Sierra Valley Aquifer Delineation and Ground Water Flow

Prepared for
Randy Wilson, Director
Plumas County Planning Department
520 Main Street, Quincy, CA 95971
530-283-7011

and

Sierra Valley Groundwater Management District
Loyalton, CA

By
Burkhard Bohm
Hydrogeologist
CHG lic. #337
Plumas Geo-Hydrology
PO Box 1922, Portola, CA 96122
530-836-2208

Final Report

December 27, 2016

Table of Contents

1. Introduction

Previous work conducted in SV

Groundwater data have been collected in Sierra Valley since the early 1950's. The first systematic study of groundwater conditions in Sierra Valley (SV) was conducted by the Department of Water Resources (DWR), the results of which were reported on in the DWR Bulletin 98 "Northeastern Counties Ground Water Investigation" in 1963. The groundwater conditions presented in the DWR (1963) study is deemed the closest to pre-development conditions. The study comprised a comprehensive classification of aquifer materials and identification of the most important aquifer zones. The report also includes a description of the basin geology, based on geologic mapping and a valley-wide gravity survey (we are still trying to track down a copy of that survey's report) and a conceptual description of the structural geology.

Although since 1963 significant amounts of hydrogeologic data have been collected in the Sierra Valley Basin (SVB), no comprehensive analysis of basin-wide hydrology has been conducted so far. At least 5 major hydrogeologic reports have been prepared by Kenneth D. Schmidt Associates, addressing mostly the central basin hydrology (KDS, 1994; 1999; 2003; 2005; 2011). Furthermore at least 10 small hydrogeologic studies have been completed to characterize ground water conditions at real estate subdivision proposals, mostly in the basin's peripheral areas.

The "Bulletin 98" study was followed by a memorandum report in 1983, reporting on ground water recharge areas, the results of well testing, and a very general overview of hydrologic conditions, including certain aspects of groundwater quality.

DWR reported on the annual results of ground level water monitoring in a series of short reports until 1991. These reports were followed by updates reported in the abovementioned reports by KDS. KDS (2003; 2005) also reported on construction and monitoring of 5 monitoring wells installed to accommodate nested piezometer to allow monitoring three ground water zones (shallow, deep and intermediate).

Since the 1963 Bulletin 98 study little has been done in terms of further conceptualizing the basin structural geology and its role in basin hydrology. In their 2003 and 2005 "groundwater updates" KDS developed four subsurface geologic cross-sections using available drilling records. In their study of geothermal resources in SV, GeothermEx developed a conceptual model of the structural geology controlling the migration of geothermal water in the west central region of SV.

In a consulting report prepared for Plumas County Oberdorfer and Hamilton (1999) evaluated the risk of groundwater contamination from poisoning Lake Davis to control invasive fish species, by conducting an analysis of groundwater flow in fractured bedrock aquifers in the canyon of Grizzly Creek.

In summary, while a significant amount of information has been collected in the last 50 years, no comprehensive analysis of the SVB ground water hydrology has been conducted so far, including ground water recharge areas and their connection to the basin aquifers, subsurface bedrock structure and topography, stream-to-groundwater interaction and groundwater quality distribution. In other words a lot of effort was invested in time-series data collection, without refining the conceptual hydrogeologic model. For the purpose of long-term effective ground water resource management, both time-series data collection and conceptual model development are essential.

Scope of the current study

At this stage, the SVB is generally seen as a fault bounded intermontane trough that has been filled with lacustrine sediments. Current thinking is that the shallow unconfined basin aquifers are recharged by streams infiltrating the peripheral alluvial fans, and the deep confined aquifers are recharged from the adjacent and underlying volcanic and granitic rock aquifers, which are recharged in the surrounding uplands.

This current study is based on recently collected isotope and water chemistry data, well driller's reports, technical reports, and geologic maps to conduct a delineation of the SVB aquifer configurations and their connections to the upland ground water recharge areas.

A companion report to this report titled "Inventory of Sierra Valley Wells and Groundwater Quality Conditions" (Bohm, December, 2016) complements this assessment of SVB groundwater hydrology and should be considered in tandem with this report in developing further studies and future management scenarios.

Based on new information, and a better understanding of the implications of existing information gaps additional data will be needed to augment the Sierra Valley Basin aquifer delineation presented here. Aspects of a 3-dimensional model of the SVB are presented in this report. A 3-dimensional geologic model of the SVB aquifer should include a characterization of important hydraulic connections to upland recharge areas, pumping volume data, and a better understanding of groundwater quality trends and ground water quality dispersion dynamics based on a comprehensive groundwater monitoring program.

These additional data and analysis needs are identified throughout the report as recommendations for further analysis of existing data, and if necessary additional data collection, as future steps towards expanding the findings and conclusions included in this report to a 3-dimensional aquifer model of the SVB

2. Groundwater Recharge Areas in Sierra Valley

Groundwater recharge area defined

The geologic formations constituting the landscape of the Sierra Nevada typically contain sufficient porosity to store vast amounts of groundwater. This groundwater migrates in response to groundwater flow gradients, which are the result of differences in amount of recharge in the topographically high areas which receive the most moisture (snow and rain). The groundwater table elevation differences are the reason for groundwater flow, provided there is a continuing source of recharge and adequate permeability.

In the forested areas groundwater recharge is the amount of precipitation after evaporation from the forest canopy (CI), evaporation from the forest floor, transpiration from the vegetation and streamflow (interflow I):

$$\text{groundwater} = P - CI - ET - I$$

Groundwater recharge depends on topography (elevation), climate, and vegetation and to some extent on geology.

Aerial contributions of groundwater recharge

A review of well-log data and a preliminary review of available Sierra Valley Basin (SVB) groundwater chemistry data indicate a more complex hydrogeology. **The assumption that the surrounding uplands bedrock aquifers have homogeneous and isotropic permeabilities is not supported by the data.** It appears that some parts of the SVB aquifers may be connected to upland recharge areas via bedrock fault zones with 1enhanced permeability, zones that may provide significant recharge into limited portions of the SVB aquifer.

The relative magnitude of a recharge area's contribution to the total inflow into the valley depends not only on the soil properties and the underlying bedrock formation geology but also on the average annual precipitation (climate) and vegetation type and density at each area. Depth of precipitation is determined not only by elevation, but also by regional climatic factors, like distance from the ocean and direction of prevailing winds. According to the isohyetal map by S.E. Rantz (which is probably outdated) the Dixie Mountain areas probably receive less than 50% of the precipitation in the southwest and the south (Yuba Pass area and Cold Stream watershed), and the mountains in the eastern Basin periphery probably receive no more than 25% of the same.

Recommendation: New weather station data should be used to update the Rantz isohyetal map as it becomes available.

Ground water recharge centers

Groundwater recharge areas are typically tied to high elevation areas provided the underlying soils and geologic formations contain sufficient hydraulic conductivity, and the combination of climate and vegetation is right. The largest amount of groundwater recharge per unit area centers on the most prominent high elevation areas. For the purpose of this study these areas are called 'recharge centers'. Each recharge center functions as an area where a combination of elevation and soil and moisture conditions are suitable to transmit sufficient snowmelt and rain into the underlying soils and fractured bedrock.

Infiltration eventually takes on a more horizontal path, while being continuously further replenished by infiltration at lower elevations on its way to the low elevation aquifers of the Sierra Valley proper. The portion of this groundwater mound that flows toward the Sierra Valley Basin is herein understood to be a recharge area, an area contributing groundwater recharge to the Sierra Valley aquifers. Topographically this constitutes an area bounded by two converging ridges the highest elevations of which meet at the recharge center. In other words a groundwater recharge area is a quasi-triangular geographic area with significant topographic relief; with its highest elevation point 'anchored' in the high elevation groundwater recharge center, and the opposite low-elevation side facing Sierra Valley.

Recommendation: This "working definition" can be refined through a literature search.

High elevation groundwater recharge may end up following one of two path ways:

1. When the underlying bedrock is well fractured (jointing and/or faulting) water may penetrate to great depth and migrate for long horizontal distances.
2. If the bedrock is poorly fractured then groundwater recharge may tend to follow a horizontal pathway through the soil and regolith that blankets the underlying bedrock until it either flows into a permeable bedrock structure to become part of the larger groundwater flow system, or it discharges into a stream.
3. Groundwater may migrate largely through bedrock joints until the combination of bulk transmissivity and hydraulic head conditions cause it to discharge into soil/regolith and into a streambed.

In lava rock (volcanics) joints (including columnar joints) and cooling surfaces between lava flows usually provide good permeability. On the other hand, pyroclastic rocks, due to their high content of fine-grained volcanic ash, usually do not retain fractures well, and are notorious for low bulk transmissivities. Granite holds open fractures well, but is typically of limited transmissivity, unless affected by faulting, which can enhance permeability significantly.

As is typical in many areas of the NE Sierra Nevada, volcanics at some depth are usually underlain by granite, either by depositional contact or by contact metamorphism.

One can envision a host of hydrologic settings in the SVB created by various combinations of the above. Increased permeability zones due to active faulting make the situation more complex. Based on available information, it appears that faulting appears to significantly affect groundwater flow in several areas of the Sierra Valley Basin, largely by creating NE and NW trending groundwater migration zones.

To summarize, current thinking is that groundwater recharge enters the aquifers of Sierra Valley by:

- Stream infiltration in the alluvial fans at the periphery of the valley (MFR).
- Flow from the fractured bedrock in contact with shallow and deep aquifers (MBR).

Defining groundwater recharge centers in the Sierra Valley watershed

With the preceding observations and hypotheticals in mind, the SVB groundwater recharge centers are identified. The estimated elevation ranges are based on what is indicated as forested areas on the topographical maps:

A. Dixie Mountain recharge center, elevation 8300 ft down to about 6300 ft. This is the entire area underlain by volcanic rocks, between Dixie Mountain peak and Frenchman Lake.
    1. Most groundwater discharge is to the north into Ramelli Creek and to the east into Little Last Chance Creek (now Frenchman Lake). ***(This is well supported by isotope data).***
    2. Discharge through the deeper bedrock flowing south into the lacustrine valley aquifers. ***(This is supported by the isotope data).***
    3. This is probably the second largest sub-basin in the Sierra Valley Basin, draining S and SW via Little Last Chance Creek (Adams Neck) into Sierra Valley.

B. Crocker Mountain, elevations 7500 down to 4900 ft.
    1. Grizzly Valley (now filled by Lake Davis), underlain by fractured granite and volcanics. This area has little bearing on the Sierra Valley Basin hydrologic budget since Grizzly Creek flows out into the MFFR. ***(This is supported by isotope data).***

C. Beckworth Peak, elevations 7200 ft down to 5000, underlain by volcanics.
    1. Ross Meadows area on the N slope has no bearing on the Sierra Valley Basin hydrologic budget since it drains into the MFFR at the outflow from Sierra Valley. ***(No isotope data available).***

    2. Carman Valley on the southern flank of Beckworth Peak, with significant discharge areas draining south and east at low elevations (Knudson Meadows). Granite in the south. ***(So far this is not supported by***

isotope data, since access to Knudson Meadow has not been obtained).

D. Yuba Pass area, elevations 7400 ft down to 5000 ft.
    1. Watersheds drained by Fletcher, Turner, and Berry Creeks, draining E and SE, underlain mostly by granite.
    2. In tandem with the Cold Stream watershed this may be one of the major water sources of the Sierra Valley Basin, however, given the limited fracture permeability of the underlying granitic formations most of this may enter the Sierra Valley as groundwater. ***(This is supported by isotope data).***
E. Truckee Summit area (HWY 89), elevations 8200 ft to 5400 ft.
    1. Cold Stream watershed, including Bonta and Cottonwood Creek watersheds, draining north into Sierra Valley near Sierraville.
    2. The area is underlain by volcanics, which is largely covered by colluvium and moraine deposits. These unconsolidated Quaternary formations are deemed unconfined upland aquifers which slowly release water to streams and underlying volcanics in the dry season.
    3. This is probably the largest sub-watershed in the Sierra Valley Basin, and given the high amount of precipitation here, may turn out to be the most significant groundwater recharge area. The underlying volcanic rocks (cropping out along H89) are apparently well jointed to permit groundwater flow. ***(This is supported by isotope data).***
F. Sardine Peak recharge center, elevations 7400 ft down to 5500 ft.
    1. Lemon Canyon watershed, E of Sierraville.
    2. Bear Valley Creek watershed, south of Loyalton, underlain by volcanics.
    3. Smithneck Creek watershed, including Dodge Canyon (E and SE of Loyalton), underlain by volcanics. ***(This is ambiguous based on the isotope data collected so far).***
G. The Antelope Valley watershed takes on a unique position, being somewhat isolated from the surrounding Lemon Canyon watershed. ***(The isotope data do not suggest much of any contribution from Antelope Valley).***
H. Mount Ina Coolbrith, elevations 8000 ft down to about 5700 ft, including three areas mostly underlain by volcanics and metavolcanics. The significance of these areas in terms of the total Sierra Valley Basin groundwater budget seems to be small, given their location on the eastern basin periphery. ***(Supported by isotope data).*** However, on the eastern Valley floor a number of irrigation wells have been identified with rather low TDS levels, suggesting close proximity to a groundwater recharge area. ***(The isotope data do not suggest Smithneck Creek as a source, but a so far unidentified second source).*** The second source(s) may be related to one or all of the following areas:
    1. A watershed drained by an unnamed stream, flowing west past Loyalton.
    2. A small watershed drained by an unnamed stream flowing NW, north of a knoll called “Elephant’s Head”.

