty in aquifer designation due to the lithogic descriptions provided in driller's log, or, if driller's log is not available, uncertainty due to a well's location outside of mapped extents of subcrop alluvium isopach and subcrop geology.

Construction information for the GeoTracker wells was extracted from the Napa County DMS where possible and through a review of data available in the GeoTracker database for wells not found in the DMS. However, even when directly referencing the GeoTracker database, not all monitored wells were found to have complete construction information uploaded to the GeoTracker database. In addition, the GeoTracker database does not include a record to indicate whether a given well has been abandoned or destroyed once a site becomes inactive or has closed. Official correspondence between the lead regulator and site owner or authorized representative is available on the GeoTracker website and can include correspondence relating to well abandonment. Because the status of monitored wells in the GeoTracker network change over time, these correspondences should be reviewed prior to contacting a well owner regarding inclusion of a particular well in the Napa County monitoring network.

9.2 Completion of Groundwater Level Monitoring Sites Relative to Aquifer System and Geologic Units

As the hydrogeologic characterization presented in Section 6 details, the aquifers underlying Napa Valley vary substantially in composition and productivity. Furthermore, most wells in the Napa Valley constructed post 1970 tend to have long intake or screened intervals, extending from the near surface alluvium, if present and across the underlying Sonoma Volcanics or Tertiary sedimentary rocks to the total depth drilled.

9.3 Recommendations for Napa County Groundwater Level Monitoring Network Expansion

The Napa County Groundwater Monitoring Plan (LSCE, 2013) includes a preliminary ranking and priorities for improving or expanding groundwater level monitoring for each county subarea. These rankings and priorities are presented in **Table 9-5** along with an updated count of current water level monitoring wells including five monitored by municipalities in Napa Valley. Six subareas are given a relatively higher priority for improving the groundwater level monitoring network based on factors of current population and groundwater utilization relative to other parts of the county, and/or the need to improve understanding of groundwater/surface water interactions. Some factors are given greater consideration in areas that currently use more groundwater than other areas. These areas include:

- NVF-Calistoga,
- NVF-St. Helena,
- NVF-Yountville,
- NVF- MST,
- NVF-Napa, and
- Carneros Subareas

Table 9-5
Groundwater Level Monitoring Sites, Napa County
(Current[1] and Future)

Subarea	No. Sites with Current Groundwater Level Data	Future Groundwater Level Monitoring		Monitoring Needs
		Relative Priority	Action (Expand/ Refine)	
Napa Valley Floor-Calistoga	**6**	**H**	E	**SP, SW**
Napa Valley Floor-MST	**29**	**H**	R	**SP, SW**
Napa Valley Floor-Napa	**18**	**H**	R	**SP, SW**
Napa Valley Floor-St. Helena	**12**	**H**	E	**SP, SW**
Napa Valley Floor-Yountville	**9**	**H**	E	**SP, SW**
Carneros	**5**	**H**	E	**B**
Jameson/American Canyon	1	M	E	B
Napa River Marshes	1	M	E	SP, SW
Angwin	0	M	E	B
Berryessa	3	L	E	B
Central Interior Valleys	1	L	E	B
Eastern Mountains	0	L	E	B
Knoxville	1	L	E	B
Livermore Ranch	0	L	E	B
Pope Valley[2]	1	L	E	B
Southern Interior Valleys	0	L	E	B
Western Mountains	0	L	E	B
Total	**87**			

[1] "Current" refers to monitored sites with wells measured for levels and/or any water quality parameter with a period of record extending to 2011 or later. "Future" refers to recommended monitoring locations.
[2] The relative priority for Pope Valley was changed from "high" in the Groundwater Report to "low" in the Plan based on input from the GRAC on the current population and groundwater use in this subarea.

L = Low Priority; add groundwater level monitoring based on areas of planned future groundwater development

M = Medium Priority; add groundwater level monitoring

H = High Priority; add groundwater level monitoring

E = Expand current monitoring network; possible alternatives for additional monitoring wells include 1) wells historically monitored by DWR/USGS/Others, preferably with well construction information; 2) existing water supply wells (e.g., private/commercial) with well construction information; 3) new dedicated monitoring wells coordinated with recent geologic investigations that are or will be conducted)

R = Refine current monitoring network (link well construction information to all monitored wells, as possible)

Monitoring Needs:
SP = Improve horizontal and/or vertical spatial distribution of data, including for the purpose of identifying such factors as climate change and to identify opportunities for enhanced groundwater recharge and storage;
SW =identify appropriate monitoring site to evaluate surface water -groundwater recharge/discharge mechanisms;
B = Basic data needed to accomplish groundwater level monitoring objectives

9.3.1 Areas of interest for groundwater water monitoring

Figure 9-1 depicts the distribution of currently monitored groundwater level sites throughout the county along with proposed areas of interest for additional monitoring wells. The areas of interest (AOI) are placed to fill spatial data gaps that exist within the various networks of currently monitored wells (**Table 9-6**). For each county subarea, **Table 9-6** shows the existing monitoring sites, provides recommendations for the number and location of additional monitoring areas, and describes the key groundwater level monitoring objectives to be addressed. Altogether, it is recommended that approximately six groundwater/surface water monitoring sites for purposes of evaluating groundwater/surface water interactions and about 18 other areas of interest (AOIs) be added to the network (**Figure 9-1**).

The areas of interest within the Napa Valley Floor and the data gaps that they fill are largely substantiated by the results of the LiDAR depth to water analysis for the Napa Valley Floor (**Figure 9-2**). In particular, the portion of the valley floor for which the implausible positive depth to water values were calculated also corresponds to the areas which lack sufficient representation in the existing monitoring network.

This inventory has found up to 13 wells with historical water level records and single aquifer completions in high priority subareas that may be suitable for inclusion in the current Napa County network, pending resolution of potential duplicate well records (see **Section 9.1.1**). An additional 20 currently monitored regulated groundwater level monitoring sites have been identified in high priority subareas.

Table 9-6
Proposed Monitoring Wells in Napa County

Subarea	Future GW Monitoring			AOI (number and GW or SW/GW)	Aquifer of Interest	Estimated alluvium depth at AOI (ft)
	Relative Priority	Needs	Objectives			
Napa Valley Floor-Calistoga	**H**	SP, SW	Conditions, Trends, Wtr Budget, SW	GW 14	Qa	unk
				GW 15	Qa	unk
Napa Valley Floor-St. Helena	**H**	SP, SW	Conditions, Trends, Wtr Budget, SW	GW 11	Qa	100 - 150
				GW 12	Qa	> 200
				GW 13	Qa	100 - 150
				SW E	Qa	100 - 150
				SW F	Qa, Tst	< 50
Napa Valley Floor-Yountville	**H**	SP, SW	Conditions, Trends, Wtr Budget, SW	GW 9	Qa	200 - 250
				GW 10	Qa, Tsvt	50 - 100
				SW D	Qa	100 - 200
				SW B	Qa	100 - 150
Napa Valley Floor-Napa	**H**	SP, SW	Conditions, Trends, Wtr Budget, SW	GW 5	Qa	> 200
				GW 6	Qa	unk
				GW 7	Qa	100 - 150
				GW 8	Qa	50
				SW A	Qa	unk
				SW C	Qa	50
Carneros	**H**	B	Conditions, Trends, Wtr Budget, Saltwater	GW 4	Qa	150 - 200
Jameson/American Canyon	M	B	Conditions, Trends, Wtr Budget, Saltwater	GW 1	Qa	unk
				GW 18	Qa	unk
Napa River Marshes	M	SP, SW	Conditions, Trends, Wtr Budget, Saltwater	GW 2	Qa	unk
				GW 3	Qa	unk
Angwin	M	B	Conditions, Trends, Wtr Budget	GW 16	Qa	unk
Pope Valley	L	B	Conditions, Trends (incl. CASGEM)	GW 17	Qa	unk

L = Low Priority; add groundwater level monitoring based on areas of planned future groundwater development

M = Medium Priority; add groundwater level monitoring

H = High Priority; add groundwater level monitoring

Monitoring Needs:
SP = Improve horizontal and/or vertical spatial distribution of data, including for the purpose of identifying such factors as climate change and to identify opportunities for enhanced groundwater recharge and storage;
SW =identify appropriate monitoring site to evaluate surface water -groundwater recharge/discharge mechanisms;
B = Basic data needed to accomplish groundwater level monitoring objectives

9.3.2 Areas of interest for additional groundwater monitoring

This review of monitored wells with current or historical data and aquifer-specific construction information did not find any such sites within a quarter mile of the mainstem Napa River that are screened exclusively in the shallow Quaternary alluvium aquifer. In response, six sites have been considered for the development of dedicated monitoring wells to provide data for groundwater/surface water monitoring.

The six proposed groundwater monitoring sites are located along the main Napa Valley Floor from the City of Napa north to St. Helena adjacent to the Napa River system (**Figure 9-1 and 9-2**). These facilities are planned to be located near to existing stream gauging stations and/or near areas where stream monitoring can also be conducted. **Table 9-7** provides a summary of the site locations and monitoring instrumentation. The proposed groundwater monitoring facilities are also being sited, where possible, adjacent to existing groundwater monitoring facilities (i.e., typically water supply wells constructed to greater depths in the aquifer system). The proposed monitoring wells will enable focused data collection regarding groundwater elevations and water quality to identify and characterize interactions with surface water.

The proposed groundwater monitoring sites described in **Table 9-7** would each include a dual casing installation with screen intervals located to provide for monitoring of the shallow and deeper portions of the alluvial aquifer at each location. In addition to the surface water monitoring equipment described in **Table 9-7**, the monitoring wells would also be equipped with automated water level recording equipment to measure changes in water levels that are more significant when studying groundwater surface water interactions than a semi-annual or even quarterly monitoring program would provide.

Table 9-7
Proposed Groundwater/Surface Water Monitoring Sites in the Napa Valley

Site	Location	Proposed MW property owner	Existing SW monitoring	Proposed additional SW monitoring	Proposed additional SW instrumentation location
F	Napa River at St. Helena	City of St. Helena	streamflow and stage (USGS)	temp, conductivity	USGS gauging station or Pope St Bridge
E	Napa River at Rutherford Rd	Napa County/State of California	none	stage, temp, conductivity	Napa River at Hoening/Round Pond property
D	Napa River at Yountville Cross Rd	Napa County	Stage (ultrasonic) at Yountville Cross Rd bridge (Napa RCD)	stage, temp, conductivity	Napa RCD gauging station
C	Napa River at Oak Knoll Ave	Napa County	streamflow and stage (USGS)	temp, conductivity	USGS gauging station or Oak Knoll Ave Bridge
B	Dry Creek at Washington St	Napa County	Stage (Napa RCD)	temp, conductivity	Napa RCD gauging station
A	Napa River at Napa	Napa County	Stage (ultrasonic) at Lincoln Ave bridge (Napa RCD)	stage, temp, conductivity	Lincoln Ave gauging station

Although no existing wells with water level records have been found to meet the needs for groundwater/surface water monitoring, four currently monitored sites with screened intervals in the shallow alluvial aquifer are located within one-half mile of the proposed groundwater/surface water monitoring locations. These sites would provide an opportunity to compare the groundwater level data collected in dedicated monitoring wells adjacent to the Napa River with data from sites somewhat farther away to assess groundwater gradients and water level trends relative to the river. These differences could be used to evaluate the interactions of groundwater and surface water seen near the Napa River with conditions farther removed from the river channel, both horizontally and vertically.

10 RECOMMENDATIONS

This study led to a broader awareness of the available geologic data, including drillers' reports, that were used to update the hydrogeologic conceptualization of Napa Valley Floor. This work also identified factors related to future assessment of groundwater availability. Spatial data coverage for stream gaging stations and groundwater level monitoring was good for some County subareas; however, for other subareas, additional stream gaging locations and monitoring network enhancements are needed. It was also learned better data are needed to develop aquifer characteristics that more accurately represent aquifers developed for groundwater utilization. Recommendations are presented to enhance and expand countywide monitoring to facilitate understanding of groundwater availability and integrated regional water management and planning efforts. Some of these recommendations, particularly recommendations related to the Carneros, Jameson/American Canyon, and Napa River Marshes Subareas, were previously discussed in reconnaissance work for the County's Comprehensive Groundwater Monitoring Program (LSCE, 2011a). The scope of the present study did not include the latter two subareas, so these recommendations still apply. The present study did attempt to develop a geologic cross-section in the Carneros Subarea and found geologic information to be lacking.

10.1 Carneros Subarea Hydrogeology

Limited data are available that describe the hydrogeologic setting of the Carneros Subarea. The available data suggest that groundwater resources are limited due to the generally low yielding nature of the formations in this area and poor groundwater quality at some locations (LSCE, 2011a). Future planning decisions require knowledge of current groundwater conditions and the possible impacts that may result from additional pumping. A complete analysis of the Carneros Subarea is recommended, including:

- Monitoring groundwater levels;
- Monitoring groundwater quality;
- Collection and interpretation of geologic data (primarily from well drillers' reports)
- Estimation of groundwater recharge using both mass balance;
- Determination of the extent and properties of aquifer materials; and
- Investigation of the influence of natural and induced hydrologic stresses occurring in neighboring subareas.

Since stream gaging information are lacking in the south part of the county, it is recommended that the focus be on enhancing the groundwater monitoring network (as discussed below) and development of additional geologic data, as feasible.

10.2 Hydrogeology and Saltwater Intrusion Potential for the Jameson/American Canyon and Napa River Marshes Subareas

Similar to the Carneros Subarea, limited data are available for the Jameson/American Canyons and Napa River Marshes Subareas which make up the southern County area. The two main issues facing this area are potential saltwater intrusion and the possibility that current water resources will not be sufficient to meet future demand. To establish current conditions and obtain information necessary for future development planning, further analysis is recommended that includes:

- Monitoring groundwater levels;
- Monitoring groundwater quality;
- Collection and interpretation of geologic data (primarily from well drillers' reports);
- Analysis of streamflow and precipitation;
- Estimation of recharge and discharge using both mass balance and streamflow infiltration methods; and
- Determination of the extent and properties of aquifer materials.

The current lack of groundwater data makes it difficult to determine the source and distribution of salinity in the southern County area with any certainty. A series of multi-level monitoring well clusters installed stepping south from the City of Napa toward San Pablo Bay would help in determining the geology of the Napa River Marsh Subarea and distribution of high salinity groundwater. This further subsurface exploration and characterization of the aquifer system, in conjunction with efforts to estimate subsurface outflow from the Napa Valley, would also help determine if freshwater within the Napa River Marshes Subarea could possibly be used to sustain increasing demand in the Jameson/American Canyon Subarea.

10.3 Aquifer Testing

As explained in this Report, the distribution of the hydraulic conductivities in the Napa Valley as presented by Faye (1973) was based on data recorded on historical drillers' reports. During the current study, it became evident, based on the approximately 1,300 reports reviewed, that most of the "test" data are insufficient to adequately determine or estimate aquifer characteristics, since most of these data were recorded during airlift operations rather than a pumping test. Currently, test methods accepted in the County's Well and Groundwater Ordinance allow bailing, airlifting, pumping, or any manner of testing generally acceptable within the well drilling industry to determine well yield. Recommendations for modifying the Napa County's Well and Groundwater Ordinance (Title 13, Chapter 13.04) have been proposed to improve the quality of data received by Environmental Management concerning reporting of well yield (LSCE, 2011c). These recommendations included removal of bailing and airlifting as acceptable methods; pumping is recommended to gather the appropriate data to reliably determine well yield,

particularly in areas where such information along with aquifer characteristics is determined to be important to accomplish other County groundwater objectives. In 2013, County staff and the GRAC plan to review this recommendation and provide guidance for updating the County's Well and Groundwater Ordinance.

10.4 Stream Gaging Stations

One of the major limitations in this study is the spatial and temporal availability of streamflow gage data. The limited availability of data from gaged streamflow locations precludes developing a more spatially distributed estimate of recharge using this method. Because streamflow as measured at a gage is an aggregate for the upstream drainage area, infiltration is assumed to be uniform throughout each gaged watershed and across all land use categories.

In order to estimate streamflow from ungaged watersheds, a rainfall-runoff model could be developed and calibrated with records from gaged watersheds. A rainfall-runoff model may also help improve the spatial resolution of infiltration within gaged watersheds. Several different platforms are available for these types of models.

The Putah Creek watershed represents approximately 46 percent of Napa County and is an ungaged watershed; however, it may be possible to estimate runoff from this watershed by calculating inflow to Lake Berryessa. Reservoir inflow calculations require close quality control of inputs and may not be possible if flood control releases from Monticello Dam are not accurate. If it is possible to calculate inflow to Lake Berryessa, this time-series could be used as the outflow component in the water balance model to estimate groundwater recharge for this area of the county.

10.5 Groundwater Monitoring Network

This Report illustrates the distribution of current groundwater level monitoring locations, which is primarily located in the Napa Valley Floor-Napa and MST Subareas. Very little groundwater level monitoring is currently conducted elsewhere in Napa County outside these two subareas. Groundwater level measurements have been recorded at a total of 87 sites since 2011. Of these sites where groundwater levels are measured, some type of well construction information (depth and/or perforated interval(s)) is available for 67 sites (41 non-regulated sites and 26 regulated sites).

A preliminary ranking and priorities for improving or expanding groundwater level monitoring were prepared for each county subarea. Six subareas are given a relatively higher priority for improving the groundwater level monitoring network based on factors of current population and

groundwater utilization relative to other parts of the county, and/or the need to improve understanding of groundwater/surface water interactions. These areas include:

- NVF-Calistoga,
- NVF-St. Helena,
- NVF-Yountville,
- NVF- MST,
- NVF-Napa, and
- Carneros Subareas

The monitoring network gaps in these six subareas might be addressed by:

1) Investigating the potential to restart monitoring where historical records are available but monitoring was discontinued;
2) Identifying existing wells of suitable construction that might be volunteered for inclusion through County and GRAC education and outreach efforts (this may include wells that are already being monitored for groundwater quality); and
3) Constructing new dedicated monitoring wells if suitable existing wells either do not exist in the area of interest or are otherwise not available.

Monitoring in other subareas with relatively medium to lower priorities is suggested to be addressed with volunteered wells. The Napa County CASGEM Network Plan submitted to DWR in September 2011 (LSCE, 2011b) also describes the County's intent to include at least one additional monitoring well in the Pope Valley and Berryessa Valley Groundwater Basins.

The County plans to conduct additional public outreach to inform more private well owners of the value of understanding the groundwater resources in the County and to encourage their voluntary participation in the Comprehensive Groundwater Monitoring Program and/or CASGEM program (LSCE, 2013).

This Report describes the existing monitoring sites, provides recommendations for the number and location of additional monitoring areas, and describes the key groundwater level monitoring objectives to be addressed. Altogether, it is recommended that approximately six groundwater/surface water monitoring sites for purposes of evaluating groundwater/surface water interactions and about 18 other areas of interest be added to the network.

The six proposed groundwater/surface water monitoring sites are located along the main Napa Valley Floor from the City of Napa north to St. Helena adjacent to the Napa River system. These facilities are planned to be located near to existing stream gaging stations and/or near areas where stream monitoring can also be conducted. The proposed groundwater monitoring facilities are also being sited, where possible, adjacent to existing groundwater monitoring facilities (i.e., typically water supply wells constructed to greater depths in the aquifer system).

The proposed monitoring wells will enable focused data collection regarding groundwater elevations and water quality to identify and characterize interactions with surface water.

Although this Report focuses on the extent of groundwater level monitoring in Napa County, a summary review of current groundwater quality monitoring sites has been conducted for the Napa County Groundwater Monitoring Plan 2013. That review found 177 sites in Napa County, across all monitoring networks, with groundwater quality data collected since 2008 (LSCE, 2013). The current monitoring networks for groundwater levels and groundwater quality differ according to monitoring entity, data collection frequency, and monitoring goals. Given these differences, a similar inventory of the groundwater quality monitoring networks is advisable in light of the County's intention to increase its capacity to consider groundwater quality in future groundwater resources management decisions.

The proposed inventory should include an effort to locate construction information and identify aquifers encountered by sites monitored for groundwater quality. The updated hydrogeologic conceptualization presented here as well as previously published studies would guide the inventory. Goals of the proposed inventory include an evaluation of the extent and quality of data provided by currently monitored groundwater quality sites and historically monitored sites with the potential for reactivation. The proposed inventory should also consider Napa County's groundwater quality monitoring needs and develop proposals to meet those needs with data from currently monitored wells, where feasible, or wells added to the Napa County monitoring network.

10.6 Future Groundwater Modeling Efforts

As described earlier in this Report, a groundwater flow model was developed for the Napa River watershed which was generally conceptualized as a large basin of impermeable rock overlain in three distinct areas by more permeable units (DHI, 2006a). The three areas that were the focus of the groundwater model were the north Napa Valley area and the MST and Carneros Subareas. The groundwater model encompasses the Napa River watershed and consists of two layers. The upper layer was designated as being unconfined and the lower layer was designated as confined. Each of the three modeled areas was represented as a separate water-producing geologic unit. The geologic unit that was conceptualized as the primary source for groundwater in the north Napa Valley area was the alluvium. Aquifer parameters and their distribution were based on previous work presented in Faye (1973), and extrapolated to the rest of the Napa Valley Floor to the south.

A model is a tool that can help facilitate the examination of water resources management scenarios, including the effects of climate change and other stresses on surface and groundwater resources. Large regional models can be especially useful tools to examine complicated

scenarios. As described in this Report, the geologic and hydrogeologic setting in Napa County and specifically the Napa Valley Floor, is extremely complex. The updated hydrogeologic conceptualization presented herein shows that the subsurface is so complex that the current two-layer model for the north Napa Valley area, which focuses on the alluvium with unconfined and semi-confined aquifer characteristics, needs significant refinement for future use and to improve the models' predicative utility. Such refinement includes, but is not limited to, incorporation of the updated physical hydrogeologic conceptualization in the model structure and consideration of revised aquifer parameters and/or sensitivity analyses of parameters until such parameters can be refined through proper testing.

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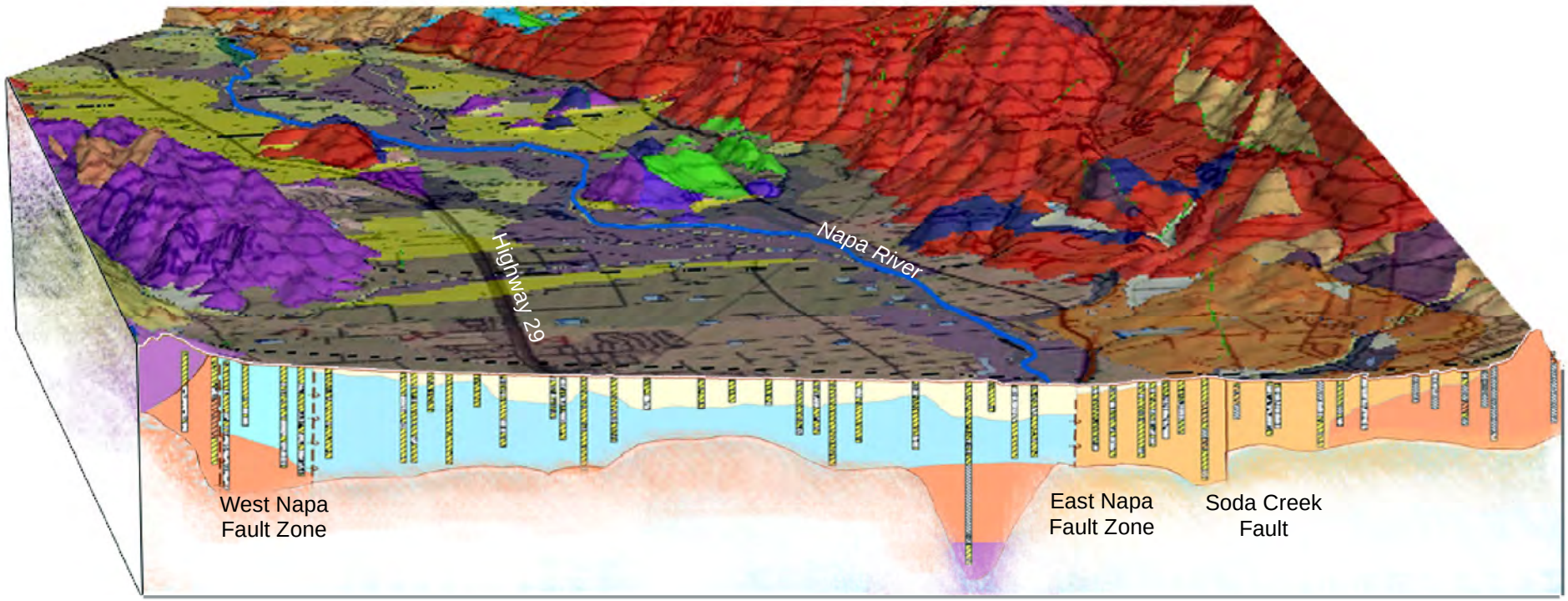

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Figure ES-1
Three-Dimensional Visualization of the Geology in the Napa Valley Area

Wells without Aquifer Specific Construction Information

- Napa County network
- DWR network
- GeoTracker network
- City of Napa network

Wells with Aquifer Specific Construction Information

- Napa County network
- DWR network
- GeoTracker network
- Town of Yountville
- Proposed GW Monitoring Sites
- Proposed GW/SW Monitoring Sites
- Napa River
- Municipal boundaries
- Subarea Boundary

Knoxville
Livermore Ranch
Pope Valley
Calistoga
Angwin
Berryessa
Central Interior Valleys
Napa Valley Floor Calistoga
St. Helena
Eastern Mountains
Napa Valley Floor St. Helena
Western Mountains
Yountville
Napa River
Soda Creek Fault
Southern Interior Valleys
Napa Valley Floor Yountville
Napa
Napa Valley Floor Napa
Napa Valley Floor MST
Carneros
Jameson/ American Canyon
Napa River Marshes
American Canyon

DWR Bulletin 118 Groundwater Basins

- BERRYESSA VALLEY
- NAPA-SONOMA VALLEY
- POPE VALLEY
- SUISUN-FAIRFIELD VALLEY

0 1 2 Miles

N

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Figure ES-4
Current and Proposed Groundwater Level Monitoring Sites in Napa County

COLUSA COUNTY

LAKE COUNTY

YOLO COUNTY

SONOMA COUNTY

SOLANO COUNTY

Legend

DWR Groundwater Basin, Subbasin

- Napa-Sonoma Valley Basin, Napa Valley Subbasin
- Napa-Sonoma Valley Basin, Napa-Sonoma Lowlands Subbasin
- Berryessa Valley Basin
- Pope Valley Basin
- Suisun-Fairfield Valley

County Boundary

N

0 4 8 Miles

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Figure 2-1
Napa County Groundwater Basins
Napa County, CA

COLUSA COUNTY

LAKE COUNTY

YOLO COUNTY

Knoxville

Livermore Ranch

Pope Valley

Berryessa

Angwin

Central Interior Valleys

Napa Valley Floor Calistoga

Eastern Mountains

Napa Valley Floor St. Helena

Western Mountains

Napa Valley Floor Yountville

Napa Valley Floor MST

SONOMA COUNTY

Napa Valley Floor Napa

Southern Interior Valleys

Carneros

SOLANO COUNTY

Jameson/ American Canyon

Napa River Marshes

Legend

Subarea Boundary

County Boundary

N

Miles

0 4 8

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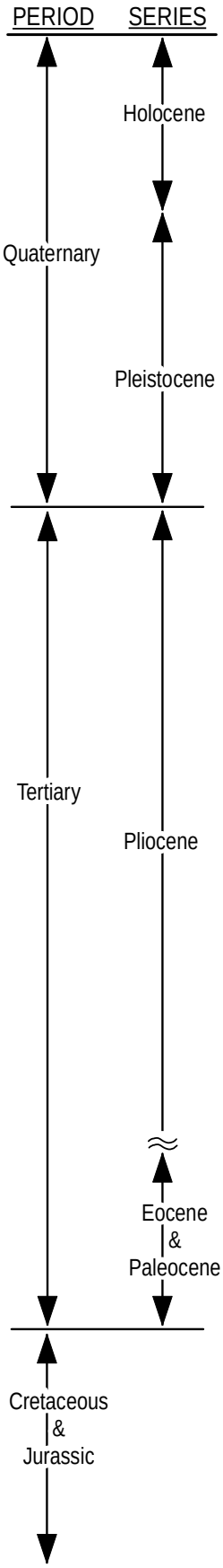
Figure 2-2
Napa County Subareas
Napa County, CA



Surficial Deposits

- af Artificial fill
- Qhc Stream channel deposits
- Qhay Alluvium, younger
- Qhty Terrace deposits, younger
- Qa Alluvium
- Qt Terrace deposits
- Qf Alluvial fan deposits
- Qls Landslide deposits
- Qpa Pleistocene alluvium
- Qpt Pleistocene terrace deposits
- Qpf Pleistocene alluvial fan deposits
- Qoa Older alluvium

Tertiary Rocks

Sonoma Volcanics

Upper Member

St. Helena Ryholite
- Tsr - flows and breccias

Petrified Forest
- Tst - tuffs and sediments

MST Cauldera
- Tstx - tuff?
- Tsrb - breccia
- Tslt - tuff breccia

Dacite of Mt. George
- Tsvdg - flows and domes

Lower Member

Stags Leap Andesite
- Tsva - flows, breccias, tuffs
- Tsvab - flow breccia
- Tsvt - tuff
- Tsai - intrusive plug

Sedimentary Rocks

Carneros Area
- QTh - Huichica formation

Conn Valley Area
- Tss/h - sands and clays

MST Area
- Tss/h - sands and clays
- Tssd - diatomite

Marine Sedimentary Rocks
- Td - Domingene sandstone

** other units not shown*

Mesozoic Rocks

Franciscan Complex
- KJfm - melange
- KJfs - graywacke
- KJfgs - greenstone

Great Valley Complex
- Kgvu - upper
- KJgvl - lower
- KJgv - sandstones and shales

Coast Range Ophiolite
- sp - serpentinite

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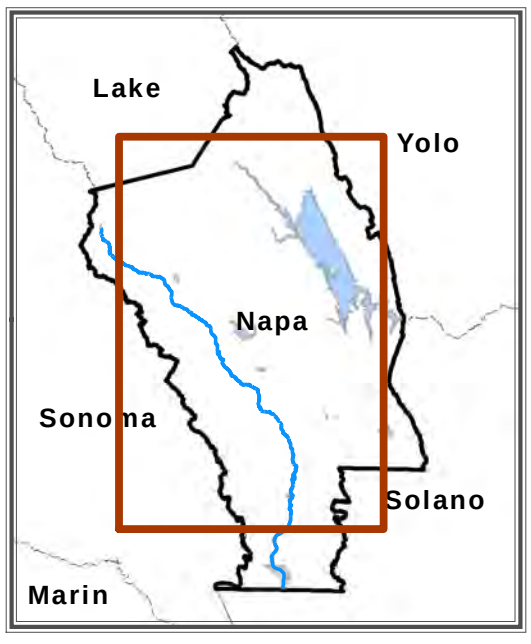
Figure 3-1a
Major Surficial Rocks and Deposits of Napa Valley

CALISTOGA

ST. HELENA

YOUNTVILLE

NAPA



USGS faults

- Certain
- Approximate
- Approximate, queried
- Concealed
- Concealed, queried
- Uncertain
- Uncertain, queried

LSCE faults

- Concealed
- Uncertain, queried
- Incorporated City or Town
- Subarea Boundary

0 1 2 Miles

N

Note: See Figure 3-1a for an explanation of major surficial rocks and deposits. The surficial geology presented here is a composite and simplification of U.S. Geological Survey (Graymer et al., 2002; Graymer et al., 2006; Graymer et al., 2007) and CA Geological Survey (Bezore et al., 2002; Bezore et al., 2004; Bezore et al., 2005; Clahan et al., 2004; Clahan et al., 2005) mapped units.