    3. A small watershed drained by several unnamed intermittent streams (Correca Canyon, et al.), flowing NW.

I. Diamond Mountains (DM) east of Frenchman Lake and NE of Chilcoot. Elevations 7700 down to about 5600 ft, predominantly underlain by granitics and contact metamorphic rocks:
    1. With its significant topographic relief this area appears to be significant but its location on the eastern periphery seems to imply only limited amounts of precipitation (and groundwater recharge).
    2. But ground water studies conducted in the Chilcoot area suggest that significant groundwater recharge may flow (fault controlled) from the Diamond Mountains southwest into the Chilcoot sub-basin. ***(The isotope data interpretation is ambiguous).***
    3. Based on the preceding observation, it may be justified to imply groundwater flow from the Chilcoot sub-basin into the larger Sierra Valley Basin via a set of SW striking faults.

Recommendation: Continue to collect isotope data to clarify ambiguities and data gaps identified above.

3. Aquifer delineation

Background

The objective of this section of this report is to summarize the results of the SVB aquifer delineation, including methodology, conceptual models, and results. This initial interpretation is based on technical reports, well driller's reports, geologic maps, environmental tracer data (groundwater chemistry and light stable isotopes), and aerial photo interpretation.

In order to further the task of developing a 3-dimensional geologic model of the SVB, and to delineate the ground water recharge areas, the following sub-tasks have been completed:

1. Mapping areal/spatial distribution of shallow and deep aquifer depth (top and bottom of screen intervals) and depth to bedrock, using more than 950 well drilling reports obtained from DWR.

2. An aerial photo survey, covering the Sierra Valley Basin and the surrounding uplands to determine the areal/spatial dimensions of the basin fill sediments.

Geologic setting of the SVB

Structural Geology of the SVB

The SVB is a fault bounded intermontane trough, filled with lacustrine and fluvial sediments. The trough was probably formed due to expansion in a limited section of the earth's crust which leads to formation of steep normal faults and downward movement of one or several fault blocks. The process is illustrated in a hypothetical example in Figure 3-1.

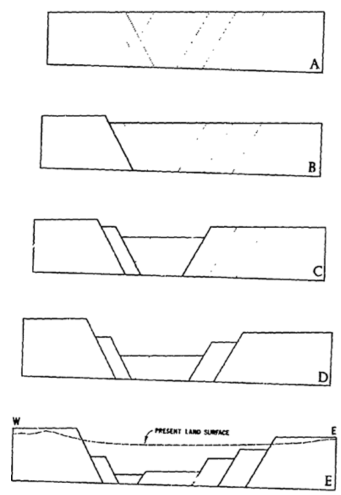


Figure 3-1 The development of a fault trough (from Thompson et al., 1967).

Crustal expansion in the northeastern Sierra Nevada is part of the regional tectonic evolution that has governed the geology of this part of the North American continent since the late Tertiary, over approximately the past 28 million years, and is probably still ongoing. Typically the floor of the fault trough basin is characterized by several bedrock blocks that subsided to varying depths among a set of NNW and NE striking faults.

Throughout its geologic history, the fault trough floor gradually subsided while being occupied by one or several lakes (Durrell, 1986). Sediments eroded from the surrounding uplands and volcanic tuffs (mud-flows and volcanic "ash") where deposited in the lake while the fault trough floor continued to subside. As indicated by well drilling records (WDR's), and a gravity survey conducted by DWR in 1960 (in Henneberger and McNitt, 1986), the SVB fault trough floor as defined by the bedrock surface buried under the sediments is not of uniform depth. Sediment thickness in the central basin as indicated by the geologic profile obtained from a geothermal exploration well (Philips Petroleum, 1972) and several deep water well drilling logs is at least 1500 ft, whereas in most peripheral areas depth to bedrock is no more than a hundred feet.

Sierra Valley Geothermal Gradient Holes						
data from GeothermEx, 1983						
depth given in ft bel. Land surface						
Well	**TD, ft**	**clay formation**	**Lithic Tuff below:**	**Lost Circulation Zones**	**depth to Bedrock**	**bedrock type**
SV-1	1150	140 - 760	780		>1150	no data
SV-2	1160	land surf. - 430	430	230, 420	1160	granodiorite
SV-3	1170	land surf. - 700	880	760, 930, 1030 ft	880	lava, tuff
SV-4	700	440 - 700	430		430	lithic tuff
SV-5	1060	50 - 825	>1000	870, 940, 1030'	>1060	no data

Stratigraphy of SVB sediments

By definition of this study the SVB floor is formed by low permeability bedrock formations. Wherever wells have penetrated through the sedimentary basin fill the "basin floor" is made of either volcanic rocks (lava) or the underlying granitic basement rock. In the centrally located geothermal areas the deeper sediments are often lithified by low grade hydrothermal alteration (Henneberger and McNitt, 1986; Ohland and Pogoncheff, 1990), resulting in a basin floor at that location that is shallower than the granitic basement by an unknown amount.

The alternating layers of sediment (clay, sand, gravel, etc.) reported in the drilling logs do not necessarily cover the entire basin area, since they are rather like lenticular shaped sediment bodies of limited extent, depending on the sedimentological setting at the time of deposition in the lake. These clay lenses probably "pinch out" at the basin periphery, unless they form a contact with adjacent bedrock due to faulting. As expected, the geologic profiles in the four geothermal gradient holes (Henneberger and McNitt, 1986) west of Loyalton, between Antelope Valley and the former Marble Hot Wells, indicate a 430 to 775 ft thick clay formation (see table).

Recommendation: This observation needs to be further substantiated by inspecting deep irrigation well drilling reports.

Fine grained sediments (silt and clay) are expected to dominate the central basin, whereas coarse-grained sediments (sand and gravel) are likely to be more abundant closer to the basin periphery (the former lake shorelines). This concept is demonstrated in the cross-section in Figure 3-3. The coarser grained sediments deposited near the basin periphery (shaded) are "interfingering" with the lenticular shaped bodies of fine-grained sediments in the central areas of the basin.

The Pilot Valley cross-section, however, does not show the combined effect of basin floor subsidence and sediment deposition. The seismic profile of a lake and its underlying sediment and bedrock basement formations shown in Figure 3-3 (from Wagner, 2014) illustrates what happens when basin-fill sediments continue to be deposited while the bedrock bottom of the basin subside. It is important to understand that continuing subsidence is the prerequisite for sediment deposition. While the most recently deposited shallow sediment layers are "flat", the deeper (older) layers are increasingly "dish-shaped" with increasing depth (age) below the lake bottom. This also explains how "thick clay lenses" are formed in the central basin, while thinner "lenses" and "wedges" of mostly sand and gravel are deposited at the basin periphery. Alluvial fan deposits are a feature typically formed after the lake has disappeared.

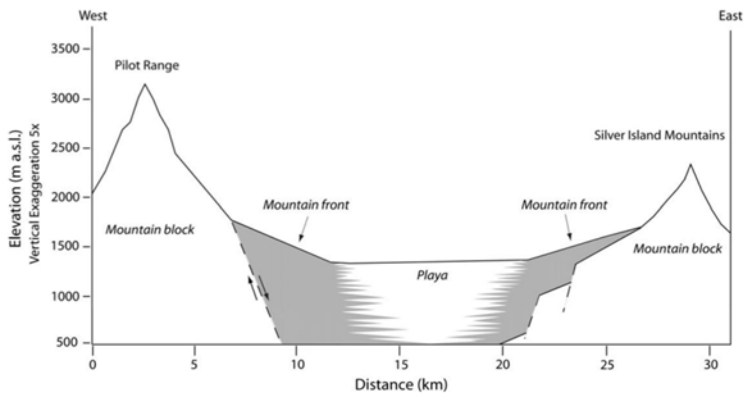
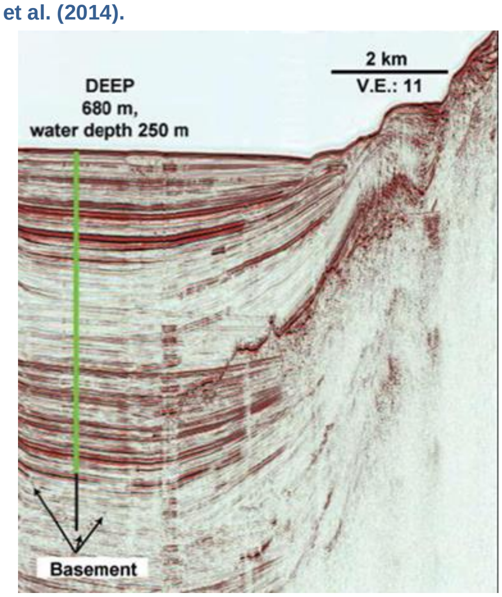


Figure 3-2 Schematic cross-section of Pilot Valley in Utah (from Carling et al., 2012, p. 17, 5:1 vertical exaggeration).

The conclusion from the preceding discussion is that the extent, shape and water storage and transmitting ability of the sediment formations that constitute the SVB aquifers is determined by the structural evolution of the fault-trough. In other words, the Sierra Valley Basin's aquifer properties are determined by:

- The basin's tectonic evolution,
- The former lake's sedimentary environment and history,
- The type of depositional conditions of the volcanic lava flows,
- The subsequent (post-sedimentary) geothermal alteration and lithification of the lacustrine tuffs, and
- The tectonic activity determining the distribution and degree of secondary permeability (joints and fracture zones) in the volcanic lavas and the granitic rocks of the Basin's floor and perimeter and in the geothermally lithified lacustrine tuffs.

Figure 3-3 Seismic profile of Lake Ohrid sediments deposited while the underlying bedrock basement is subsiding. From Wagner et al. (2014).



<u>Deep and shallow aquifers in Sierra Valley</u>

Flowing ("artesian") wells are a common feature in the SVB, and apparently were more common in the past, based on what is indicated on the topographic maps. The term "flowing well" is usually associated with a confining layer (aquitard), which seems to be difficult to identify in the SVB.

It is more likely that the artesian wells are the result of upward directed hydraulic heads which are characteristic for groundwater discharge areas. The upward hydraulic heads are probably by slightly elevated groundwater temperatures. It would be interesting to plot well or screen depth versus static water levels in selected areas of the SVB.

Recommendation: plot well or screen depth versus static water levels in selected areas.

Therefore, although the concept of "deep" and "shallow" aquifers is deeply embedded in the debate about Sierra Valley groundwater hydrology, it is deemed necessary to examine its justification. In the historic drilling reports no particular depth intervals are assigned to either aquifer. Perhaps use of these terms has become ingrained in the public conversation because since the 1950's wells drilled in Sierra Valley became increasingly deeper, leading to the "shallow" and "deep" aquifer terms eventually becoming "officially" adopted in the comprehensive groundwater studies by DWR (DWR,1963; DWR, 1983). Nevertheless, analysis of data from drilling reports, groundwater chemistry, and groundwater temperature so far seem to yield no convincing argument for two distinctive aquifers in the lacustrine sediments.

Recommendation: Develop more analysis on aquifer configuration and groundwater flow gradients based on drilling data and vertical temperature profiles.

Conceptual model of SVB hydrogeology

A conceptual model is a qualitative description of the hydrologic system that is investigated.

Conventionally it is assumed that the shallow unconfined basin aquifers are recharged by streams infiltrating the peripheral alluvial fans, and the deep confined aquifers are recharged from the adjacent and underlying volcanic and granitic rock aquifers (DWR, 1963; 1983). The fractured bedrock formations are recharged in the surrounding uplands (DWR, 1963), which constitute unconfined fractured bedrock aquifers presumably with heterogeneous and anisotropic permeabilities. Most likely the SVB sediment aquifers are mostly connected to the upland recharge areas by distinct zones of high permeability fractured rock. Hopefully the environmental tracer data interpretation may eventually permit identification of these zones of enhanced groundwater flow from the upland bedrock formations to the SVB sediment formation aquifers (this is very important). These upland areas are what are commonly referred to as groundwater recharge areas.