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Figure 3-1b
Napa Valley Surficial Geology

Figure 5-1a Cross Section B-B' From Kunkel and Upson (1960)

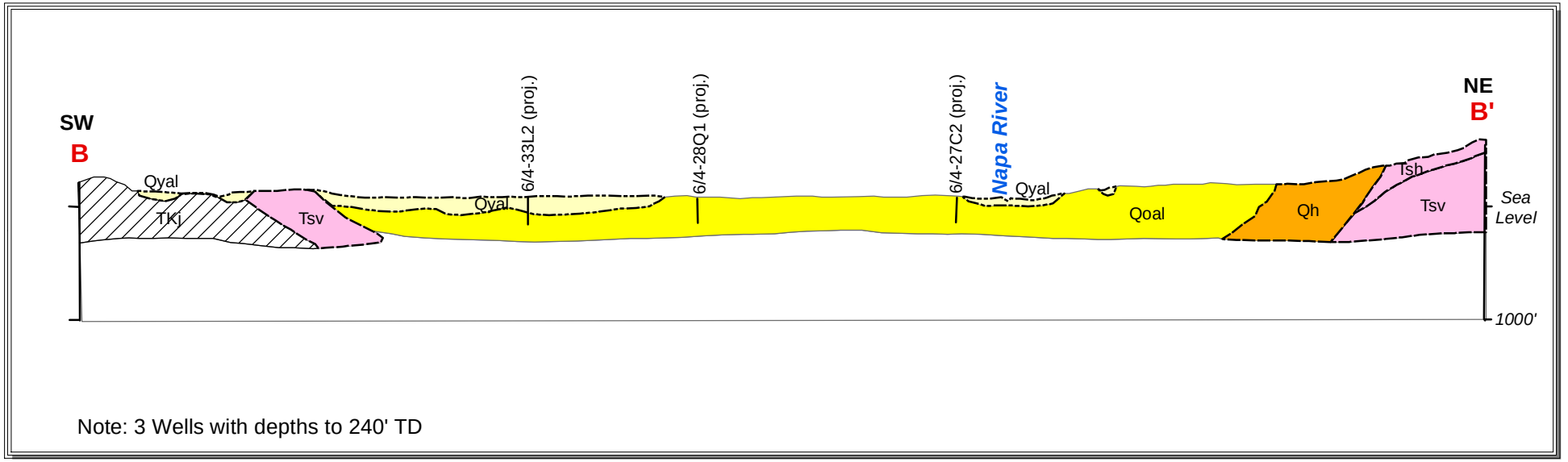

Figure 5-1b annotated Cross Section B-B', Schematic Geologic and Well Information From LSCE (2013)

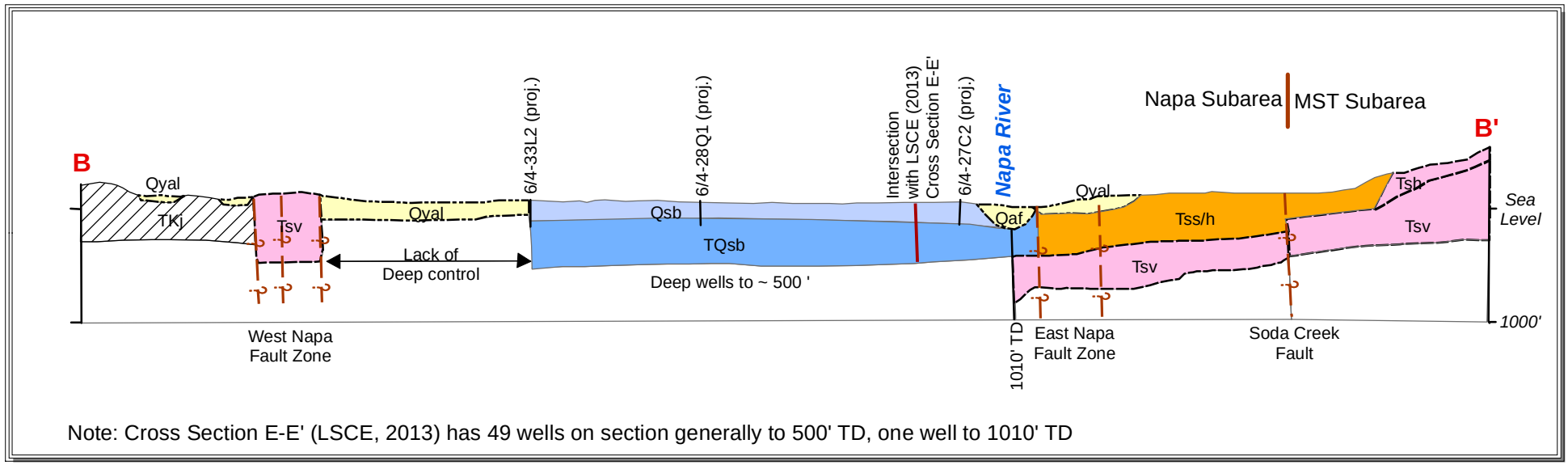

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Figure 5-1
Kunkel and Upson Geologic Cross Section

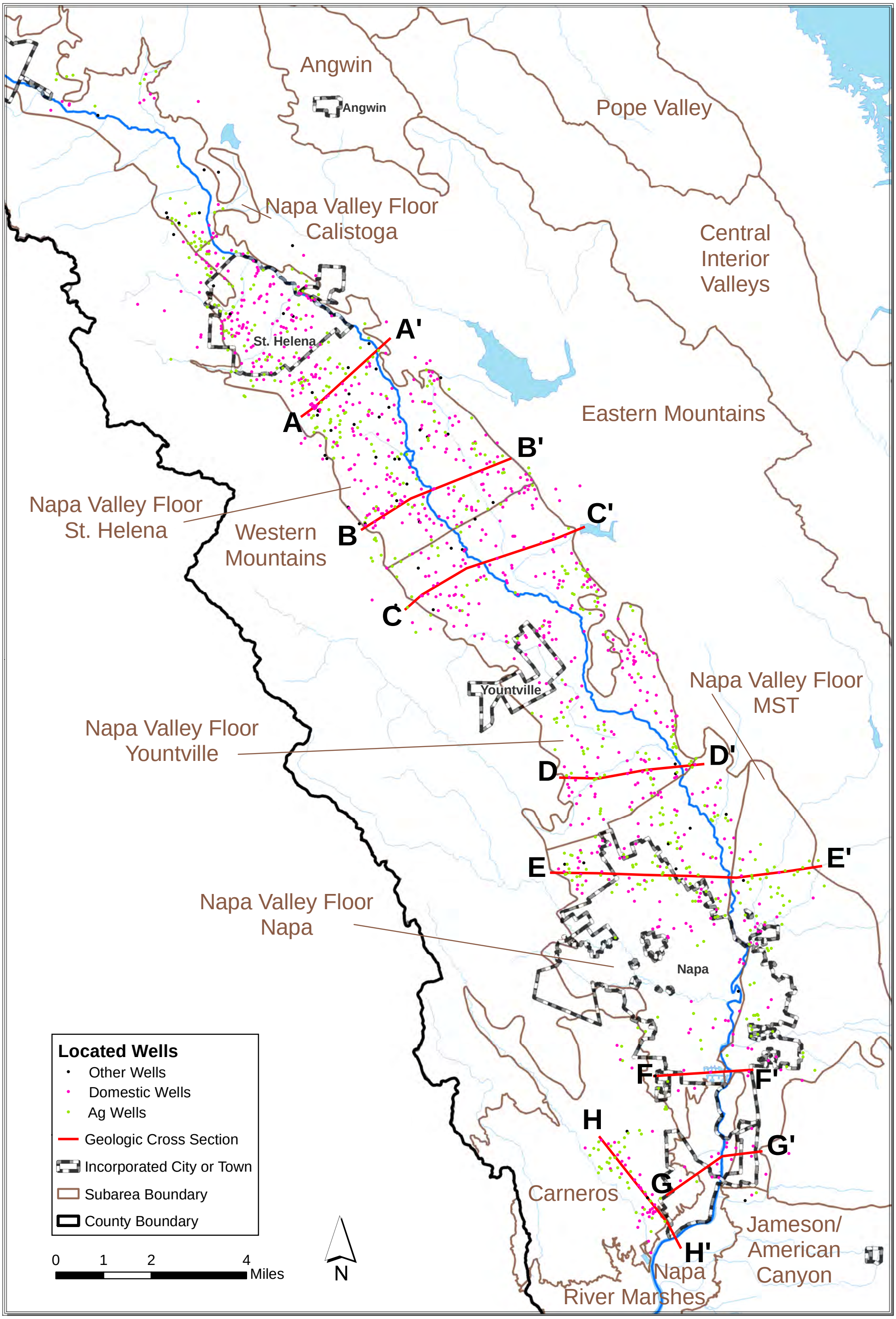

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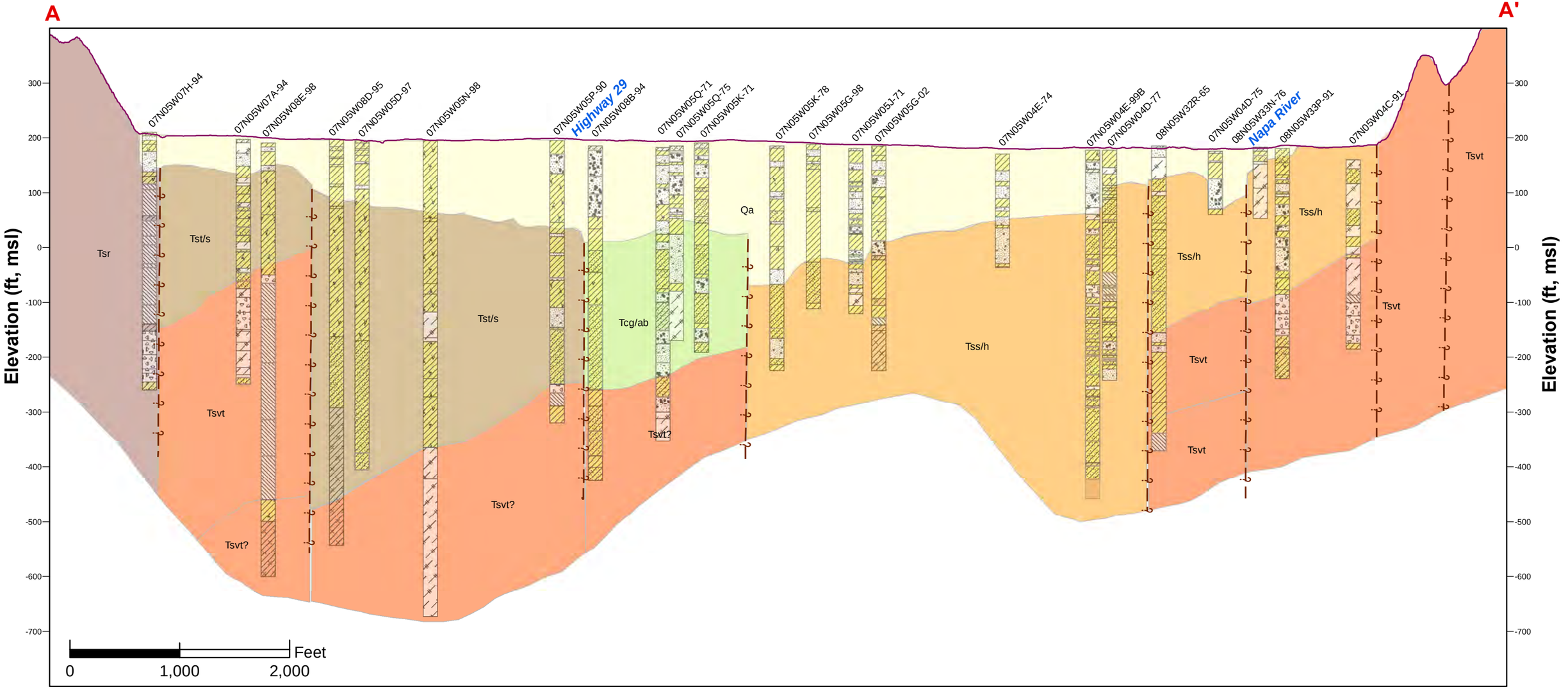
Figure 5-2
Geologic Cross Section Location Map



Legend

- Basalt
- Clay
- Clay and Basalt
- Clay and Gravel
- Clay and Sand (or Sandstone)
- Clay and Tuff
- Clay, Sand, and Gravel
- Gravel
- Rock
- Sand
- Sand (or Sandstone) and Gravel
- Sand and Clay
- Sandstone
- Tuff or Ash
- Unknown
- Faults

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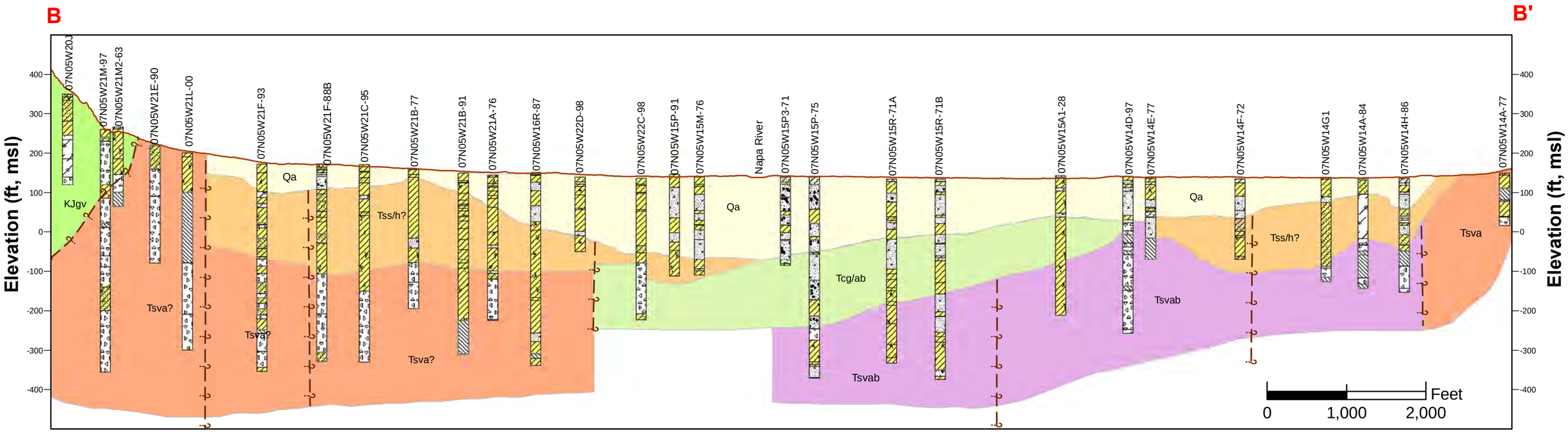
Figure 5-3
Cross Section A – A'
Northern NVF-St. Helena Subarea, Napa County, CA



Legend

- Basalt
- Clay and Basalt
- Clay and Sand (or Sandstone)
- Clay, Sand, and Gravel
- Rock
- Sand (or Sandstone) and Gravel
- Sandstone
- Clay
- Clay and Gravel
- Clay and Tuff
- Gravel
- Sand
- Sand and Clay
- Tuff or Ash
- Unknown
- Faults

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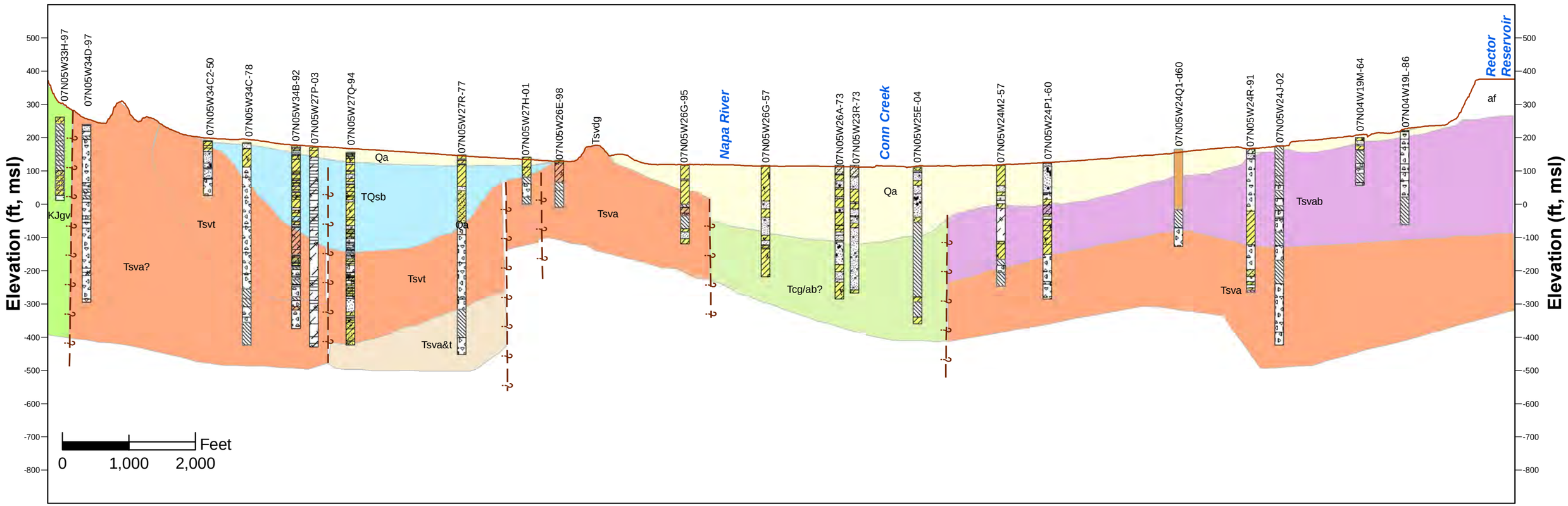
Figure 5-4
Cross Section B – B'
Southern NVF-St. Helena Subarea, Napa County, CA