One useful conceptual hydrogeologic model can be adapted from Manning and Solomon (2015), shown in Figure 3-4. Of the two conceptual models presented (a) applies more likely to the poorly fractured granitic areas around Yuba Pass. The volcanic rock areas in the Dixie Mountain volcanic complex north of Sierra Valley and probably the well fractured granitic formations of the Chilcoot Sub-basin more likely fit into the (b) model.

Although, most SVB groundwaters have elevated temperatures between 15 and 30 ^{o}C, these are apparently heated by conduction while penetrating only to moderate depth. But these are not typical geothermal waters (not even in the deep basin), since none of them display the O-18 shift that is so characteristic of geothermal waters, with one exception. The only exception is the boiling well on the Filipini Ranch, which is reportedly 1200 ft deep, which does show a significant O-18 shift. However, none of the groundwaters sampled in the SVB seem to even contain a mixing component of geothermal water.

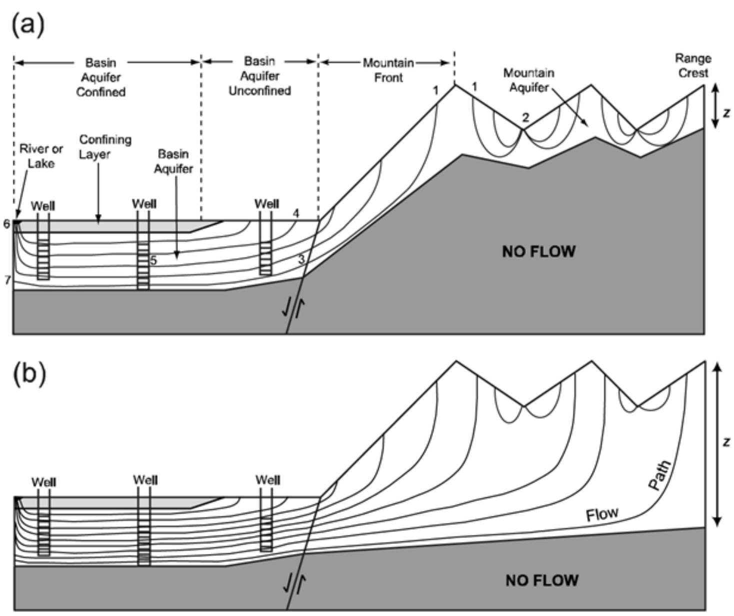


Figure 1. Schematic cross section showing conceptual model of groundwater flow in a mountain block and adjacent basin fill aquifer. (a) Major recharge and discharge components include 1, mountain recharge, which may become either mountain stream discharge or MBR; 2, mountain stream discharge; 3, MBR; 4, valley recharge, including infiltration from streams, precipitation, etc.; 5, discharge to wells; 6, discharge to basin river or lake or evapotranspiration by associated vegetation; 7, water that underflows river or lake and discharges at a location off of cross section. The shallow circulation case shown (small *z*) results in lower MBR rates, and nearly all MBR originates on the mountain front. (b) Deep circulation case (large *z*), which results in higher MBR rates; some MBR originates between mountain front and range crest.

Figure 3-4 Mountain block recharge and mountain front recharge conceptual models. From Manning and Solomon (2015).

Sierra Valley hydrostratigraphic units

Given the shortcomings of the data that can be obtained from the drillers' logs, an alternative approach was also pursued. As indicated above, the well drilling data, groundwater chemistry, and vertical temperature profiles seem to suggest that the lacustrine sediments that constitute the Sierra Valley Basin fill, act more like one “hydrostratigraphic unit” (though not like a single aquifer).

By definition hydrostratigraphic units are bodies of rock with considerable lateral extent that act as a reasonably distinct hydrologic system, which may include a formation, part of a formation, or a group of formations (Maxey, 1964). For the purpose of this study it is proposed to distinguish two separate hydrostratigraphic units:

1. The “basin fill unit” makes the excellent “valley floor aquifers” that the hundreds of domestic, irrigation and municipal wells are drilled into.

2. The “bedrock unit” is made of fractured volcanic lava flows, fractured granitics (“basement rock”), and at some locations, hydrothermally cemented and fractured tuffaceous sediments. The bedrock unit delineates the depth and boundary (outline of aerial extent) of the sedimentary basin-fill and aerially/spatially (horizontally).

Recommendation: Eventually it may become necessary to include a third group for the less conductive sediments once they become better understood.

The main distinctive characteristic between basin fill and bedrock hydrostratigraphic units are their type and ranges of permeability (hydraulic conductivity). These two “hydrostratigraphic units” to the Sierra Valley watershed, largely defined by their range of hydraulic conductivity (permeability), and by their location:

1. The basin fill unit with a wide range of grain-sizes from silt to sand and gravel has primary (intergranular) permeability and porosity.

2. The bedrock units (fault-trough) are characterized by secondary (fracture) permeability and porosity.

Most importantly, the bulk bedrock hydraulic conductivity is about seven orders of magnitude smaller than the average conductivity of the sedimentary basin fill.

Aquifer parameters in valley fill formations

Pumpingtest results, Sierra Valley

Location	well #	T, gpd/ft	S	K, gpd/ft2	t-max, hrs	Q, gpm	SWL, ft	h-max, ft	SPC	screen, ft	TD, ft	pw/obs?	comments
Lucky Herford Old Well #4	2215.36J1	17,900	nd	36	12	1,800	40	120	22	504	775	p	DWR (1983)
Genasci Well	2115.12P3	19,500	nd	69	23	1,330	35	153	11	284	514	p	DWR (1983)
Lucky Hereford #10	2316.32Q1	110,900	nd	375	20	3,150	69	126	55	296	820	p	DWR (1983)
		98,200	0.00031									o	DWR (1983)
Sposito resid. Well, Calpine		9,825	0.0051	68	72	119	9.8	119	1	145	145	o	Smith(2007)

Valley fill aquifer parameters

There are not many pumping test data available from the sedimentary aquifer formations. In a 1973 memorandum report a few specific capacity values of a limited selection of wells is given (DWR, 1973, p. 153). Specific capacities ranging between 0.7 and 6.9 gpm/ft, where the lowest value applies to shallow wells. An anomalous high value of 19.9 gpm/ft is from a 426 ft deep irrigation well.

In the fall of 1981 three wells were tested in eastern Sierra Valley (DWR 1983, App. D), yielding transmissivities between 17,900 (Lucky Herford R.) and 110,900 gpd/ft (Genasci R.). Due to difficulties with obtaining good observation well data only one storativity value of 0.00031 was obtained (see the table above). Also included in the table are the results of a test in Calpine.

Bedrock aquifer parameters

The bedrock units may actually constitute several hydraulic units (HU's), with fairly low bulk hydraulic conductivities (K), interspersed, but well delineated fault-induced zones of high fracture permeability (see the table of bedrock parameters). Given the much lower bulk permeabilities in the bedrock units (compared to the sedimentary basin-fill formations), the bedrock units are deemed "impermeable" for all practical purposes – with the exception of highly permeable fault zones. That is the reason why all the high yield wells are drilled in sediments (with some exceptions).

For example injection tests conducted for the installation of the grout curtain under the Lake Davis dam yielded hydraulic conductivities between 0 and more than 1.13 m/day (Oberdorfer and Hamilton, 1999, p. 16), indicating the dependence of bedrock well yields on intersecting sufficient number of fractures. In other words, the bedrock formations are highly heterogeneous porous media with very anisotropic permeabilities.

Aquifer properties

A number of groundwater studies (pumping tests) have been conducted in the basin periphery that generated aquifer parameter data from Sierra Valley bedrock formations. Well yields in this type of bedrock aquifers are typically variable depending on the number of fractures intersected, which itself depends on proximity to recurrent faults. Recurrent faulting depends on seismic activity - a feature that is certainly not lacking in this part of the Sierra Nevada. However, the physical properties of these formations largely depends on the rock material's ability to hold open fractures and joints, resulting typically in low yield wells – unless a well intercepts an open fracture near a fault zone. Typically bedrock wells need to be on average at least 450 ft deep to intercept enough fractures to assure adequate yields and to provide enough available drawdown ('pump-chamber') even during a prolonged drought when static well water levels (SWL) are deeper. Greater well depths are required at higher elevation sites where depth to SWL is greater.

If a well just does not yield enough water, drilling at an alternative nearby location can sometimes yield better results, in particular if the site is close to a fault.

Bedrock aquifer parameters									
Sierra Valley bedrock aquifers									
from selected well tests									
			aquifer thickness b, ft	**Transmissivity T**		**Hydraulic Conductivity, K:**			
Well name/project:	location	aquifer formation		gpd/ft		gpd/sq-ft	m/day	m/s	Data Source
Calpine VFD well	Calpine	granite	single fracture	-----	K measured	4.2	0.172	2.0E-06	Bohm (2010)
Anderson test well	Sierraville	T. volcanics	210	1271	K measured	6.1	0.247	2.9E-06	Bohm(2006)
Amodei dom. Well	Sierraville	T. volcanics		1012	K measured	8.3	0.341	3.9E-06	Bohm(2006)
John Amodei, dom well	Sierraville	T. volcanics	50	1000	T measured	20.0	0.816	9.4E-06	Bohm(1998)
test well, "The Ridges"	Chilcoot	granite	185	1440	K measured	7.8	0.318	3.7E-06	Bohm(2006)
Test w. RH-2, Beckw. Pass	Chilcoot	granite	160	4911	T measured	30.7	1.252	1.4E-05	Bohm & Juncal (1989)
SPI well No. 3	Loyalton	T. volcanics	190	787	T measured	4.1	0.169	2.0E-06	Bohm (1997)
River valley Subd.	RV-1	T. volcanics	350	3440	T measured	9.8	0.401	4.6E-06	Bohm (2002)
River valley Subd.	RV-1	T. volcanics	350	6000	T measured	17.1	0.699	8.1E-06	Bohm (2002)
Frenchman Lake Road Esta	FLRE-1	granite	265	1162	T measured	4.4	0.179	2.1E-06	Juncal & Bohm, 1986)
Frenchman Lake Road Esta	FLRE-2	granite	254	27	T measured	0.1	0.004	5.1E-08	Juncal & Bohm, 1986)
Frenchman Lake Road Esta	FLRE-3	granite	96.74	13	T measured	0.1	0.005	6.3E-08	Juncal & Bohm, 1986)
Frenchman Lake Road Esta	FLRE-1	granite	265	2364	T measured	8.9	0.364	4.2E-06	Bohm (1995)
Well 1B, Cedar Crest, 14 day test		granite	433	1380	T measured	3.2	0.130	1.5E-06	Bohm (1997)
		maximum		6000		30.7	1.252	1.4E-05	
		minimum		13		0.1	0.004	5.1E-08	

Aquifer delineation

Objectives

The purpose of aquifer delineation is to develop a three-dimensional model of the pertinent aquifer formations in SVB, by using well drillers' logs, geologic maps, and aerial photos. Prior to this study not much geologic interpretation had been conducted to develop a comprehensive model of the Sierra Valley aquifer system. The following is an outline of steps in subsurface characterization of the SVB aquifer system.

For the purpose of this discussion "aquifer delineation" implies characterizing the physical dimensions of the aquifers in the Sierra Valley Basin. The initial objective of aquifer delineation was to determine the horizontal and vertical dimensions of the Sierra Valley Basin aquifers (basin fill), using aquifer data gleaned from well drilling reports. However, as will be explained later, the information that can be gleaned from the drilling reports is only of limited utility, and the well locations cover the valley only to a limited extent. It was therefore proposed to also conduct an aerial photo survey to map the major faults in Sierra Valley and the bedrock trough boundaries. This enhanced understanding of the basin's structural geology should yield a reasonably accurate version of the physical extent of the aquifer formations that provide most of the water pumped for irrigation.

Recommendations: Incorporate a discussion of KDS reports and nested piezometers to better characterize:

a. Vertical flow gradients based on well water levels
b. Vertical gradients of groundwater temperature, chemistry, and isotopes.
c. Areal/spatial trends of groundwater chemistry and isotope data.

Aquifers and depth to bedrock identified by means of drilling reports

With more than 950 well drillers' reports available for Sierra Valley, these remain the most important data item available for this task. Although the entire valley is fairly well covered with wells, areal/spatial coverage by drilling information is rather uneven. Most wells are located in the east central basin.

Another problem is that the well locations are given in the T-R-S system (well number). In other words most of the well locations are indicated only within a one square mile area (5280 by 5280 ft lot). A small number of well location data also include the "tract" (letters A through R), i.e. at best within a 1/16 square mile area (1320 x 1320 ft lot).

The utility of well drillers' logs to identify geologic formations or to map geologic formations is limited since geologic materials descriptions in the reports are usually inconsistent and somewhat ambiguous. Screen intervals in high yield irrigation and municipal wells are often determined by means of downhole geophysical logs which are less subjective than drill-sample descriptions. At best the logs provide accurate information about depth intervals where plenty of water is to be had, enough to justify the cost for completing the well. Therefore the screened intervals, together with total depth (TD) and depth to bedrock, are the most accurate data items available from drillers' logs. Most importantly, the formation sections covered by the screen intervals do meet the definition of the term "aquifer" as defined in Freeze and Cherry (1979):

> *An aquifer is "a saturated permeable geologic unit rock formation that can transmit significant quantities of water under ordinary hydraulic gradients", enough to "yield economic quantities of water to wells".*

It is thus justified to identify aquifer depth by means of the screened intervals. To extract the pertinent data, a number of spreadsheets have been developed to organize the data contained in the drilling logs

1. Since most square mile sections contain well screen data from several wells each section is represented by the average screen interval depth, average well depth and bedrock depth (if drilled to bedrock).
2. A criterion was adopted to determine which one of these screened intervals corresponds with the "deep" or the "shallow" aquifer. The top of the screen interval above or below 400 ft level was adopted as the deciding criteria for shallow or deep aquifer, based on observations obtained from consulting reports etc. Thereby most wells in this database are completed in the "shallow aquifer".

3. The Basin floor area comprises about 20 to 25 “townships” (T-R), each with 36 one-square mile sections. That can result in up to 700 to 900 data points with upper and lower aquifer boundaries and well depth.
4. Since for many areas (mostly south of the County line) no drilling records are available, only 184 “cells” contain depth to bedrock data.
5. Further data were added from a number of geothermal gradient wells (GeothermEx, 1984; HLA, 1986).
6. A considerable amount of interpretation was necessary for some of the basin periphery areas, where the sedimentary basin aquifers contact the surrounding bedrock formations.

Based on this approach the subsurface topography of the “shallow and deep aquifers” and “bedrock” were approximated in a grid with one square mile “cells” (sections). Each ‘section’ is treated like a ‘hypothetical well’ located at the center of each square mile section.

Even with this limited selection of well data it becomes clear that in the central valley floor well drillers have found two zones suitable for groundwater development, a shallow zone, and a deep zone. The deep zone has apparently been drilled into only in the central area, but not in the northern valley floor, where sampled well depths do not exceed 400 ft. The reason why wells in the northern periphery are not deeper than 400 ft may be that the deeper zone found in the central valley does not extend that far north.

As explained later in this report, depth to bedrock turned out to be the most pertinent data item to characterize the three-dimensional configuration of the basin-fill hydrostratigraphic unit. If needed, in sections without wells drilled to bedrock, bedrock depth can be substituted with maximum total depth (TD) measured in ‘deep aquifer wells’ which did not reach bedrock.

Aerial photo intepretation

General

Fault zones can be mapped when fault movement in bedrock imprints itself as lineaments through the overlying unconsolidated sediments, sometimes even through several thousand feet of basin fill sediments. In some cases lineaments identified in the thin upland soils can be projected into the thick basin fill sediments.

Based on observations made elsewhere in the area on rock outcrops in deep river gorges, well drilling data and downhole TV surveys in bedrock wells, the fault attitudes are near-vertical. Helpful is the observation that typically lineaments are sub-parallel to certain prevailing directions, which are characteristic for the faults in the geologic setting of NE California.

Certain directional elements that can be readily recognized on the topographic maps were confirmed on the aerial photos, i.e. most mapped lineaments adhere to certain predominant directional trends, which are apparently characteristic for faults in the geologic setting of NE California.

Methodology

Fracture traces were identified by tracing lineaments on two sets of stereographic aerial photos obtained from the Aerial Photo Field Office (APFO) in Salt Lake City, Utah:

a. 33 black-and-white images taken in 1993.
b. 21 cololor IR images taken in 1984.

The photos were examined with a WILD mirror stereoscope to identify lineaments in the landscape that could indicate the existence of fracture zones in the underlying bedrock. The lineaments were traced on Mylar overlay sheets with indelible fine point color felt tip pens. Lineaments indicative of faults were identified by looking for continuing, albeit not always connected, linear topographical features in the landscape. Such features are typically associated with perennial and ephemeral streams, abandoned stream channels, and other drainage features. But they can also signify fault scarps caused by repeated vertical movements.

Since faults in a particular landscape typically align along certain predominating directions it is common to observe stream channels following so-called trellis patterns.

a. Strike-slip faults can lead to horizontal offsets of stream channels in alluvium and bedrock areas, leading to so-called “trellis patterns”.
b. Vertical fault motion (“normal faults”) can lead to formation of “fault-scarps” which can trigger formation slumps, if not minor landslides which form “bowls” and other similar features in alluvial slope sediments.

While the lineaments are usually discontinuous some can be traced over long distances, sometimes up to several miles. It became readily apparent that an abundance of lineaments can be identified in SV. Caution has to be exercised to distinguish which of these lineaments are “cultural” features, or the result of over-interpretation (“fictitious”), and which are truly indicative of fault traces.

The photo lineaments were traced on Mylar overlay sheets using indelible fine point color felt tip pens. Once the lineament mapping was completed and the most prominent lineaments identified as faults, the faults were transferred onto a topographic map using the Terrain Navigator topographic map package.

Recommendation: The most prominent features should eventually be visited on the ground to be field-verified. Scanned copies of the Mylar overlays with the lineaments traced on the stereographic photo can be made available.

Results of aerial photo interpretation

Based on the results of the lineament analysis the evidence of faults in the Sierra Valley Basin is pervasive, suggesting that regional seismicity is adequate to keep fault traces from becoming leveled by erosion.

The mapped lineaments adhere to at least three consistent trends (NNW, NW and NE). The repeated occurrence of these trends is a strong indication that these lineaments indicate fault traces:

a. The NW and NNW trending lineaments are interpreted to be associated mostly with a horizontal ("strike-slip") and to a lesser extent with a vertical ("normal") fault motion component.
b. A set of NE striking lineaments is interpreted to be associated mostly with vertical ("normal") fault movement.

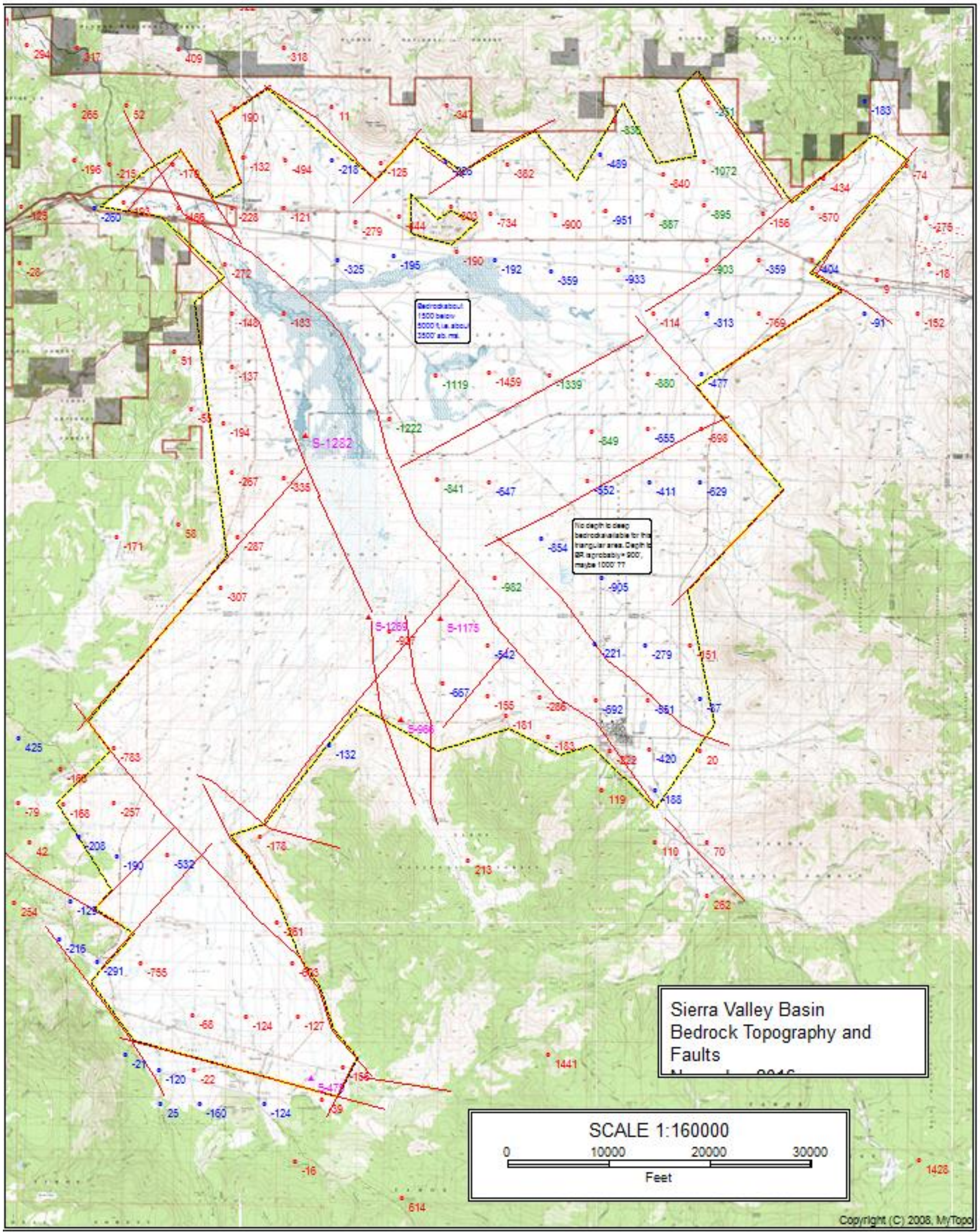
SVB structural geology and groundwater flow

The fault lineaments identified in Map 3-1 are highlighted by how they are expected to affect groundwater flow and how they affect the response to long term pumping:

1. There are two faults striking about NNW, dissecting the basin into a southwestern one-third and a northeastern two-thirds.
    a. The western fault is called the "Hot Springs Fault" (HSF) "runs" from Antelope Valley NNW into Big Grizzly Canyon. The eastern fault (called the "Loyalton Fault") is traced from Smithneck Creek Canyon to a point west of Beckwourth, where it apparently merges with the HSF.
    b. Considering the regional geologic setting these two faults are the reason for these two faults are mostly strike-slip faults and, given the significant west-to-east bedrock topography in Map 3-1, with a significant dip-slip component.
    c. In a pumping test these faults would probable cause a barrier boundary effect.
2. A major SW-to-NE striking fault zone was traced from east of Calpine to the Little Last Chance Creek Canyon (Adam's Neck) north of Vinton. For the purpose of this report this zone is referred to as the "Vinton-Calpine Fault Zone" (VCFZ).
    a. This feature is apparently more than a distinct fault, but a zone that is affected by a series of "normal faults", which create conspicuous linear ridges which can be readily identified on the aerial photos.
    b. Apparently this zone constitutes an important pathway for groundwater flow, evident in the linear stream channels ("Sierra Valley Channels" on the topographic maps).
    c. The VCFZ is apparently part of the Upper Long Valley fault zone identified on the Chilcoot geologic map quadrangle (Grose and Mergner 2000; Grose 1992).

3. The Mohawk Fault Zone apparently defines much of the topography of the uplands west Sierraville and Sattley, including Turner Creek Canyon and Chapman Saddle.
4. A topographically low spot occurs where the VCFZ and the two NNW striking faults intersect. It is here where most high temperature wells are located.

Recommendation: further evaluate how structural geologic features affect the course of stream channels and groundwater flow in the SVB.



Map 3-1 Sierra Valley Basin bedrock topography and faults.

It is worth noting that the major topographical features that characterize the Sierra Valley floor, including the major streams (Middle Fork Feather River and Little Last Chance Creek) adhere in their general outlay to one or both of the two abovementioned lineament trends.

The course of the major NNW trending faults is similar as mapped by previous investigators (DWR, 1963; GeothermEx, 1986), the most prominent being the Hot Springs and Loyalton Faults. However, a new structural feature added by the current interpretation is the signiicance of NE striking faults. The most prominent NE striking feature is a zone that extends from the southern valley (near Calpine) to "Adams Neck" noorthwest of Chilcoot. Most likely this zone constitutes a series of gravity faults (normal faults) which are the result of crustal extension associated with the strike slip fault movements of the Loyalton and Hot Springs Faults..

As elsewhere in NE California, faults that are prominent enough to show on aerial photos typically are high angle faults, which are not more than 10 or 20 degrees from normal (70 to 90 degrees). No low angle faults have been identified from an analysis of how the fault traces cross topographical features in the uplands.