Legend

Basalt	Clay and Gravel	Clay, Sand, and Gravel	Sand	Sandstone
Clay	Clay and Sand (or Sandstone)	Gravel	Sand (or Sandstone) and Gravel	Tuff or Ash
Clay and Basalt	Clay and Tuff	Rock	Sand and Clay	Unknown
				Faults

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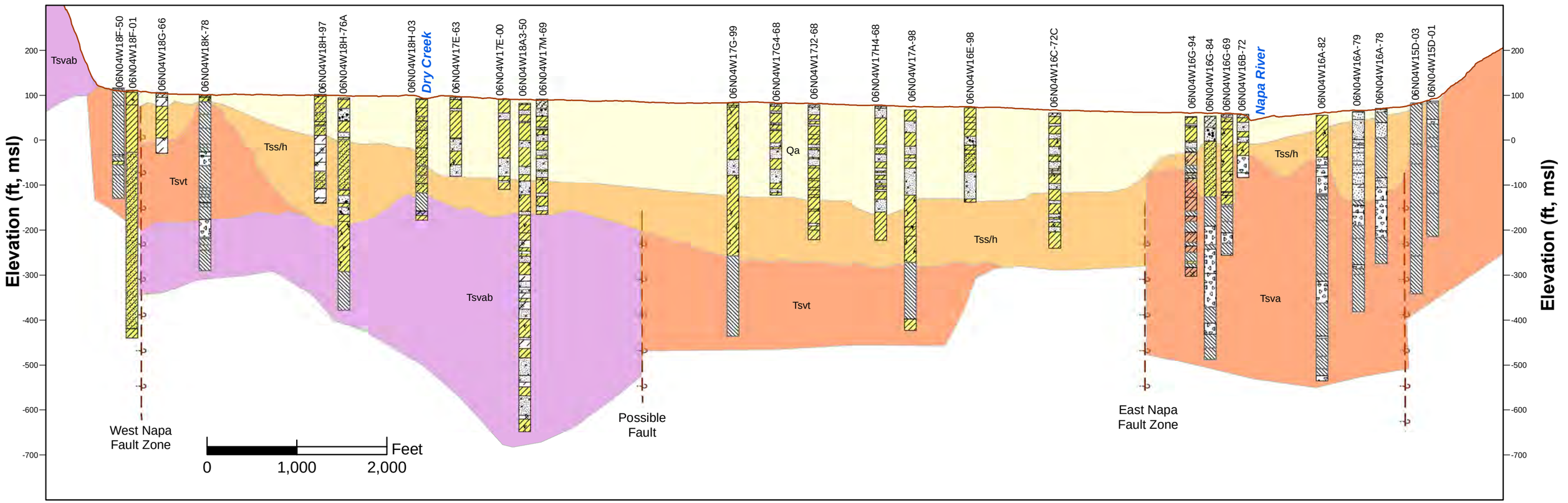
Figure 5-5
Cross Section C – C'
Northern NVF-Yountville Subarea, Napa County, CA

D

D'



Legend

- Basalt
- Clay and Basalt
- Clay and Sand (or Sandstone)
- Clay, Sand, and Gravel
- Rock
- Sand (or Sandstone) and Gravel
- Sandstone
- Clay
- Clay and Gravel
- Clay and Tuff
- Gravel
- Sand
- Sand and Clay
- Tuff or Ash
- Unknown
- Faults

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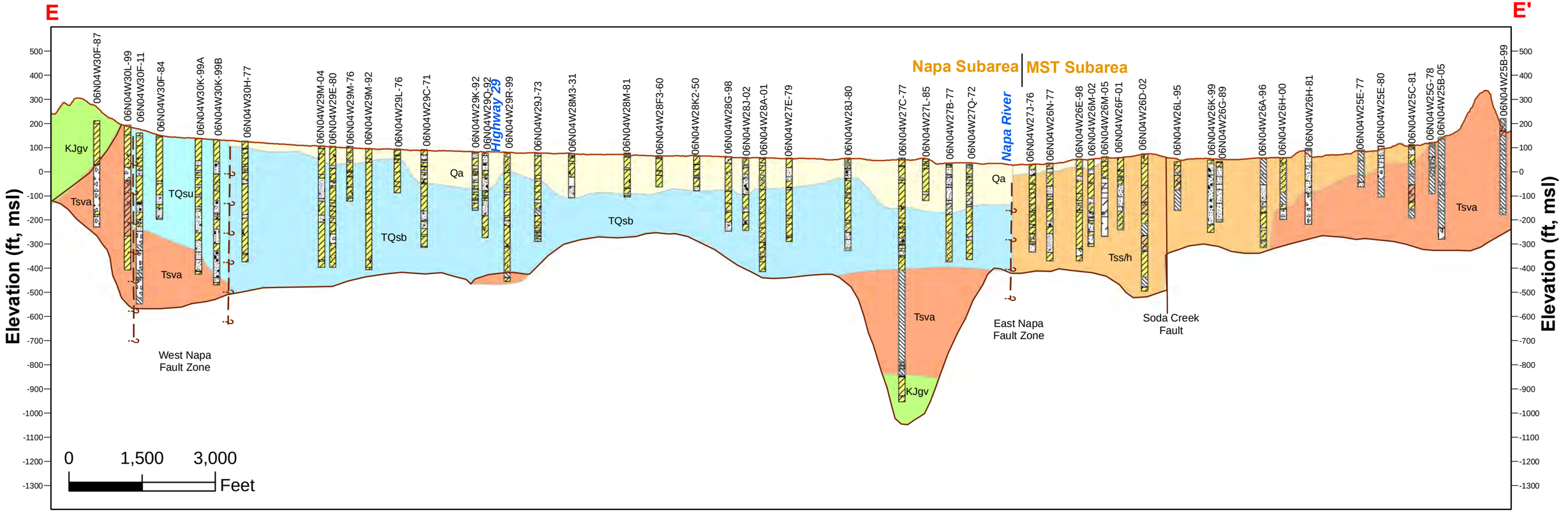
Figure 5-6
Cross Section D – D'
Southern NVF-Yountville Subarea, Napa County, CA



Legend

- Basalt
- Clay
- Clay and Basalt
- Clay and Gravel
- Clay and Sand (or Sandstone)
- Clay and Tuff
- Clay, Sand, and Gravel
- Gravel
- Rock
- Sand
- Sand (or Sandstone) and Gravel
- Sand and Clay
- Sandstone
- Tuff or Ash
- Unknown
- Possible Faults
- Faults

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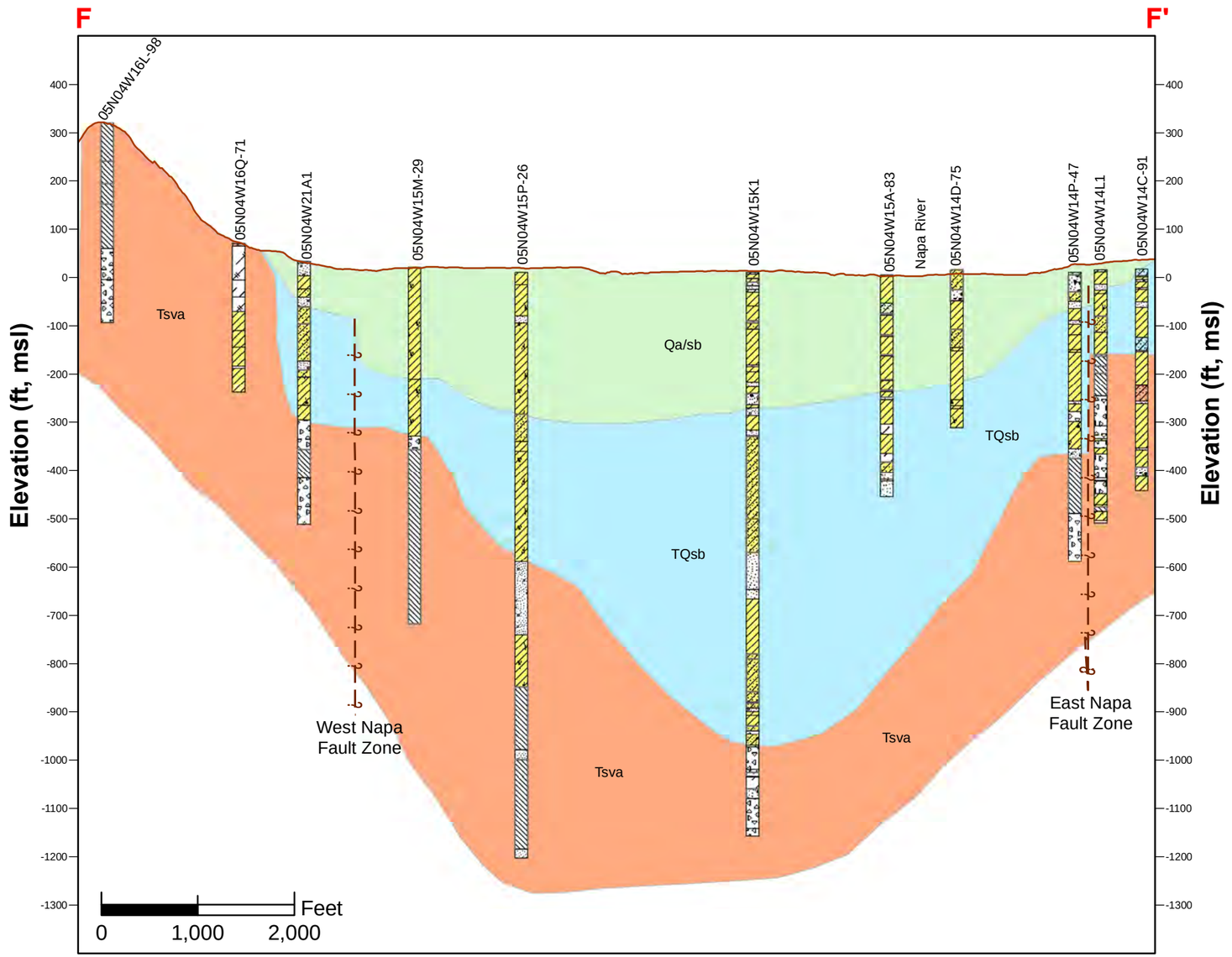
Figure 5-7
Cross Section E – E'
Northern NVF-Napa Subarea, Napa County, CA



Legend

- Basalt
- Clay
- Clay and Basalt
- Clay and Gravel
- Clay and Sand (or Sandstone)
- Clay and Tuff
- Clay, Sand, and Gravel
- Gravel
- Rock
- Sand
- Sand (or Sandstone) and Gravel
- Sand and Clay
- Sandstone
- Tuff or Ash
- Unknown
- Faults

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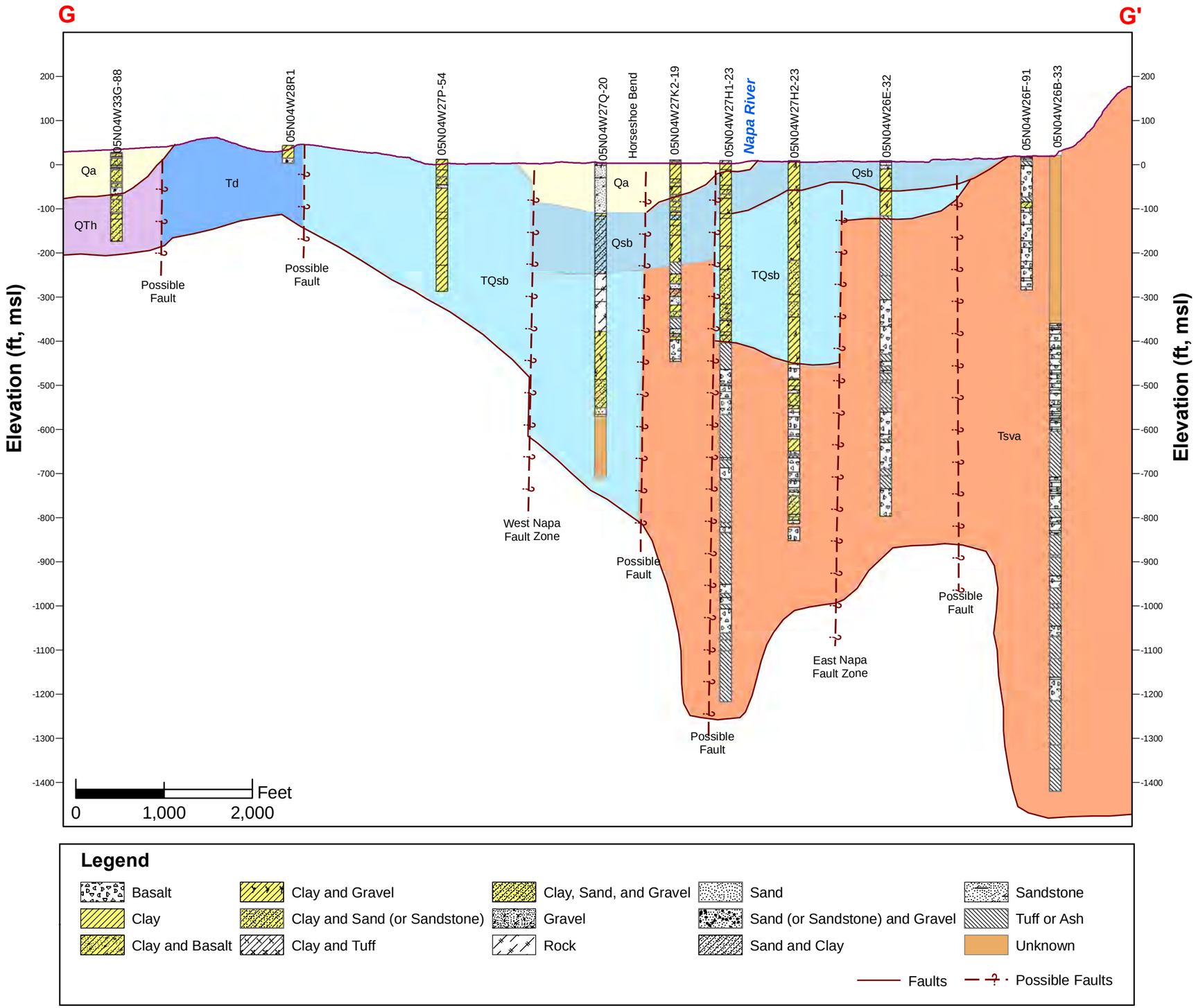
Figure 5-8
Cross Section F – F'
Southern NVF-Napa Subarea, Napa County, CA



Legend

Basalt	Clay and Gravel	Clay, Sand, and Gravel	Sand	Sandstone
Clay	Clay and Sand (or Sandstone)	Gravel	Sand (or Sandstone) and Gravel	Tuff or Ash
Clay and Basalt	Clay and Tuff	Rock	Sand and Clay	Unknown

Faults — Possible Faults

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Figure 5-9
Cross Section G – G'
Carneros/Napa River Marshes/NVF-MST Subareas, Napa County, CA

H

H'

Elevation (ft, msl)

Elevation (ft, msl)

800
700
600
500
400
300
200
100
0
-100
-200
-300
-400
-500

05N04W-29D-'80
05N04W-29C-'99
05N04W-29C-02
05N04W-29F-'85
05N04W-29K-'80
05N04W-29J-'91
05N04W-29K-'04
05N04W-29R-'90
05N04W-29R-'77
05N04W-33D-'05
05N04W-33D-'00a
05N04W-33E-'90
05N04W-33F-'89
05N04W-33M'78b
05N04W33G-88
05N04W-33M-78
05N04W-33M-'01
05N04W-33Q-'77
Napa River
04N04W-4F-'03
04N04W-4C-'83

KJgv

QTh

QTh

Qa?