Results of aquifer delineation

Map 3-1 shows the lineaments mapped on the aerial photos, transferred into the topographic map of SV, using the Terrain Navigator topographic map package, presenting the following information:

a. Depth to bedrock (red circles), estimated from the drilling report data.
b. Major faults (red lines) identified in the aerial photo survey.
c. An outline of the bedrock basin, proposed for use in the groundwater flow model (black lines, highlighted in yellow).

In general, it is assumed that the NNW and NW striking faults are strike-slip and/or dip-slip faults, whereas the NE striking faults are normal (gravity) faults. The latter type is the result of crustal extension, whereas the preceding faults are due to horizontal movement.

Essentially Map 3-1 is our current interpretation of the SVB structural geology, transferred onto a topographic map. Thereby the SVB structural elements were digitized as follows:

Depth to bedrock

In Map 3-1 the deepest well total depths (TD's) for each section (square mile) are plotted as circles with a central dot, labeled with depth in ft below the 5000 ft level (negative numbers). The location plots and depth labels come in three different colors:

- Red - the deepest depth to BR (bedrock) measured in that particular section, i.e. only wells that did encounter bedrock.

- Dark green - the <u>deepest TD</u> of “deep aquifer” wells measured in that particular section, i.e. deep wells which did not encounter BR.
- Blue - the <u>deepest TD</u> of “shallow aquifer” wells measured in that particular section, i.e. shallow wells which did not encounter BR.
- Purple triangles - represent additional well data obtained from other sources, e.g. the five temperature gradient test holes drilled in 1985 (GeothermEx, 1986).

As noted earlier, only a limited number of sections contain wells that were drilled to bedrock, in selected sections the minimum depth to bedrock was estimated from the TD of those deep wells that did not reach bedrock. In other words those sections with red dots and blue or green labels indicate that depth to bedrock is greater than the value shown. This bedrock level was estimated only when the TD was reasonably similar to nearby bedrock wells.

It may be tempting to manually shape and "smoothen" the buried bedrock surface to the hillslope on the valley margin, like a smooth surface. However, that would not accurately reflect the reason why the basin exists, i.e. vertical fault movement.

In some cases large areas are not represented by bedrock wells, like the triangular area north of Loyalton (10 to 15 square miles). In such cases there are two alternative analytical approaches:

a. Each section can be assigned a bedrock level by using the deepest TD of each available deep ‘alluvial well’.
b. Assign to each section a bedrock level equivalent to the deepest bedrock or alluvial well deemed representative of that area.

In summary every measured bedrock label shown in red is derived from the maximum bedrock (BR) depth measured in that section, whereas red circles with blue or green labels indicate an unknown bedrock level deeper than indicated in the label.

Using this rationale the estimated volume of the alluvial sediments in the SVB is somewhere between the real volume and the maximum estimate. A minimum volume estimate would be implied by using the minimum depth to bedrock values.

<u>Recommendation:</u> Consider this factor in more detail for the groundwater flow characterization when the modeling results become available.

<u>Faults</u>

Faults as mapped on the aerial photos are shown on the topographic map as red lines. The lines are dotted when the faults are either hidden or inferred.

The yellow line that loops around the entire periphery of Sierra Valley is the proposed Sierra Valley Basin boundary, based on aerial photo mapping. Most importantly this yellow line does not represent the watershed boundary, but the boundary of the SVB bedrock trough. It is the outline proposed for the groundwater flow model.

As is common in northeast California the strike of the mapped faults adheres to one of three trends, either NNW, NW or NE directions. Undeniably these trends are predominant. For that reason the basin boundary topography was interpreted by inferring NE or NW trending faults – with some exceptions. One exception includes the southern Basin around Sattley and Sierraville. Another area includes the basin boundary east of Loyalton. In these areas the combination of well depths and basin boundary topography has so far not been possible to interpret satisfactorily.

The Chilcoot sub-basin as a recharge area

The Chilcoot sub-basin was not included in the SVB, based on its topographic setting. The Chilcoot sub-basin should be considered a recharge area, with a thin veneer of alluvium (less than 200 ft) discharging into the greater SVB. The same applies to the Frenchman Lake Basin.

Potential significance of structural elements for groundwater modeling

The faults that define the SVB periphery imply for all practical purposes barrier boundaries (impermeable) and would most likely occupy that function in pumping tests conducted on nearby wells in the basin fill. On the other hand wherever faults intersections provide important avenues for groundwater entering the basin from the surrounding uplands they are conduits rather than barriers. Such situations are evident wherever a perennial stream enters the basin.

The large NW striking faults crossing the SVB are mostly caused by horizontal motion (strike-slip faults); although a limited amount of vertical motion may occur. Strike-slip fault motion can create barriers to groundwater flow due to formation of fault gouge or by juxtaposition of high permeability formations against low-permeability formations. On the other hand the strike-slip motion can lead to enhanced permeability near the fault.

On the other hand the northeast striking faults are most likely conducive to facilitate groundwater flow through enhanced permeability associated with normal faults. This has been demonstrated in a groundwater study in the upland bedrock aquifers conducted for a suburban subdivision proposal in Grizzly Valley.

Recommendation: As the effects of the major faults and fault zones on groundwater flow in the SVB are better understood, further study of selected fault zones and faults may eventually become important for groundwater flow modelling in the SVB.

4. Groundwater Flow Based on Light Stable Isotopes and Chemistry

Study Objective

The objective of this part of the study is to characterize groundwater flow in SV, i.e. identify directions and sources of groundwater flow in the basin and to determine how the uplands recharge tie into the Sierra Valley Basin (SVB) aquifers, using naturally occurring isotope tracers and major dissolved ion chemistry in springs, wells, and streams.

Types of data collected

The tracers used include the light stable isotopes of hydrogen (^{2}H) and oxygen ($^{\text{oxygen-18}}$) in the water molecule (from here on referred to as “isotopes”), temperature, EC, the major cations (Ca, Mg, Na, and K) and the major anions (SO4, Cl, and HCO3). The data used were obtained in a two-phase field investigation

- Isotope data from selected springs and streams in the uplands, including field parameters (temperature, EC, alkalinity).
- Isotope and chemistry data from selected wells in the valley floor (basin aquifers).

Sierra Valley upland waters

For the purpose of this study the uplands are defined as the elevated areas surrounding the SVB. Elevated areas that define the Sierra Valley watershed are areas higher in elevation than the Sierra Valley “proper”. They are areas with groundwater levels significantly higher than in the wells of the Valley Floor. These “upland waters” constitute springs and streams that are deemed by professional judgment, to be representative of water that recharges the aquifers in the Sierra Valley Basin. The SVB is defined as the lacustrine and alluvial aquifers utilized for pumping. Therefore upland water sources including mostly springs that are determined by professional judgment, to be representative of groundwater (groundwater) recharge.

Sierra Valley Basin aquifer waters

The SVB is defined as the fault trough that contains the lacustrine and alluvial aquifers from which significant amounts of water are pumped for irrigation (and to a lesser degree to meet suburban water needs) in the SV.

Valley floor wells (VFW) are wells drilled into the basin-fill aquifers in the Sierra Valley proper, accessing either/or both bedrock aquifers and/or unconsolidated sediment aquifers such as lacustrine and alluvial fan deposits.

Stream waters

Stream waters (SW) are treated as a third category, although they are also derived from upland recharge waters.

Concepts and assumptions in tracer data Interpretation

The basics of stable light isotope hydrology

A small fraction of the water molecules H_2O contain hydrogen atoms twice as heavy as the usual hydrogen 1H. This "isotope" is called deuterium (^{2}H). Similarly, a small fraction of the oxygen (^{16}O) in water is made of the slightly heavier isotope "oxygen-18" ($^{oxygen-18}$). Therefore a small fraction of water molecules is slightly heavier. Although their chemical properties are the same as in regular water molecules, their physical properties are slightly different.

For the purposes of this report the "light stable isotopes" in water are simply referred to as "isotopes", expressed in units of deuterium and oxygen-18, or as "D" and "O-18". The isotope composition is reported by how much it differs from ocean water (using the delta notation, "δ"). Since ground and stream water derived from water vapor is isotopically lighter than ocean water, isotope data from continental waters are reported as negative numbers.

All precipitation is derived by evaporation from the oceans. Upon evaporation the heavier molecules tend to evaporate 'slower' leaving the residual ocean water (not evaporated) slightly "isotopically enriched" and the water vapor slightly "isotopically depleted". As the water vapor rises and condensates into clouds the rain or snow becomes "isotopically enriched" (heavier), and the water vapor remaining in the atmosphere becomes "isotopically depleted" (lighter).

Therefore as the moisture laden air-masses travel west to east from the Pacific Ocean and across the Sierra Nevada Mountains the water vapor becomes progressively "lighter". Therefore every time the moist air masses condense into rain or snow the moisture in the clouds becomes more isotopically depleted. This so-called "rain-out" effect can be observed in the spring and stream water samples collected in the high elevation uplands surrounding the Sierra Valley Basin. The results of this rain-out effect are exemplified in waters from the Yuba Pass area, Cold Creek and Smithneck Creek.

Due to the physical laws governing water evaporation and condensation globally the relation of deuterium and oxygen-18 in atmospheric ("meteoric") waters was determined from thousands of precipitation water samples collected from around the globe. This average global meteoric water line (GMWL) serves as a reference condition, described by the equation (Craig 1961, in Clark and Fritz, 1997, p. 36):

$$\delta\, ^2H \quad = \quad 8 \times \delta^{\text{oxygen-18}} \quad + \quad 10$$

This baseline is included as a common reference line in the standard isotope plots (oxygen-18 versus 2H) as the “GMWL”.

Also more localized rain-out effect occurs over each individual recharge area, where the precipitation at the highest elevation becomes isotopically most depleted. Each area in a landscape has a distinct average isotope “signal”, which is determined by two site specific conditions:

- What happened to the atmospheric moisture before arriving at that spot, in other words its average ‘rain-out’ history’, and
- The site specific average temperature and moisture conditions at the time of precipitation becoming groundwater recharge.

Deviations in the isotope signal from the average GMWL by plotting either above or below the GMWL depend on physical processes while rain drops travel from the clouds to the land surface. These shifts are another useful site specific characteristic. Therefore each source area is characterized by its distinct isotopic composition, by:

- How far it’s isotope composition has shifted to the lower left hand corner on the standard isotope plot, and
- How far it plots above or below the GMWL.

Concepts of isotope data interpretation

A. The assumptions underlying the data interpretation to tie together the basin aquifers and their upland source (recharge) areas are: Groundwater recharge per definition cannot be sampled in the uplands since it has infiltrated through the soil into the underlying unconfined upland aquifers to emerge in the low elevation discharge areas (valley floor wells). However, some of that groundwater recharge “daylights” in the uplands where the groundwater table intersects the land surface in springs and stream channels.
B. The isotope signature of a particular basin aquifer is similar (if not identical) to the isotope signature of the corresponding recharge area(s)’ spring and stream waters.
C. Streams entering the basin become a source of groundwater recharge if the stream channel elevations are higher than the basin aquifers’ water table. Thereby groundwater can occur either:
    a. In an unconfined (shallow) aquifer underneath a stream channel crossing an alluvial fan.

b. Through the contact between bedrock and lacustrine aquifer at the basin periphery (flowing horizontal) and through the ‘basin floor’ (flowing upward).

Note: Whenever necessary, further details of isotope data interpretation will be explained in the site specific subsection in the further course of this report.

The following figure depicts how plotting EC versus isotopes can be used to differentiate waters that percolated deep as far away as Dixie Mountain, from water discharging after only short subsurface residence time such as in the granitics of Yuba Pass.

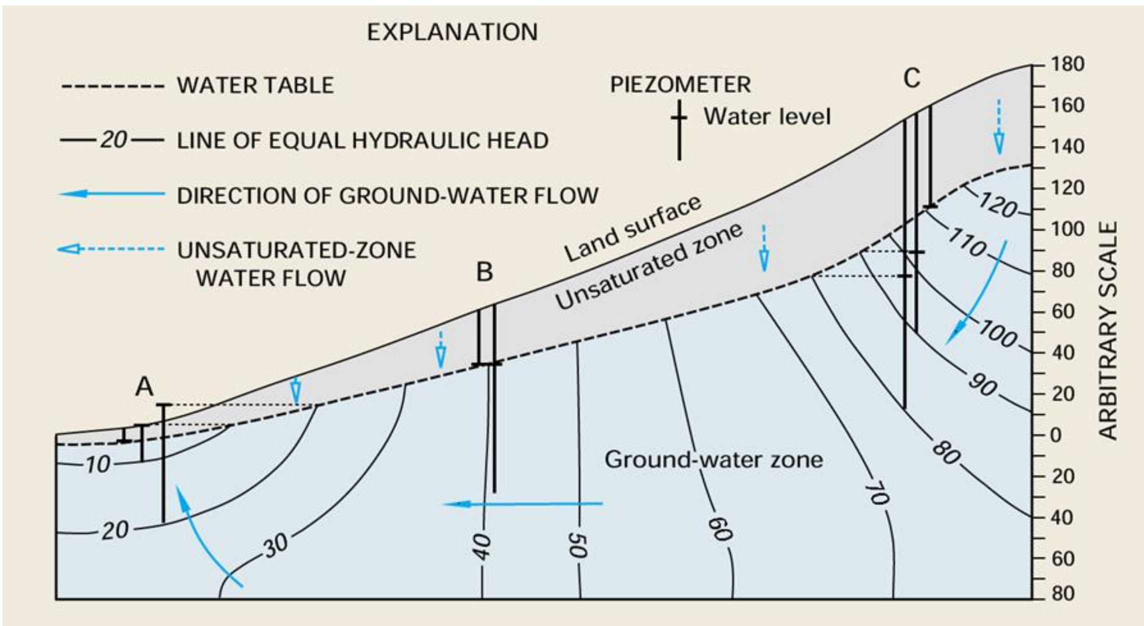


Chart 4-1 Conceptual depiction of a typical groundwater flow system. From Winter et al. (1998).