QTh?

Qsb?

TQsb?

Possible Fault

Feet
0
1,000
2,000

Legend

- Basalt
- Clay
- Clay and Basalt
- Clay and Gravel
- Clay and Sand (or Sandstone)
- Clay and Tuff
- Clay, Sand, and Gravel
- Gravel
- Rock
- Sand
- Sand (or Sandstone) and Gravel
- Sand and Clay
- Sandstone
- Tuff or Ash
- Unknown
- Faults

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Figure 5-10
Cross Section H-H'
Carneros Subarea, Napa County, CA

ST. HELENA

YOUNTVILLE

NAPA

LACK OF DATA

Qaf

Qaa

Qsb

Qsb?

Alluvium Isopach, ft

- isopach
- isopach, align. uncertain
- isopach, depression
- isopach, depression, align. uncertain
- Napa River

Alluvium Facies

- Quaternary Alluvial Fan
- Quaternary Fluvial, High yields
- Quaternary Fluvial, Moderate yields
- Quaternary Sedimentary Basin
- Quaternary Sedimentary Basin, inferred
- Incorporated City or Town
- County Boundary

LSCE_faults

- Concealed
- Uncertain, queried

USGS faults

- Certain
- Approximate
- Approximate, queried
- Concealed
- Concealed, queried
- Uncertain
- Uncertain, queried

0 1 2 Miles

N

Document Path: X:\2011 Job Files\11-090\GIS\SubCrop Geology and Contours\isopach map.mxd

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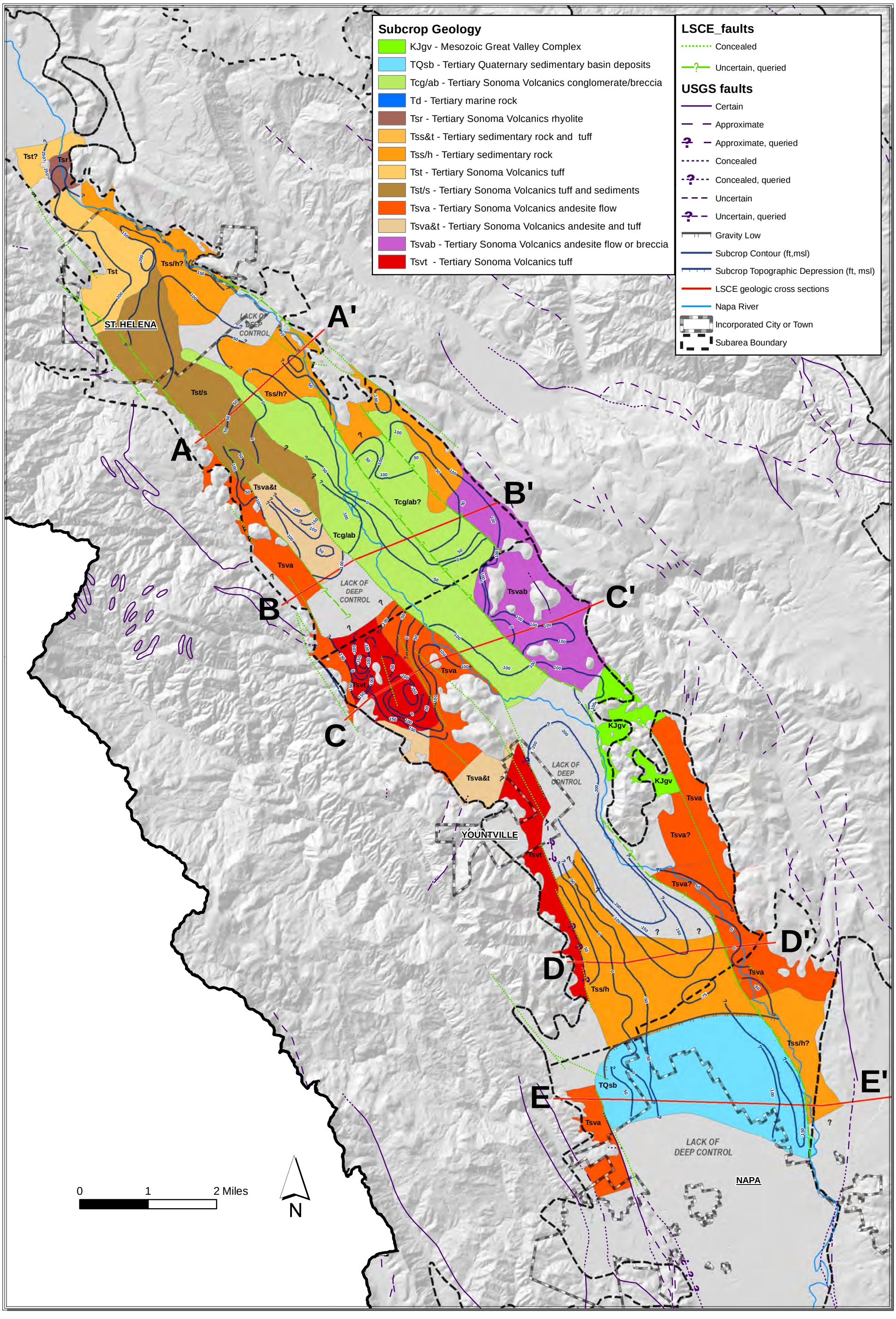
Figure 5-11
Napa Valley Floor Isopach and Facies Map of Alluvium



Document Path: X:\2011 Job Files\11-090\GIS\SubCrop Geology and Contours\structure contour map.mxd

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Figure 5-12
Napa Valley Floor Structure Contours and Pre-Alluvium Subcrop Geology

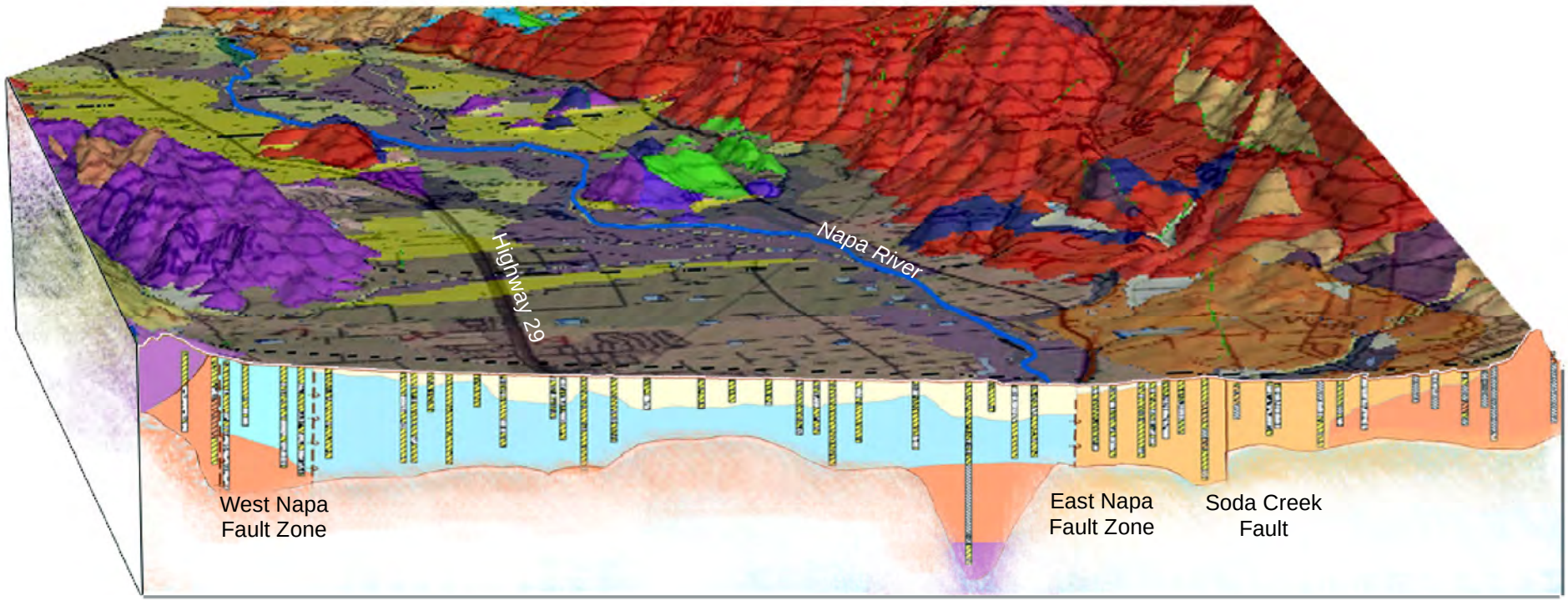

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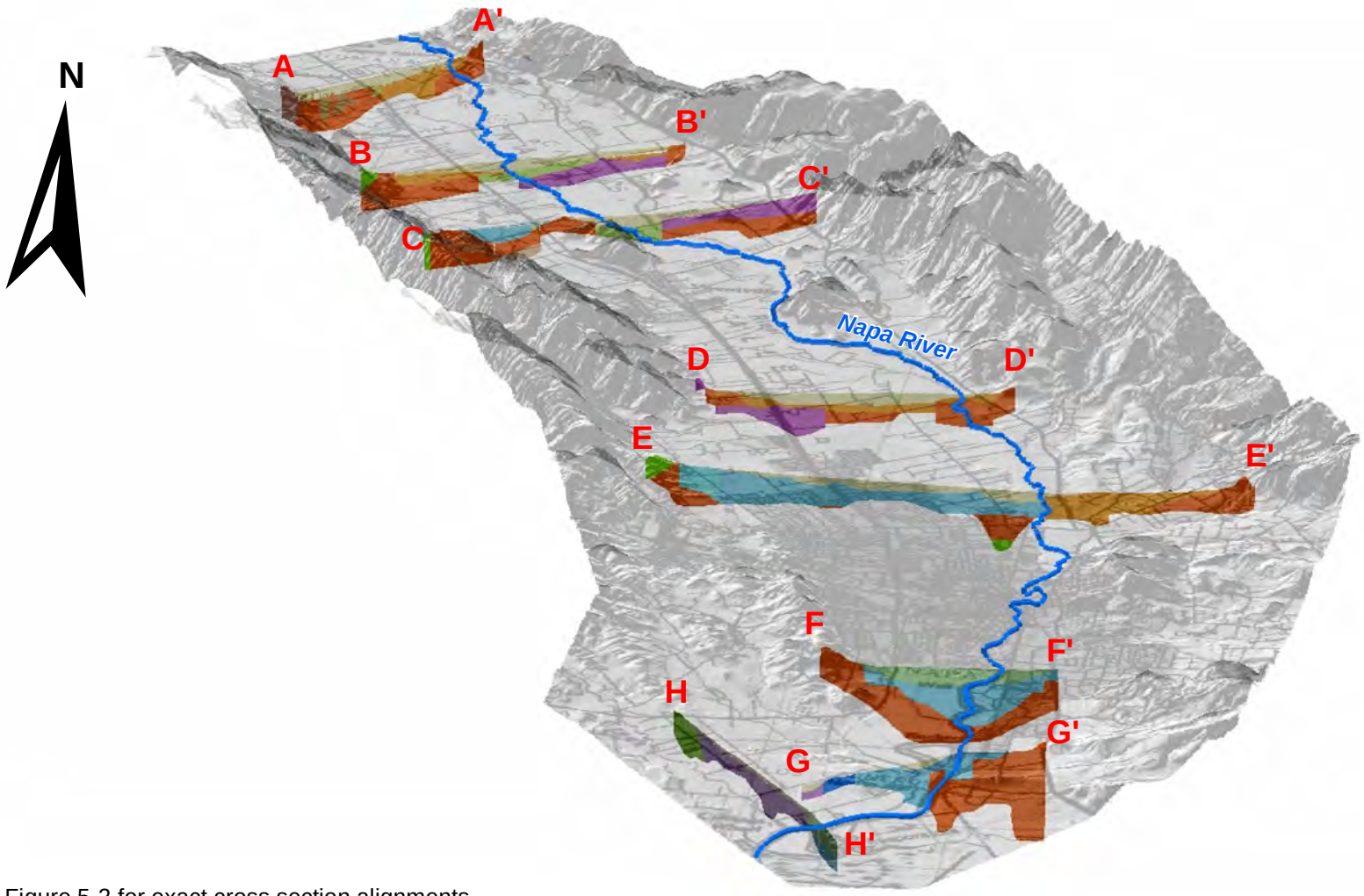
Figure 5-13
Three-Dimensional Visualization of the Geology in the Napa Valley Area



See Figure 5-2 for exact cross section alignments.
See Figures 5-3 through 5-10 for individual cross sections.
Vertical Exaggeration = 3x

C:\Users\tnguyen.LSCEDOMAIN\Desktop\000\Job files\Napa County\gis\map files\2013\02\Napa Cross Section 3D.mxd

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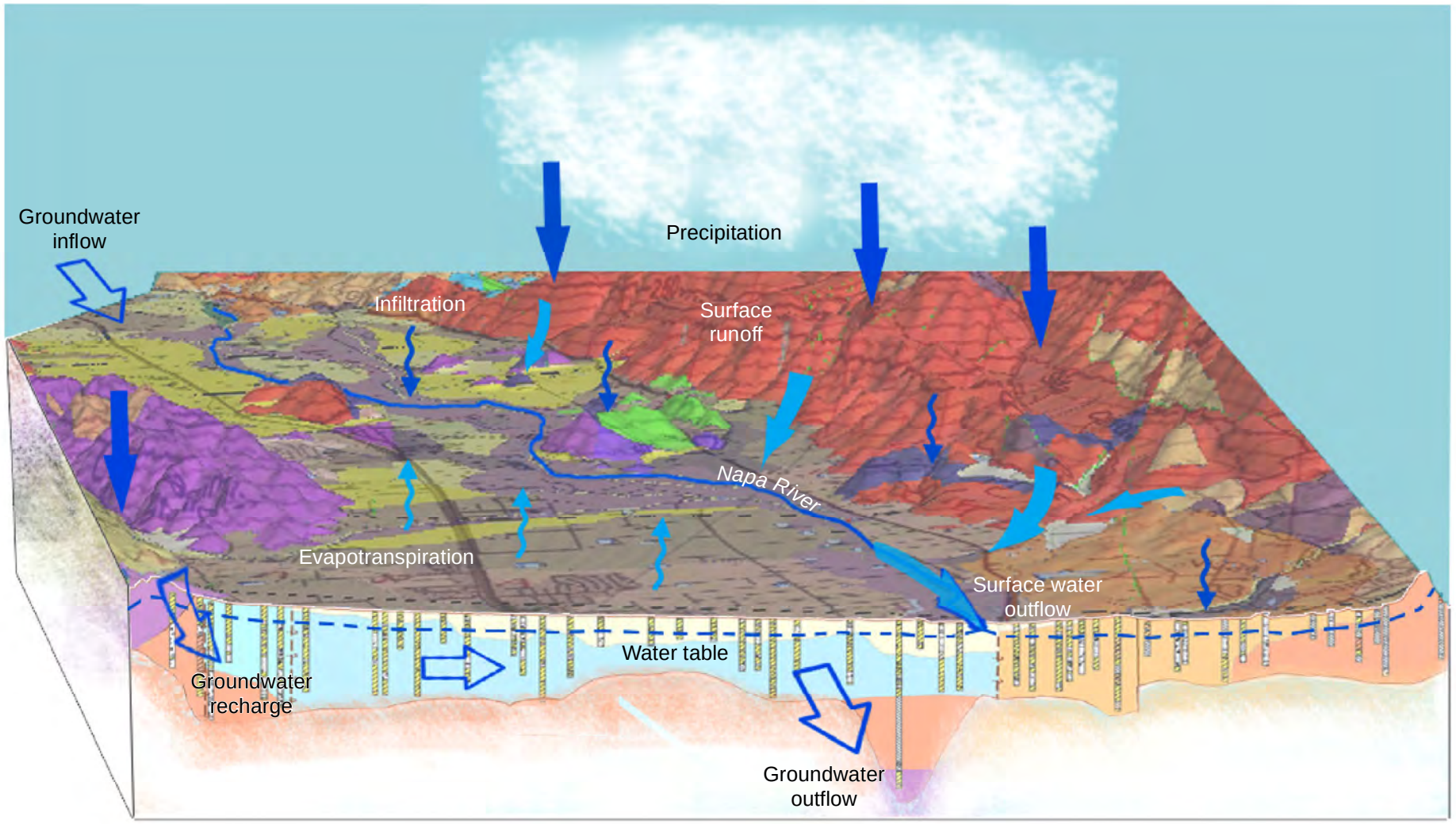
Figure 5-14
Napa Valley Geologic Cross Section Fence Diagram



C:\Users\tnguyen.LSCEDOMAIN\Desktop\000\Job files\Napa County\gis\map files\2012\12\ee_xsection_3d_2.mxd

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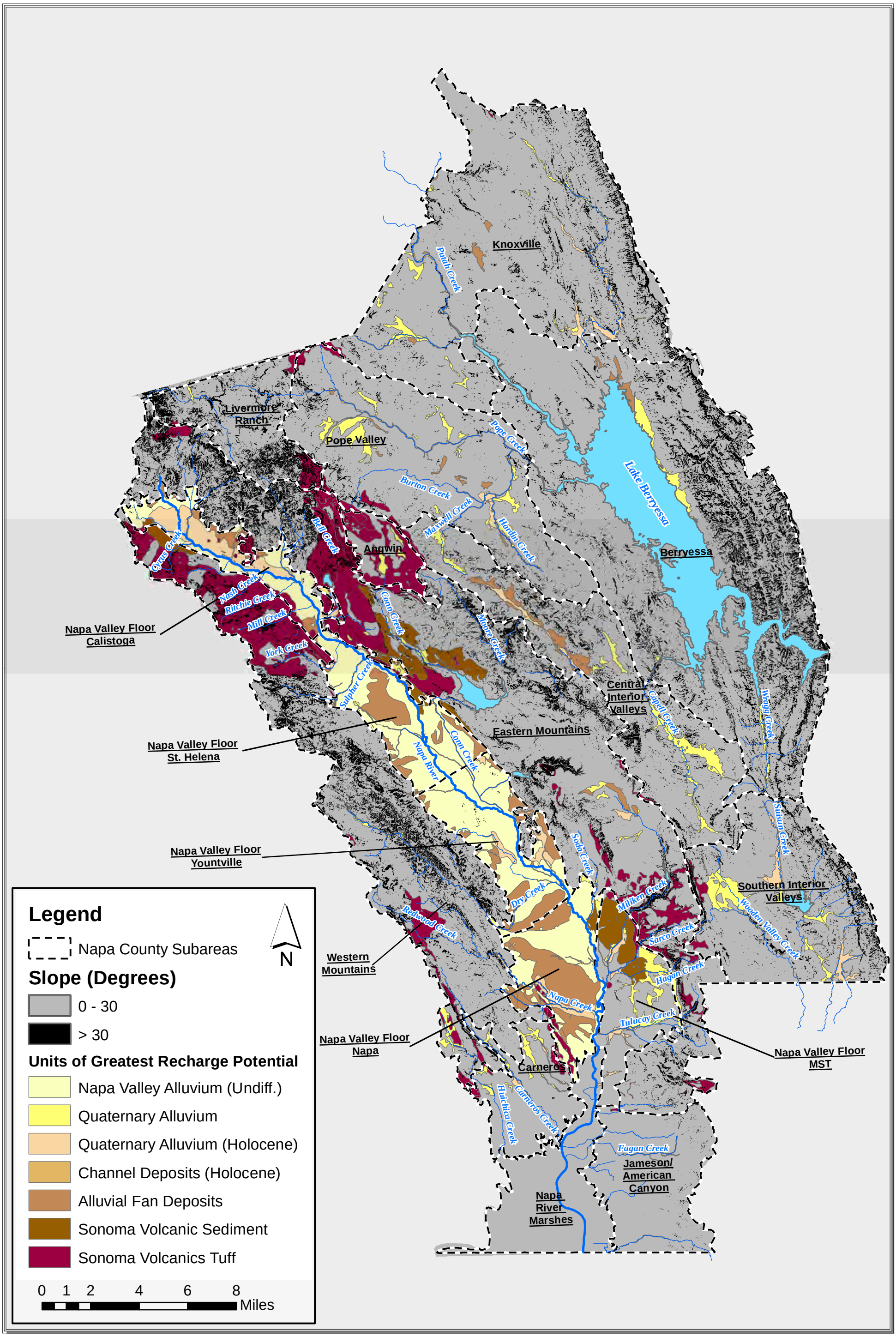
Figure 6-1
Conceptual Illustration of Major Hydrologic Processes in the Napa Valley Area



File: X:\2009 Job Files\09-012\Data\GIS\Recharge\Fig2.6.1-CountyRechargePotential.mxd Date: 1/11/2013

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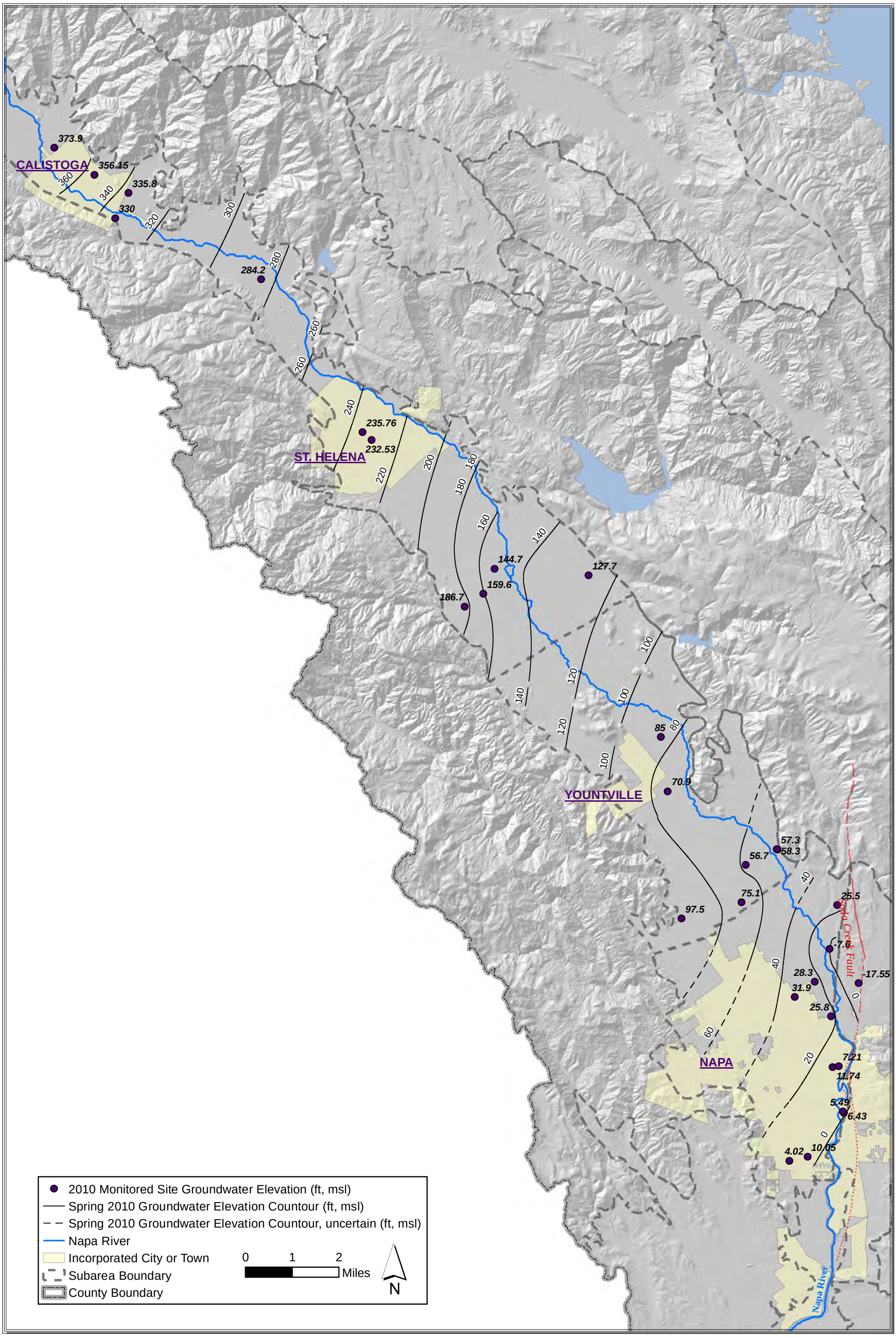
Figure 6-2
Geologic Units of Greatest Recharge Potential
Napa County, CA



Path: X:\2011 Job Files\11-090\GIS\WL contours\2010 NVF_WLcontours.mxd

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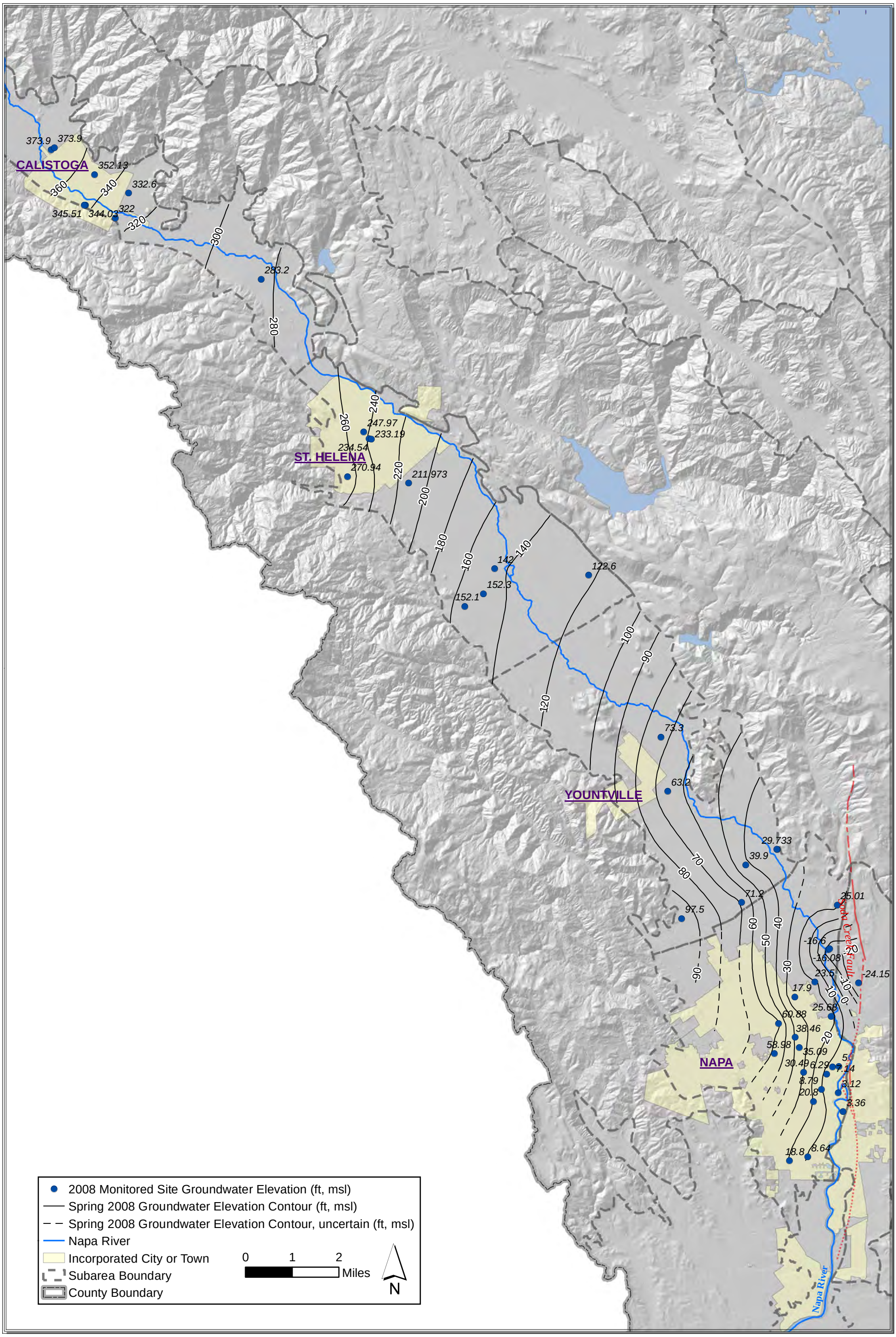
Figure 7-1
Contours of Equal Groundwater Elevation
Napa Valley, Spring 2010



Path: X:\2011 Job Files\11-090\GIS\WL contours\2008 NVF_WLcontours.mxd

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Figure 7-2
Contours of Equal Groundwater Elevation
Napa Valley, Spring 2008

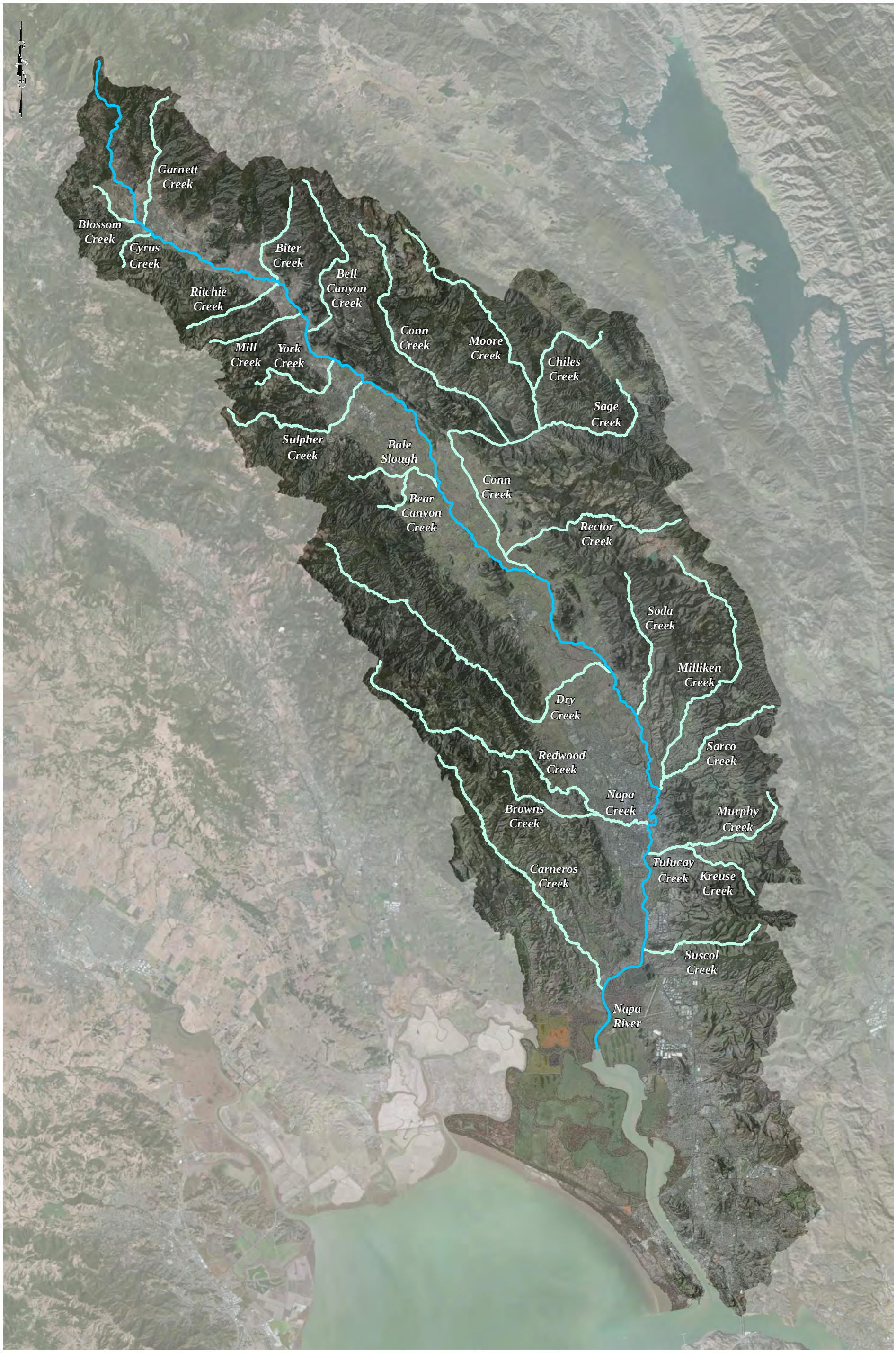

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Figure 7-3: Napa River and Tributaries in Estimated Stream Thalweg Mapping