Concepts of geochemical data interpretation

The unique utility of isotope signatures in ground and stream waters is that these signatures won’t be changed by subsurface chemical processes (with some exceptions). Usually, once a volume of water has infiltrated past the soil zone its isotope signal will not change until it surfaces in a spring, well or stream. On the other hand major ion chemistry (Ca, Mg, Na, K, SO4, Cl, HCO3) in ground and stream waters changes with increasing subsurface residence time, depending on temperature and aquifer rock composition (to a limited extent). The longer water percolates underground and the higher the temperature, the higher the major ion concentrations and the total dissolved solids (TDS).

The principal features of a groundwater flow system illustrated in the figure above show how groundwater migrates through the earth’s crust, from an upland recharge area to a valley aquifer. The blue arrows are an approximation of the groundwater flow lines. As a general rule the higher the recharge elevation, the deeper groundwater penetrates and the greater the distance from recharge to discharge area. Therefore isotope data in combination with TDS, temperature and certain major ion ratios can serve as semi-quantitative indicators of distance of flow and subsurface residence time. Therefore, isotope data, and major ion chemistry can be very helpful in interpreting and conceptualizing groundwater flow.

Data collection

Field data and sample collection

Two major categories of data were collected:

1. Selected springs and streams were sampled in the uplands, within the bounds of the Sierra Valley watershed (with a few exceptions which were located outside the watershed). Temperature, electric conductivity, and alkalinity were measured in the field. Isotope samples were collected in 20 ml glass vials.
2. Selected wells with pumps in the Sierra Valley Basin (valley floor) were sampled for stable isotopes, major cations and anions, fluoride, and boron. Electric conductivity and temperature were measured in the field.

Also sampled were the five nested piezometer sets installed by the District, which required purging and sampling with a special pump. The two-inch diameter piezometers are of particular interest since their screen intervals are in very well defined discrete depth intervals. A select number of piezometers were also sampled for tritium analysis.

Literature data

The technical literature, available consulting reports, DWR data bases, and government agency reports were searched for groundwater chemistry and light stable isotope data.

Lab analysis

Chemistry lab-analyses was conducted by Sierra Environmental Monitoring (SEM) Labs, a CA certified lab located in Reno, NV. Lab analysis for deuterium and oxygen-18 (^{2}H and $^{oxygen\text{-}18}$) was conducted by the UC Davis Stable Isotope Facility.

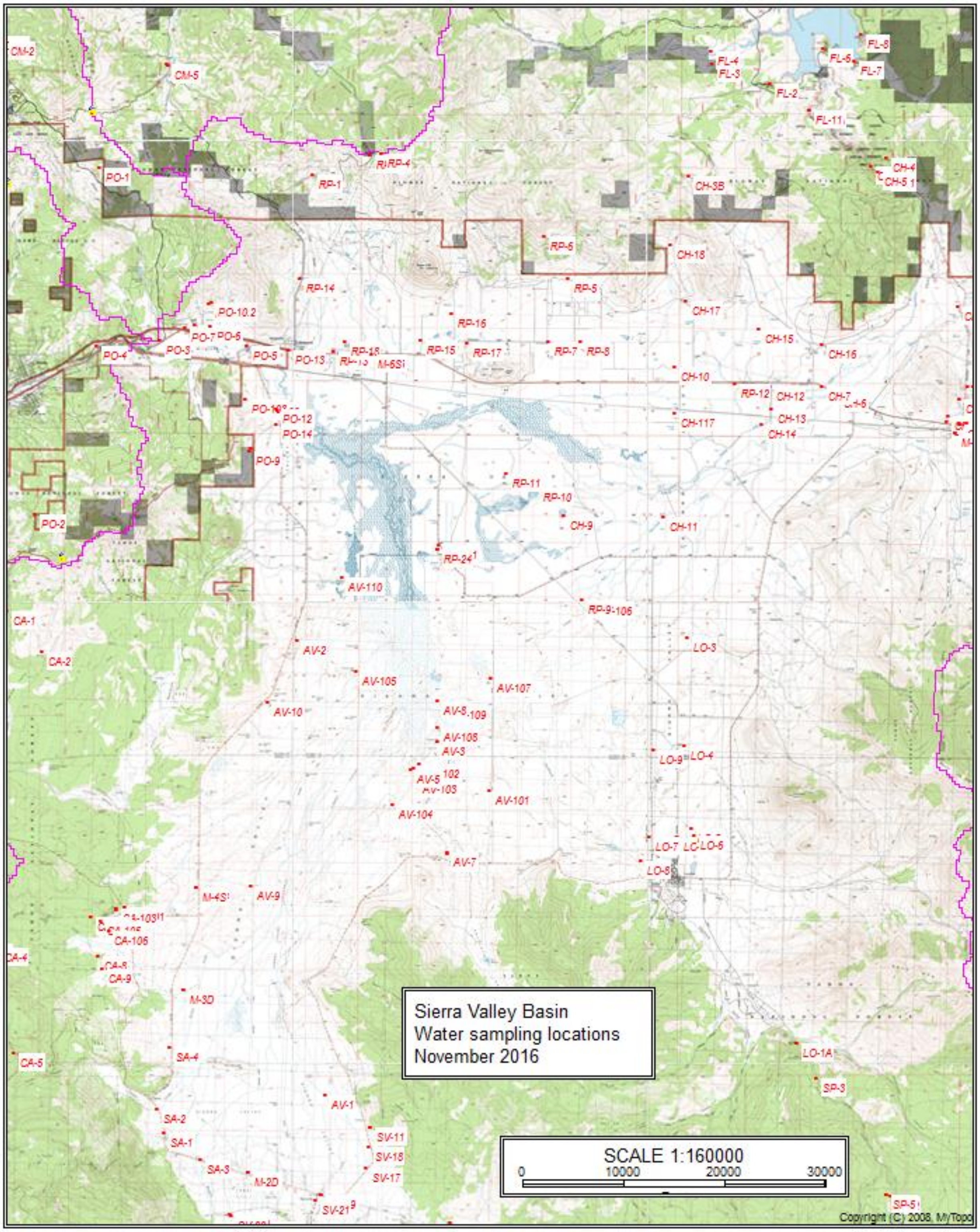
Sample location maps and sample identification codes

The field sample locations were recorded with a handheld GPS unit and were, together with the literature data locations, plotted on the topographic maps (Map 4-1) at the end of this chapter:

1. The two-letter sample locations indicate the USGS topographic quadrangle. Ground and surface waters sampled for this project were numbered between 1

and 99. For example “PO-16” is the 16th sample collected on the Portola 7.5 minute quadrangle. An exception is the nested piezometers which are labeled MW-1 through MW-6, i.e. “MW” is not a map code.

2. Duplicate samples are coded A, B, C, etc. for example LO-01B would be the second duplicate sample collected at site LO-01.



Map 4-1 Sierra Valley sampling locations on the basin floor. The map does not include all upland locations.

3. Data obtained from technical reports or the scientific literature was numbered between 101 and 199. For example CH-104 is the 4th data location obtained from the literature on the Chilcoot quadrangle.
4. A limited number of precipitation samples were collected, numbered from 201 to 299 (e.g. CA-201 through CA-218 would be 18 precipitation samples collected on the Calpine quadrangle).

In the following discussion of data interpretation specific wells, springs or stream samples are usually referred to by their data point number. For example the well at the Caltrans roadside resting area is referred to as "PO-7" and its location can thereby be traced on Map 4-1.

Note that Map 4-1 does not include the entire watershed. A more inclusive sample map is to be included in the data table section.

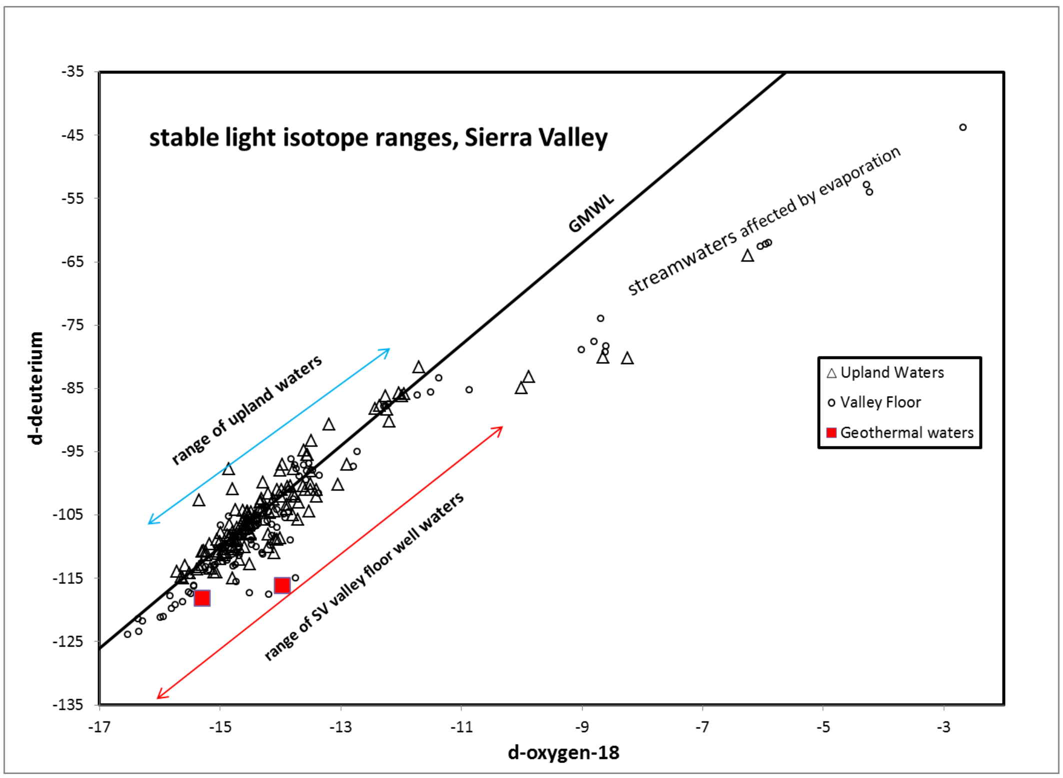


Chart 4-2 Sierra valley stable light isotope ranges

NOTE

The following data interpretation intended to characterize groundwater flow is not complete. The data deserve significant more analysis, sometimes supported by more sampling in selected areas. To do justice to its high information content the data should be subjected to further review.

Overview: isotopes in valley floor wells, upland springs and streams

Chart 4-2 is a standard isotope plot of the two main categories of data collected, i.e. upland waters (blue triangles) and valley floor wells (red dots).

Key Observations:

While most upland waters plot in an elongated cluster roughly parallel to the GMWL on an 8.0 slope, waters with 2H and oxygen-18 greater than -12.0 and -90.0 per mil plot on a lesser slope (about 5.0). These are stream water samples collected from Little Last Chance and Grizzly Creek, waters affected by evaporation in Frenchman Lake and Lake Davis.