NAPA RIVER BASIN

SCALE:	1" = 3 miles
JOB NUMBER:	3327
REQUESTED BY:	LB
DRAWN BY:	MB
DATE:	11/26/2012

Bar Length On Original Drawing Equals One Inch. Adjust Scale Accordingly

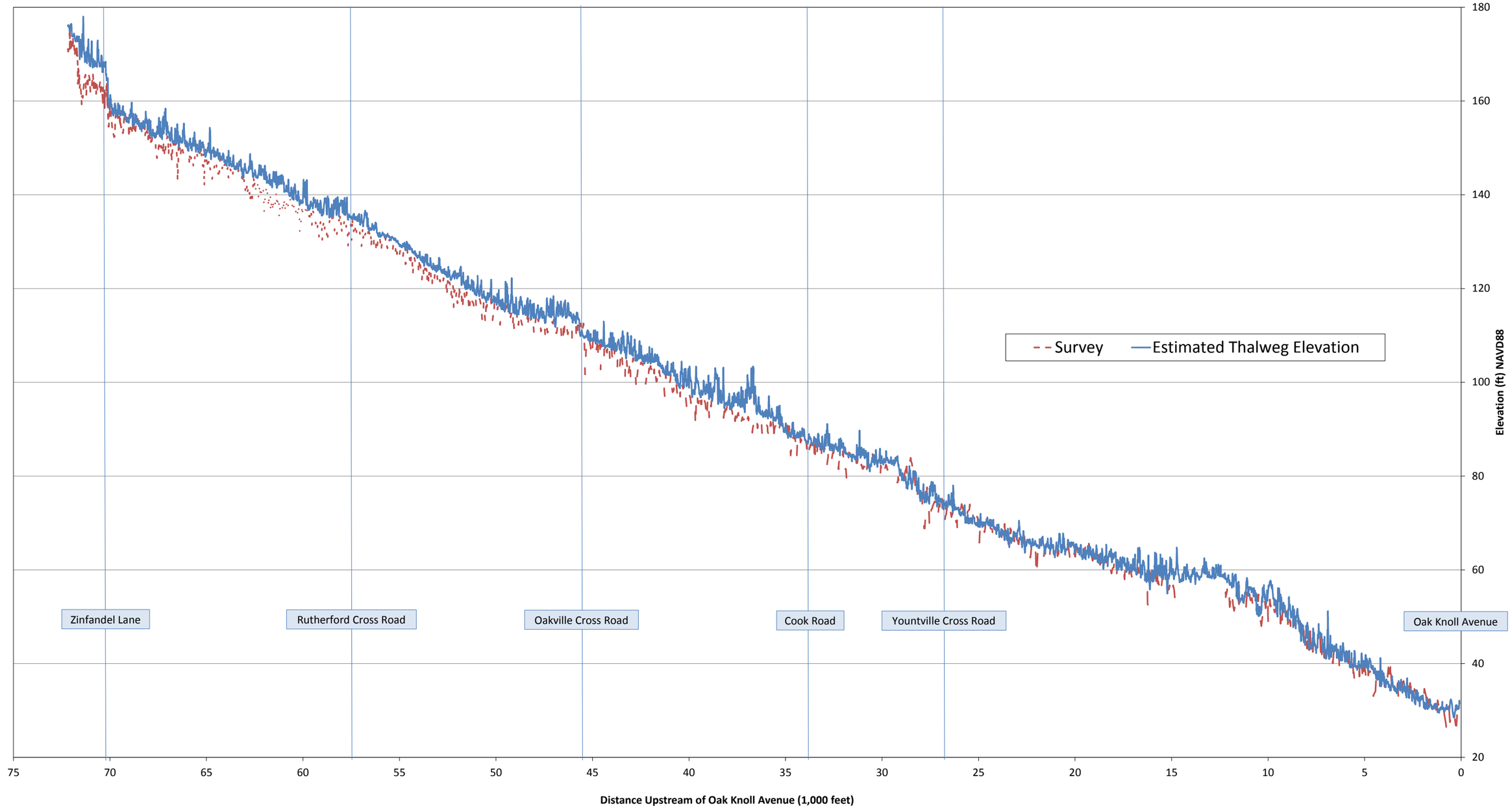
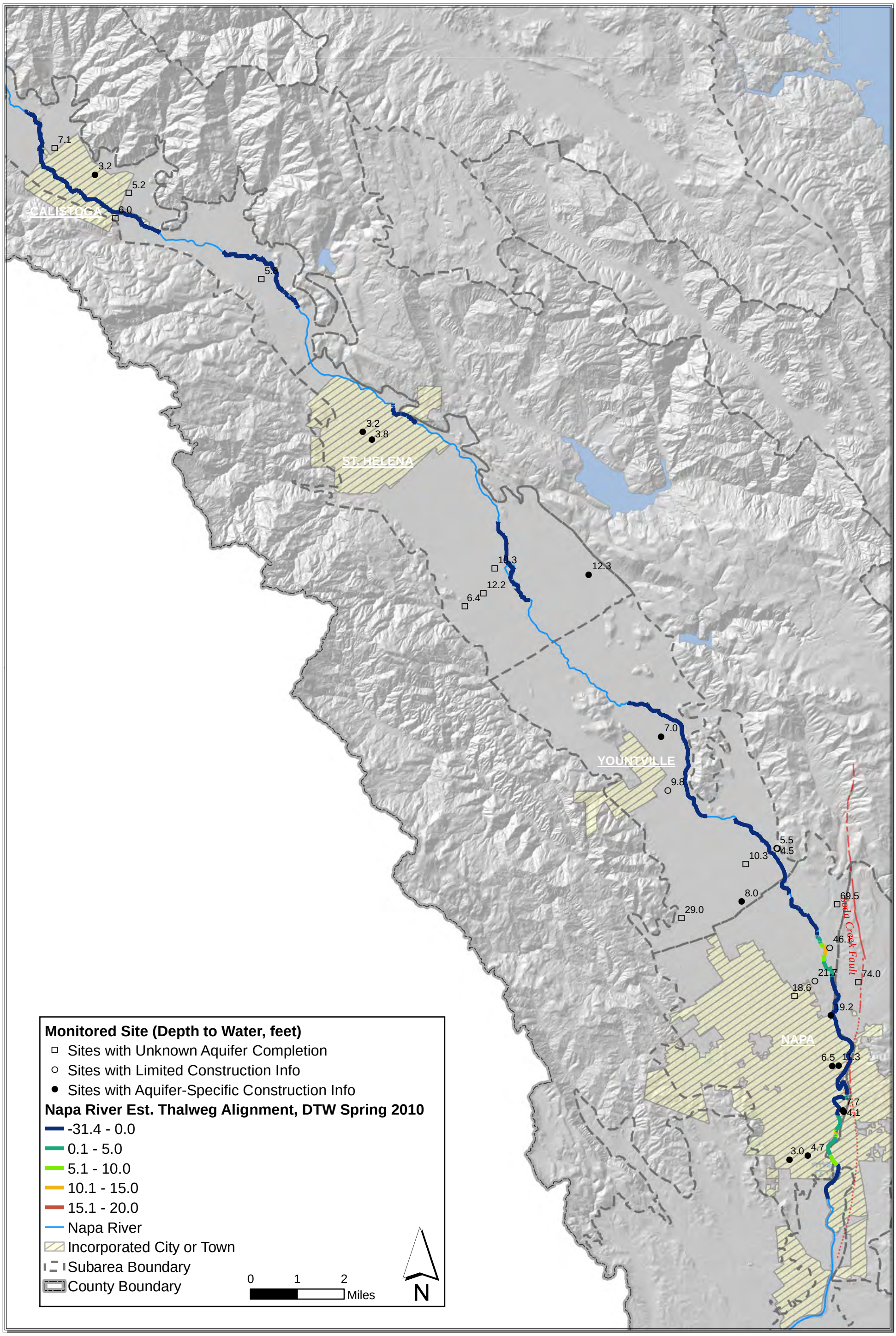


Figure 7-4: Comparison of Estimated Stream Thalweg Elevation with Surveyed Data



Path: X:\2011 Job Files\11-090\GIS\Recharge\ThalwegDTW version 2.mxd

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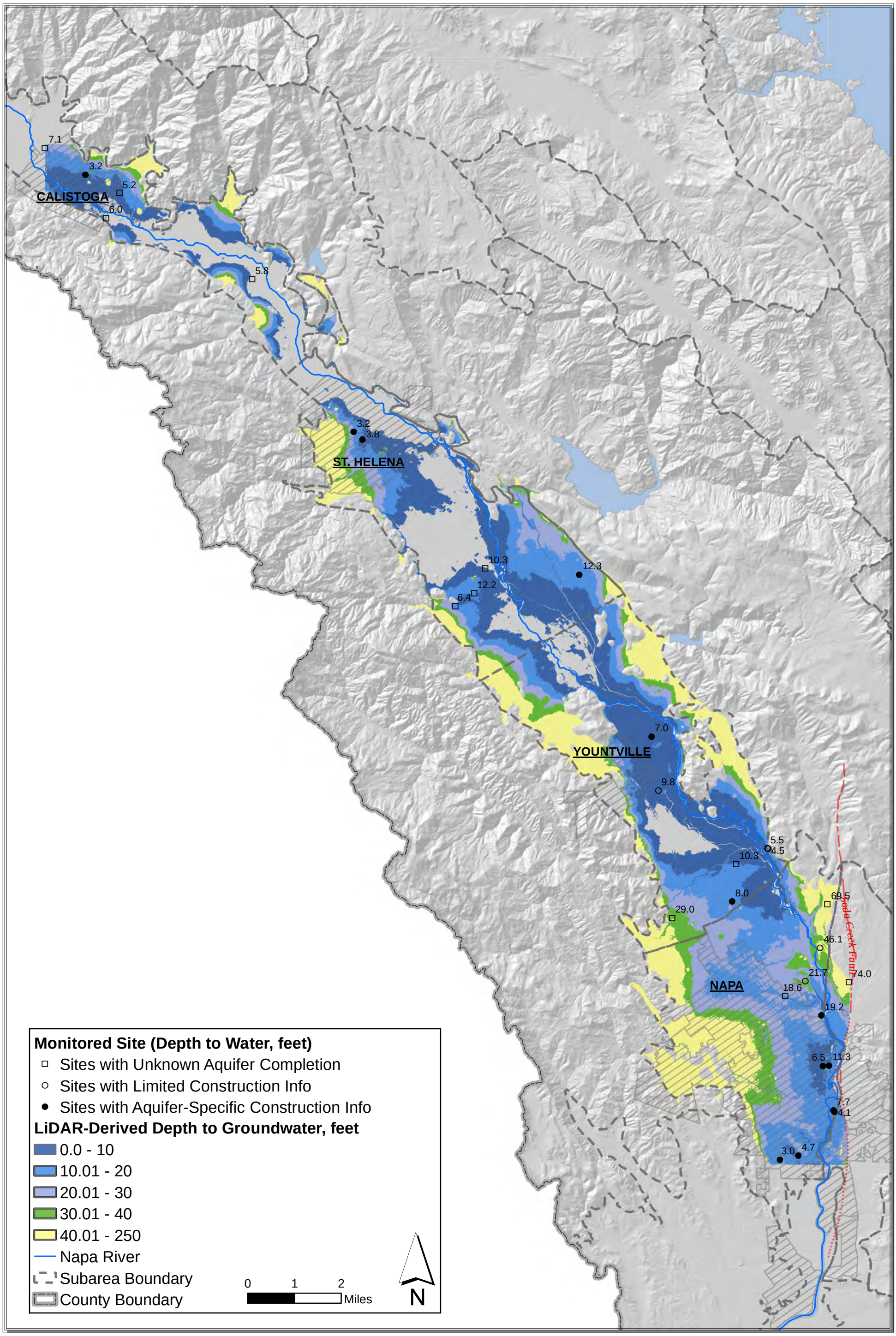
CONSULTING ENGINEERS

Figure 7-8
Calculated Depth to Groundwater at Napa River Thalweg within One Mile of Monitored Wells, Spring 2010



Path: X:\2011 Job Files\11-090\GIS\Recharge\NVF_DTW.mxd

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Figure 7-9
Calculated Depth to Groundwater
Napa Valley Floor, Spring 2010

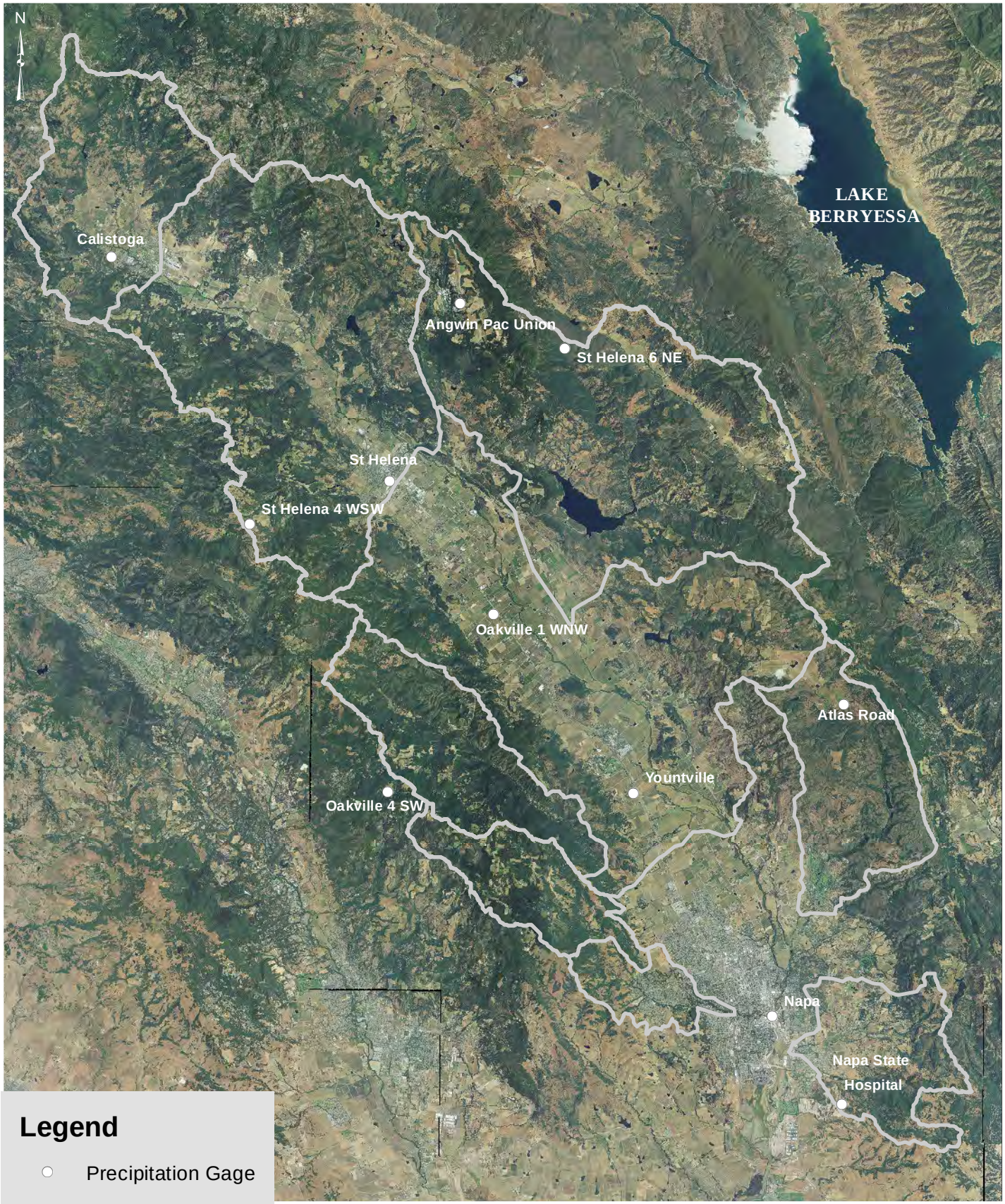

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Figure 8-3: Available NCDC Precipitation Gages in the Model Domain