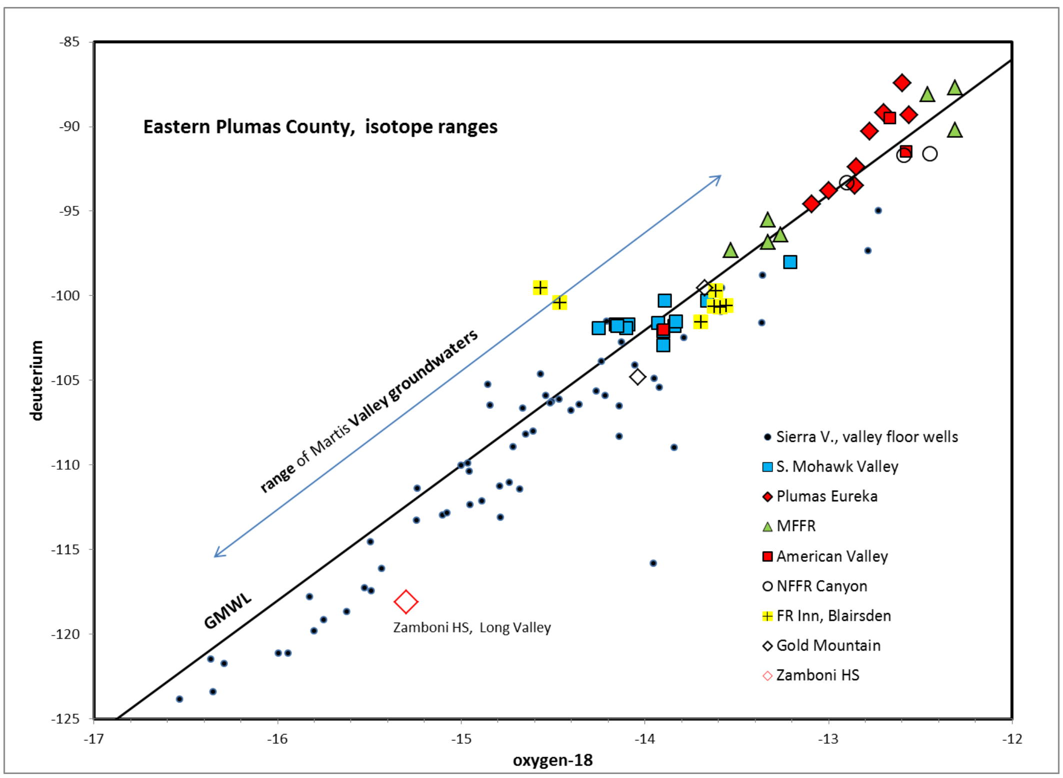


Chart 4-3 - Stable isotope ranges, Eastern Middle Fork Feather River Basin.

The data collected from the Valley Floor Wells plot on a trend similar to the upland waters. However, at the lower end the valley floor wells data occupy a range wider than that occupied by the upland waters. The latter observation is very important, since it implies that the upland data base may not cover all areas that could be potential groundwater recharge areas for the basin aquifers. The implications are:

a. One or several of the pertinent Sierra Valley groundwater recharge areas are not represented in the upland data matrix, **or**
b. Some groundwater in the SVB originates from a source located outside the Sierra Valley watershed.

Applying the prevailing rationale in isotope hydrology the isotopically most depleted groundwaters in Sierra Valley implies that they may originate from the highest elevation of a recharge area east of Sierra Valley (unless a so far unidentified alternate process can be identified).

The valley floor wells which plot at isotope ranges outside (less than) the upland waters, are almost exclusively located in the Central Sierra Valley areas, covering the central valley floor from the outlet of Antelope Valley to the areas between Highway 70 and the northern Sierra Valley periphery north and northwest of "The Buttes". On the other hand those wells plotting within the range of the upland waters are typically located in the areas at the valley periphery (see Chart 4-4).

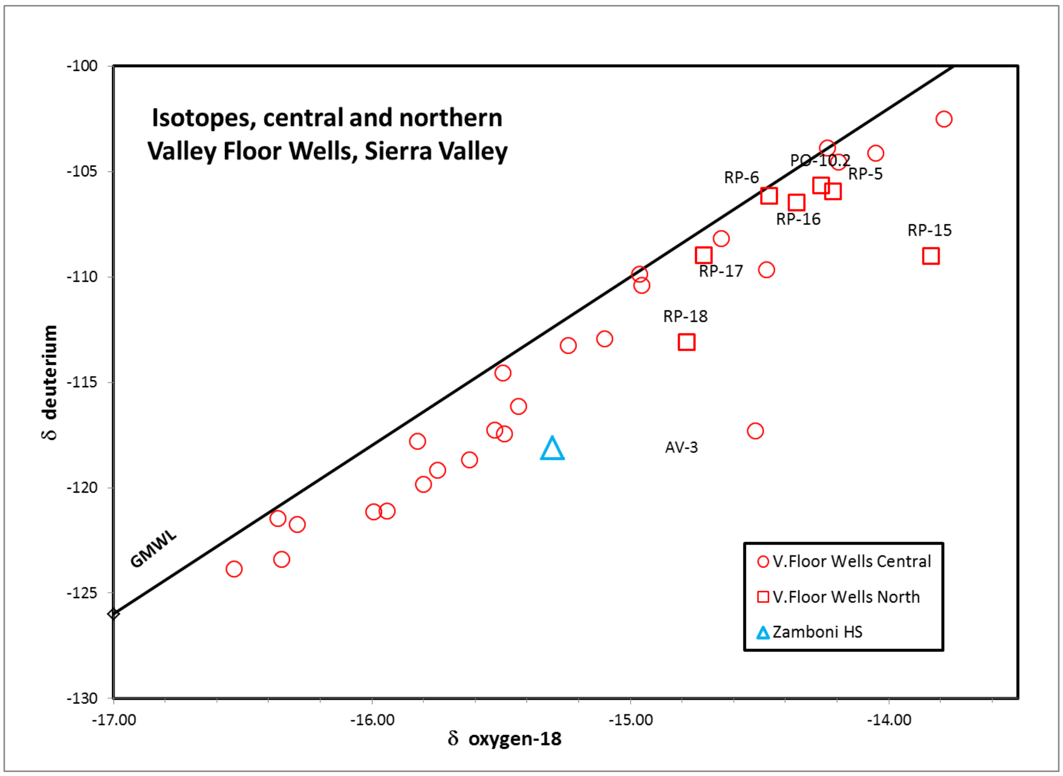


Chart 4-4 Isotopes, central and northern valley floor wells

<u>Searching for possible groundwater sources outside the Sierra Valley watershed</u>

In search of other potential groundwater recharge areas for the central Sierra Valley Basin waters the valley floor waters were plotted together with other groundwaters in this part of the Sierra Nevada (Chart 4-3). These include waters from Mohawk Valley, the

MFFR canyon, Indian Valley, the NFFR Canyon, and the Last Chance watershed – all areas located west and north of Sierra Valley. In Chart 4-3 none of these data span the entire range of the central Sierra Valley floor wells.

The light stable isotope range of groundwater sampled in Martis Valley (Reference?), the next large groundwater basin south of Sierra Valley, indicated by the blue double arrow in Chart 4-3 is significantly smaller and less depleted than in Sierra Valley. Therefore groundwater influx from Martis Valley is deemed unlikely.

Since the average water level in Stampede reservoir is about 1,000 ft higher than the floor of SV, it is tempting to suspect interbasin groundwater flow through a fault zone indicated in the course of Smithneck Canyon, SE of Loyalton. However, this is unlikely since the lower Sierra Valley mixing endmember presents no evidence of evaporation, unlike the streams fed by Lake Davis and Frenchman Lake outflow. Therefore interbasin transfer from Stampede Reservoir is also unlikely.

The Zamboni hot spring located in Long Valley at the base of the eastern slope of Diamond Range was added to Chart 4-3. Since it also plots inside the Sierra Valley data range, it is not representative of a mixing end member.

Since the deep central valley floor waters are so much isotopically depleted (more than any other water collected in SV), the source area must be not only at a higher elevation, but also sought east of SV. The only area left and which could potentially meet these criteria is the high ground east of Sierra Valley which forms the separation from Long Valley, with the highest elevation of about 7100 ft. This recharge area has not been sampled because it has only very few springs which are difficult to access (private land).

Recommendation: In order to resolve this query we need to obtain isotope data from the SV/LV boundary area.

Similar queries have plagued researchers in the Great Basin, where for similar reasons geothermal water composition cannot be tied to an existing groundwater recharge area. One possible explanation proposed by Mariner (1983).is that these are waters recharged under colder climatic conditions.

Isotope composition and well location

The valley floor well (VFW) data contain a wide variety of groundwater chemical and isotope composition. Dependence of isotope composition on well location in the central and northern valley floor wells is examined in Chart 4-4. The central valley wells cover the area between the mouth of Antelope Valley and "The Buttes", excluding the northern valley floor. For the purpose of this study, the northern valley floor is the narrow east-to-west strip north of H70. The central valley floor wells (VFWs) are plotted as “open circles”, covering the entire range of the chart, under and subparallel to the GMWL. On the other hand the wells along the northern valley periphery (plotted as “open squares”) plot only in the upper right hand corner of the Chart 4-4. Clearly the isotope composition in these VFWs depends on location.

In Chart 4-5 the deeper wells are associated with more depleted deuterium (and O-18) values, indicating two groups of wells:

- Most of a group of shallow wells not deeper than 400 ft are located on the northern valley floor, though a few central valley floor wells are also in this group.
- A group of deep wells between 400 and 1,000 ft deep (or deeper?), with deuterium ranging between -125 and -115 per mil, a range distinctly different and smaller than in the shallow wells.

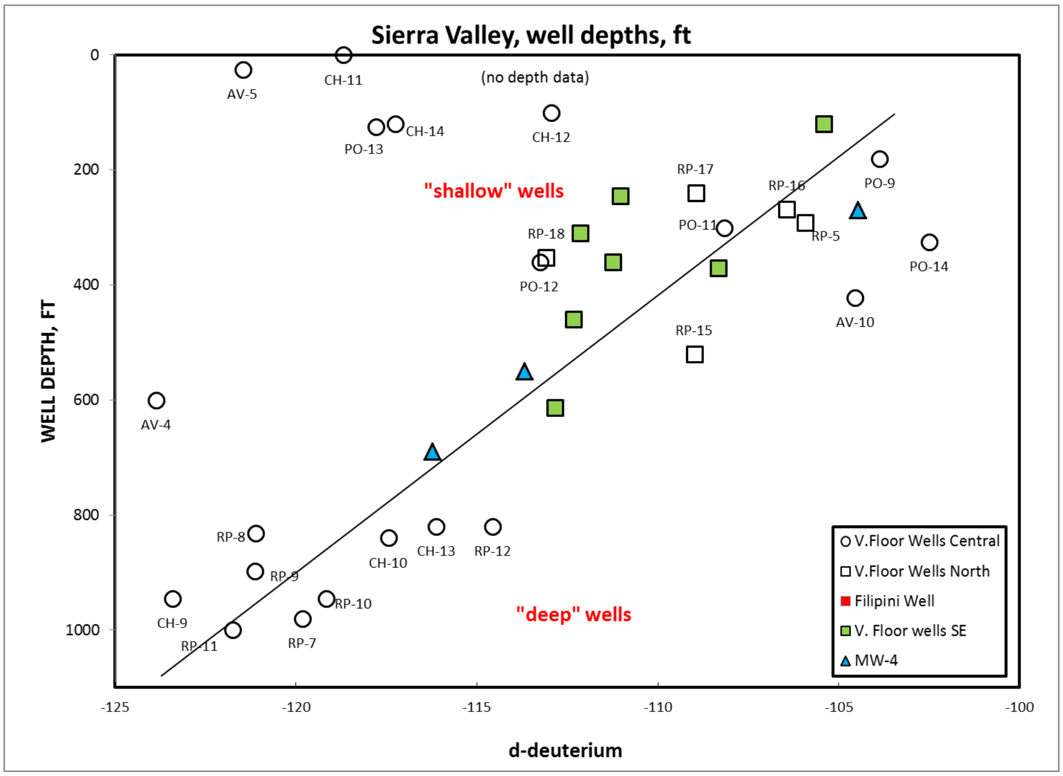


Chart 4-5 Well depth and deuterium, Sierra Valley

A similar pattern occurs in the eastern basin periphery, in a group of irrigation wells (only up to 613 ft deep) located north of Loyalton on an N-S line east of Dyson Lane. A similar pattern is also observed when plotting the three piezometers of MW-4, located closer to the western periphery (up to 700 ft deep). Unfortunately here data are available at only one location. The depth trend is indicated with a red line.

Similar can be made when plotting oxygen-18 with depth (not shown). The correlation between isotopes and depth is not perfect; probably because total depth (TD) is plotted instead some average of the screened interval depth. But the correlation is convincing and remarkable considering that most of these wells are located several miles apart (see map 1). Whereas the deep group of wells includes only wells (VFWs) on the central valley floor (VF), the shallow group of wells is from both central and northern VF areas, similar as in Chart 4-4.

This is an important observation, since it supports the conceptual model of groundwater flow systems in an alluvial basin as depicted in Chart 4-1. According to this concept the isotopically most depleted waters (recharged at the highest elevations and flowing the longest distance) are discharged in the deepest and central part of the basin.

In Chart 4-5 Well AV-4, a 600 ft deep residential well on the Filipini Ranch, stands out as an anomaly. Presumably it is affected by geothermal water migrating upwards along a fault zone, thereby acquiring a deuterium composition like the deep wells. The same applies to the shallow well AV-5. And a similar situation may apply to wells CH-11, CH-12, CH-14, and PO-12.