NAPA RIVER BASIN

SCALE:	1" = 3.5 miles
JOB NUMBER:	3327
DRAWN BY:	P.Ho
DATE:	OCT 2012
	FIGURE 8-1

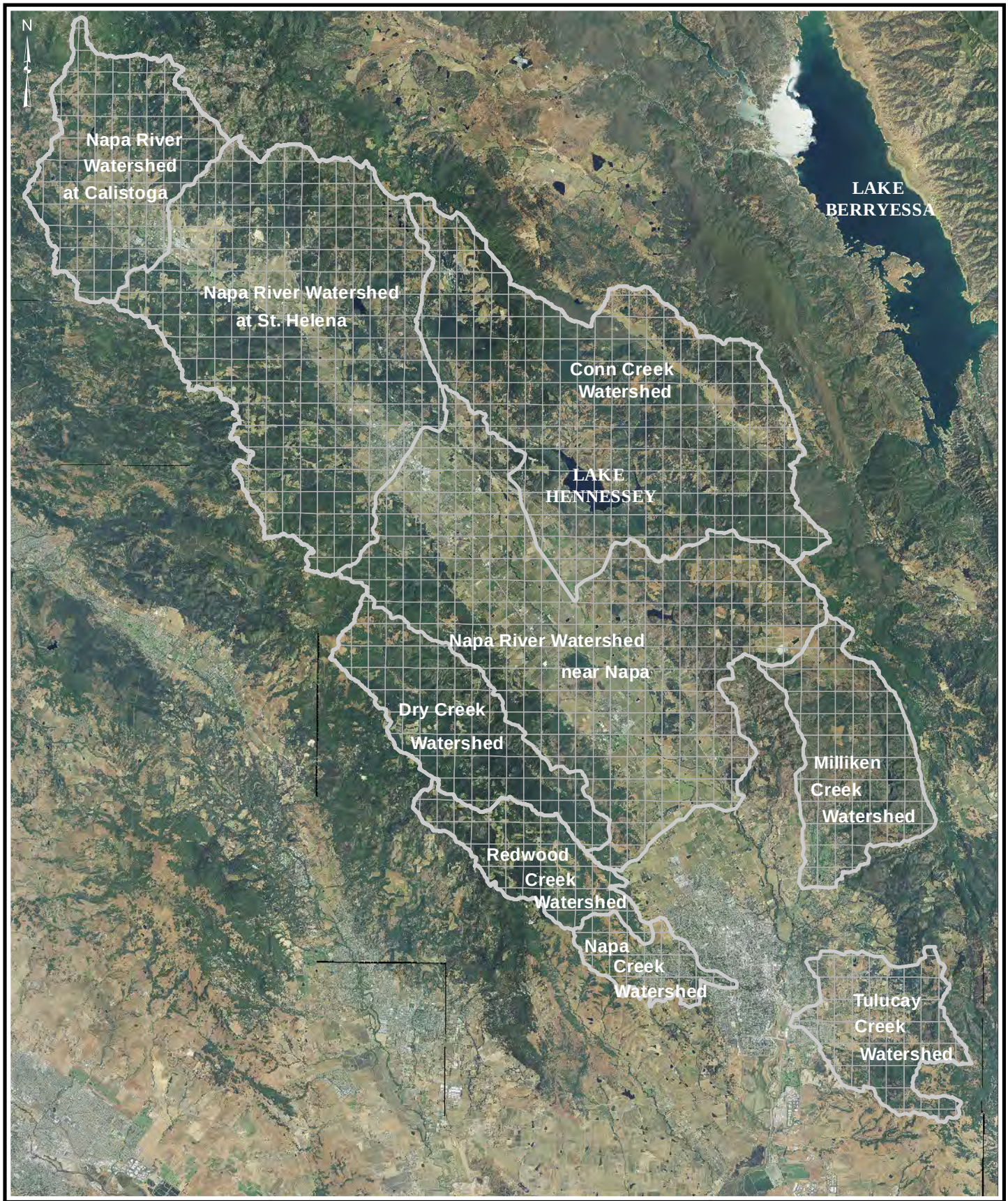

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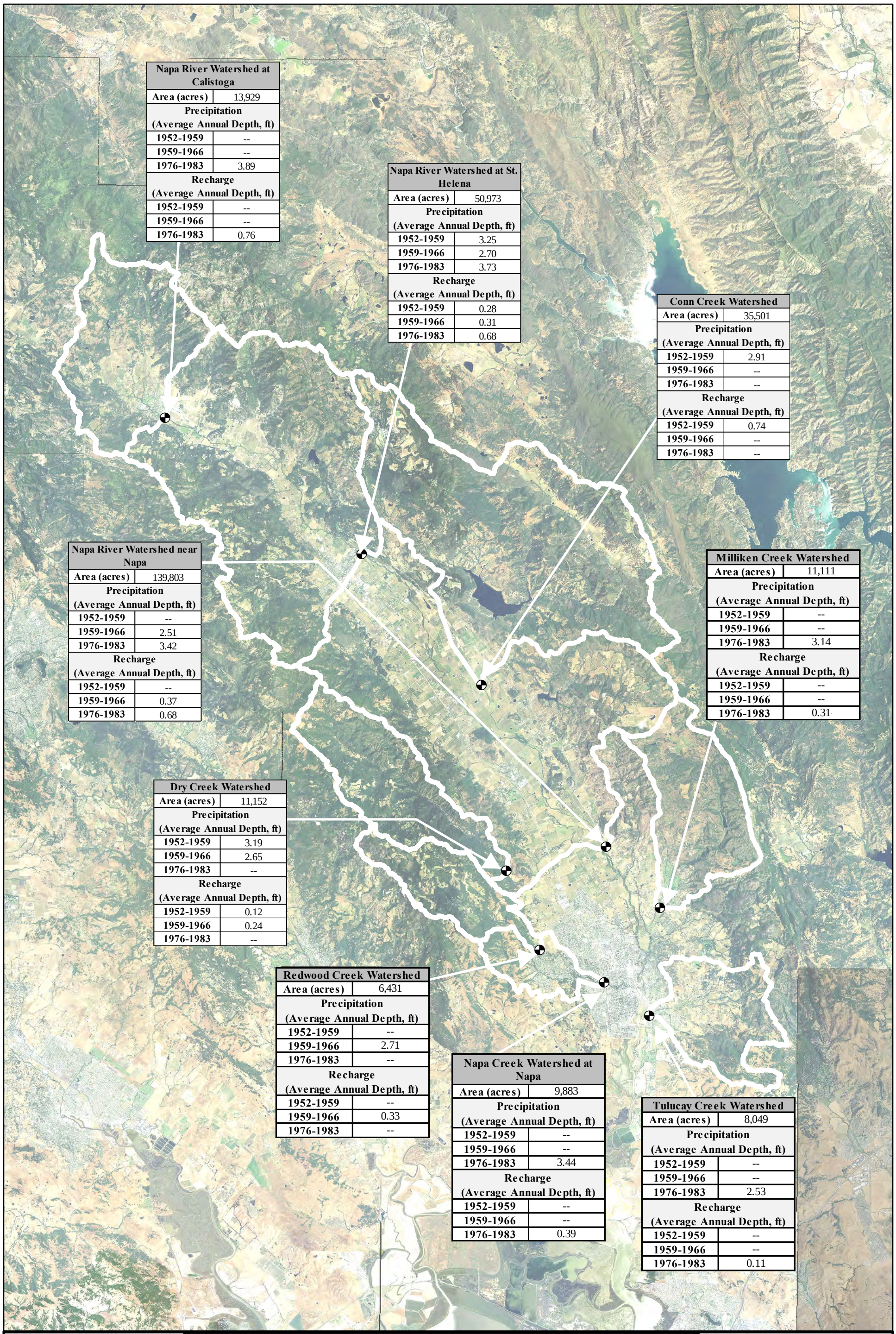
Figure 8-4: PRISM 800 Meter Precipitation Grid and Watersheds in the Model Domain

NAPA RIVER BASIN

SCALE:	1" = 3.5 miles
JOB NUMBER:	3327
DRAWN BY:	P.Ho
DATE:	OCT 2012
	FIGURE 8-2



Napa River Watershed at Calistoga	
Area (acres)	13,929
Precipitation (Average Annual Depth, ft)	
1952-1959	--
1959-1966	--
1976-1983	3.89
Recharge (Average Annual Depth, ft)	
1952-1959	--
1959-1966	--
1976-1983	0.76

Napa River Watershed at St. Helena	
Area (acres)	50,973
Precipitation (Average Annual Depth, ft)	
1952-1959	3.25
1959-1966	2.70
1976-1983	3.73
Recharge (Average Annual Depth, ft)	
1952-1959	0.28
1959-1966	0.31
1976-1983	0.68

Conn Creek Watershed	
Area (acres)	35,501
Precipitation (Average Annual Depth, ft)	
1952-1959	2.91
1959-1966	--
1976-1983	--
Recharge (Average Annual Depth, ft)	
1952-1959	0.74
1959-1966	--
1976-1983	--

Napa River Watershed near Napa	
Area (acres)	139,803
Precipitation (Average Annual Depth, ft)	
1952-1959	--
1959-1966	2.51
1976-1983	3.42
Recharge (Average Annual Depth, ft)	
1952-1959	--
1959-1966	0.37
1976-1983	0.68

Milliken Creek Watershed	
Area (acres)	11,111
Precipitation (Average Annual Depth, ft)	
1952-1959	--
1959-1966	--
1976-1983	3.14
Recharge (Average Annual Depth, ft)	
1952-1959	--
1959-1966	--
1976-1983	0.31

Dry Creek Watershed	
Area (acres)	11,152
Precipitation (Average Annual Depth, ft)	
1952-1959	3.19
1959-1966	2.65
1976-1983	--
Recharge (Average Annual Depth, ft)	
1952-1959	0.12
1959-1966	0.24
1976-1983	--

Redwood Creek Watershed	
Area (acres)	6,431
Precipitation (Average Annual Depth, ft)	
1952-1959	--
1959-1966	2.71
1976-1983	--
Recharge (Average Annual Depth, ft)	
1952-1959	--
1959-1966	0.33
1976-1983	--

Napa Creek Watershed at Napa	
Area (acres)	9,883
Precipitation (Average Annual Depth, ft)	
1952-1959	--
1959-1966	--
1976-1983	3.44
Recharge (Average Annual Depth, ft)	
1952-1959	--
1959-1966	--
1976-1983	0.39

Tulucay Creek Watershed	
Area (acres)	8,049
Precipitation (Average Annual Depth, ft)	
1952-1959	--
1959-1966	--
1976-1983	2.53
Recharge (Average Annual Depth, ft)	
1952-1959	--
1959-1966	--
1976-1983	0.11

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Figure 8-13: Napa Valley Area Recharge by Hydrologic Period

SCALE:	1" = 3.0 miles
JOB NUMBER:	3327
DRAWN BY:	P.Ho
DATE:	11-26-2012

Wells without Aquifer Specific Construction Information

- Napa County network
- DWR network
- GeoTracker network
- City of Napa network

Wells with Aquifer Specific Construction Information

- Napa County network
- DWR network
- GeoTracker network
- Town of Yountville
- Proposed GW Monitoring Sites
- Proposed GW/SW Monitoring Sites
- Napa River
- Municipal boundaries
- Subarea Boundary

Knoxville
Livermore Ranch
Pope Valley
Calistoga
Angwin
Berryessa
Central Interior Valleys
Napa Valley Floor Calistoga
St. Helena
Eastern Mountains
Napa Valley Floor St. Helena
Western Mountains
Yountville
Napa River
Soda Creek Fault
Southern Interior Valleys
Napa Valley Floor Yountville
Napa
Napa Valley Floor Napa
Napa Valley Floor MST
Carneros
Jameson/ American Canyon
Napa River Marshes
American Canyon

DWR Bulletin 118 Groundwater Basins

- BERRYESSA VALLEY
- NAPA-SONOMA VALLEY
- POPE VALLEY
- SUISUN-FAIRFIELD VALLEY

0 1 2 Miles

N

Path: X:\2011 Job Files\11-090\GIS\MW inventory\MW_inventory_and proposed_WL_sites.mxd

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Figure 9-1
Current and Proposed Groundwater Level Monitoring Sites in Napa County

Proposed GW Monitoring Sites
Proposed GW/SW Monitoring Sites

Napa River Est. Thalweg DTW Spring 2010 (ft)

-31.4 - 0.0
0.1 - 5.0
5.1 - 10.0
10.1 - 15.0
15.1 - 20.0
Napa River
Subarea Boundary

Knoxville
Livermore Ranch
Pope Valley
Angwin
Berryessa
Central Interior Valleys
Napa Valley Floor Calistoga
Napa Valley Floor St. Helena
Eastern Mountains
Western Mountains
Napa Valley Floor Yountville
Napa Valley Floor Napa
Napa Valley Floor MST
Carneros
Jameson/ American Canyon
Napa River Marshes
Southern Interior Valleys
Soda Creek Fault

CALISTOGA
ST. HELENA
YOUNTVILLE
NAPA

17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1
F E D C B A

DWR Bulletin 118 Groundwater Basins

BERRYESSA VALLEY
NAPA-SONOMA VALLEY
POPE VALLEY
SUISUN-FAIRFIELD VALLEY

0 1 2
Miles

N

Path: X:\2011 Job Files\11-090\GIS\MW inventory\Wells with WL data_LiDAR DTW.mxd

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Figure 9-2
Proposed Groundwater Level Monitoring Sites Related to Depth to Water at Napa River Thalweg

Appendix A

Cross Section Stratigraphy, Pre-Alluvium Subcrop Geology, and Well Lithology Legends

Appendix A - Cross-Section Stratigraphy, Pre-Alluvium Subcrop Geology, and Well Lithology Legends

Stratigraphy

- QTh: Quaternary Tertiary Huichica formation
- Qsb: Quaternary sedimentary basin deposits
- Tst/s: Tertiary Sonoma Volcanic tuff and sediments
- TQsu: Tertiary Quaternary sedimentary deposits, undifferentiated
- KJgv: Mesozoic Great Valley Complex
- Qa: Quaternary alluvium
- Qa/sb: Quaternary alluvium/sedimentary basin deposits
- TQsb: Tertiary Quaternary sedimentary basin deposits
- Tcg/ab: Tertiary Sonoma Volcanic conglomerate/breccia
- Tcg/ab?: Tertiary Sonoma Volcanic conglomerate/breccia
- Td: Tertiary marine rock
- Tsr: Tertiary Sonoma Volcanic rhyolite
- Tss/h: Tertiary sedimentary rock
- Tss/h?: Tertiary sedimentary rock
- Tst: Tertiary Sonoma Volcanic tuff
- Tsva: Tertiary Sonoma Volcanic andesite flow
- Tsvat: Tertiary Sonoma Volcanic andesite and tuff
- Tsva?: Tertiary Sonoma Volcanic andesite flow
- Tsvab: Tertiary Sonoma Volcanic andesite flow or breccia
- Tsvt: Tertiary Sonoma Volcanic tuff
- Tsvt?: Tertiary Sonoma Volcanic tuff
- Tst?: Tertiary Sonoma Volcanic tuff

Well Lithology

- Basalt
- Clay
- Clay and Basalt
- Clay and Gravel
- Clay and Sand (or Sandstone)
- Clay and Tuff
- Clay, Sand, and Gravel
- Gravel
- Rock
- Sand
- Sand (or Sandstone) and Gravel
- Sand and Clay
- Faults
- Sandstone
- Tuff or Ash
- Unknown
- Possible Faults