<u>Recommendation:</u> To present a more complete picture it would be helpful to obtain depth for, well CH-11 in Fig 2 (“DMS 64, Roberti Ranch”, now plotted with ‘zero depth).

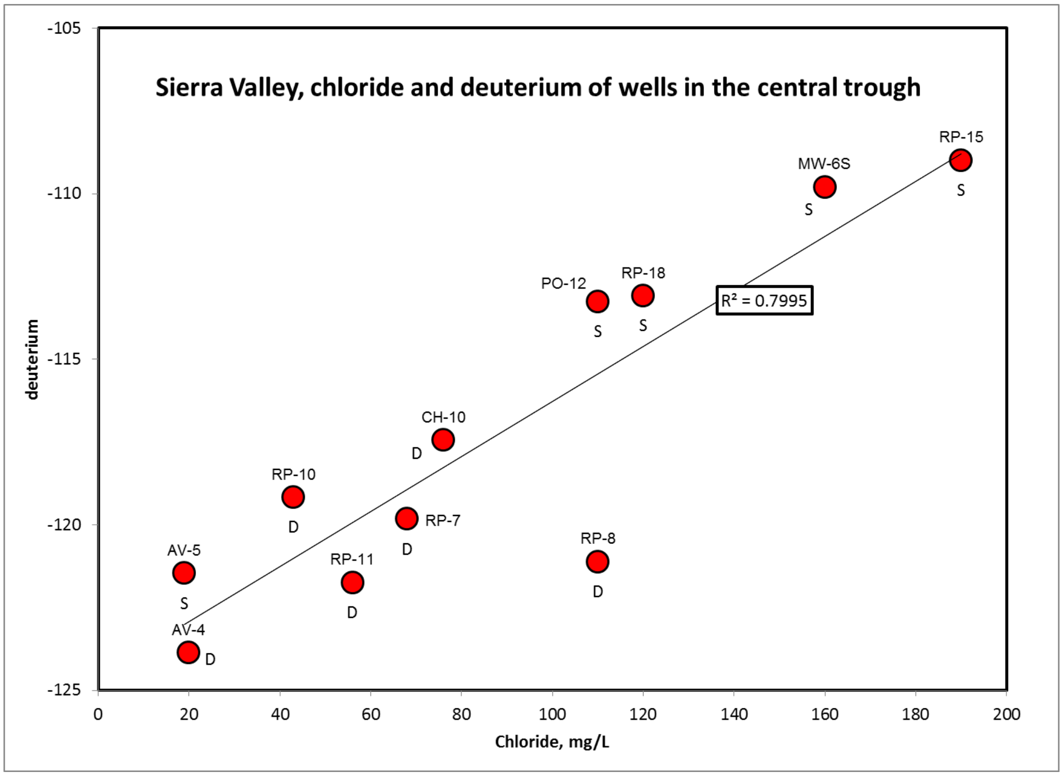


Chart 4-6 Chloride and deuterium in selected Sierra Valley wells.

<u>Central valley floor well characteristics</u>

Chloride levels in Sierra Valley groundwaters range between 0.1 and 200 mg/L. When cross-plotting deuterium and chloride only for wells with more than 5 mg/L chloride a reasonably well defined trend of increasing chloride with increasing deuterium is observed in Chart 4-6. A similar pattern occurs when plotting oxygen-18 against Cl (not shown).

The eleven wells which indicate this correlation are part of a conspicuous geographic pattern in the central part of SV, an area covering the central basin and in part overlying what is probably some of the deepest part of the SVB bedrock trough, referred to herein as the “central trench” (or simply “the trench”). This group includes both deep and shallow wells, with a wide range of chloride levels (5 to 200 mg/L). Similar observations are made by plotting oxygen-18 versus Cl and Cl/HCO3 and other ion ratios. For the sake of this discussion these wells are referred to as “type B” waters.

A second, though much more subtle trend includes only wells with Cl concentrations less than about 5 mg/L, with a poorly defined inverse correlation between deuterium and Cl. This group also includes deep and shallow wells which are typically located closer to the peripheral areas of the Basin. For the sake of this discussion these wells are referred to as “type A” waters.

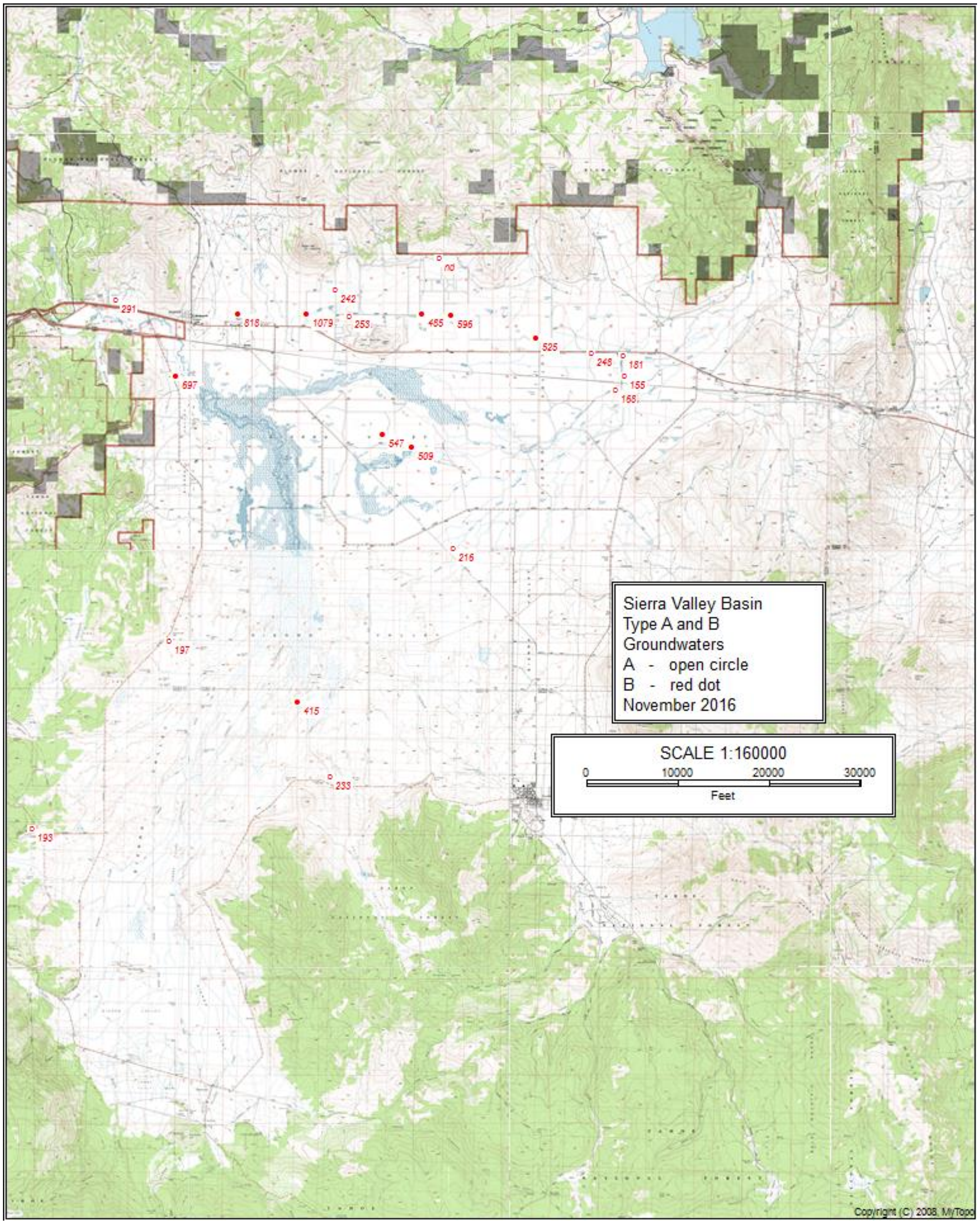
In other words, we are able to identify two distinct types of groundwater by specific chemical and isotopic characteristics. Following these characteristics will be further explored to help conceptualize basin hydrology.

The same types of well waters were plotted in Chart 4-7, comparing TDS and O18:

- The type A wells with lower TDS plot as a separate group in a narrow TDS range between 100 and 250 mg/L and a wide range of oxygen-18. It will be shown later in this report that most groundwaters in the SVB fit into the ‘A category’.
- The trench wells form a group (“B”) of their own with distinctly higher TDS levels ranging between 300 and 800 mg/L. The trend of increasing TDS with increasing oxygen-18 that is part of this group will be discussed later.
- Since on Chart 4-7 the two groups are distinctly separate entities, apparently waters A and B do not mix (at least based on these limited data).

The type B “trench wells” are indicated on Map 4-2, together with all sampled deep and shallow wells, labeled with their respective field EC values. Since type A and B waters are identified by their isotope signatures in Map 4-3 all available wells were plotted, and labeled with their EC values. Valley wide the EC values show interesting aerial patterns:

1. While EC in the centrally located type B wells ranges between 400 and 1300 uS/cm, a few of the type A wells with lower EC values (130 to 260 uS/cm) are located on a NE trending linear pattern, aligned along the NE striking Vinton-Calpine fault zone identified in the aquifer delineation section.
2. Type A waters also cover the area south of Green Gulch Ranch, and more such wells are expected to be found in Little Last Chance Creek Canyon NE of Vinton (‘Adams Neck’).



Map 4-2 Type A and Type B groundwaters, Sierra Valley. For explanations see text.

<u>Groundwater mixing in the central trench wells</u>

As mentioned above the dilute "A" waters apparently do not mix with the Central Trench "B" waters. It also should be noted that the two linear plotting patterns that each type adheres to in the isotope plot of Chart 4-8 are not in line when compared to the GMWL, thus indicating different source areas for the two well types. The “trench” wells (type B) plot in the lower left, and the type A wells (shallow and deep) plot in the upper right.

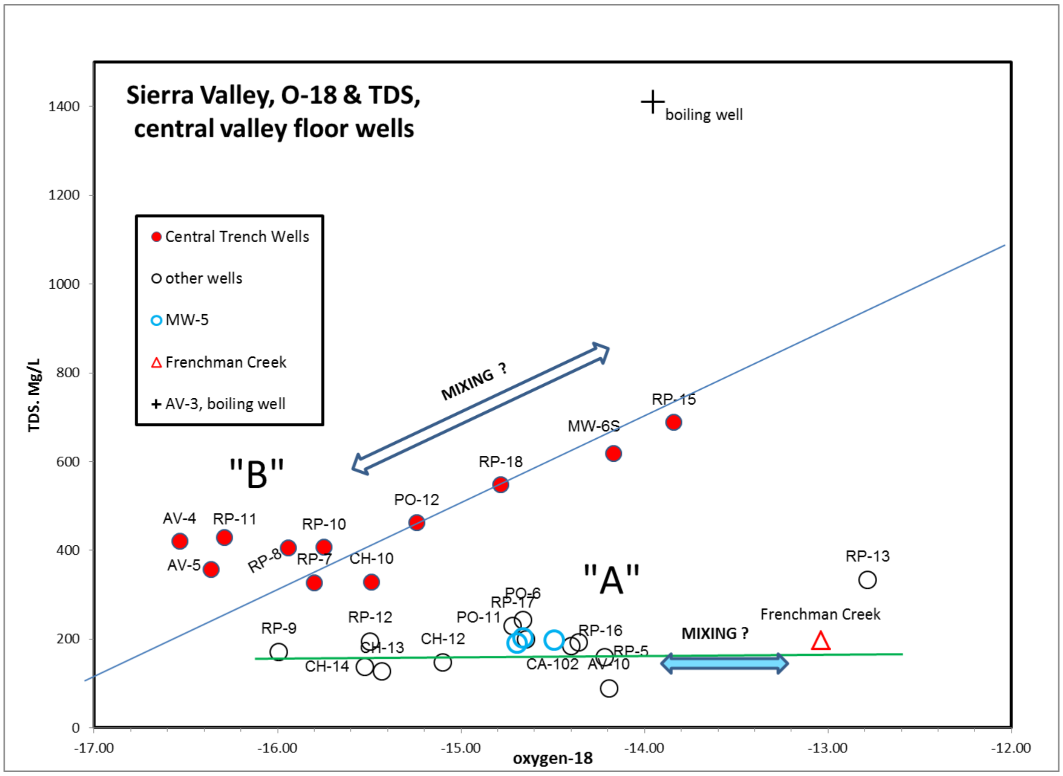


Chart 4-7 TDS and oxygen-18 in Sierra Valley wells.

On the other hand the apparent overlap between the two groups can be interpreted as indicative of mixing in some instances.

Recommendation: To further refine the patterns of mixing and non-mixing zones depicted above, sample more wells in this area.

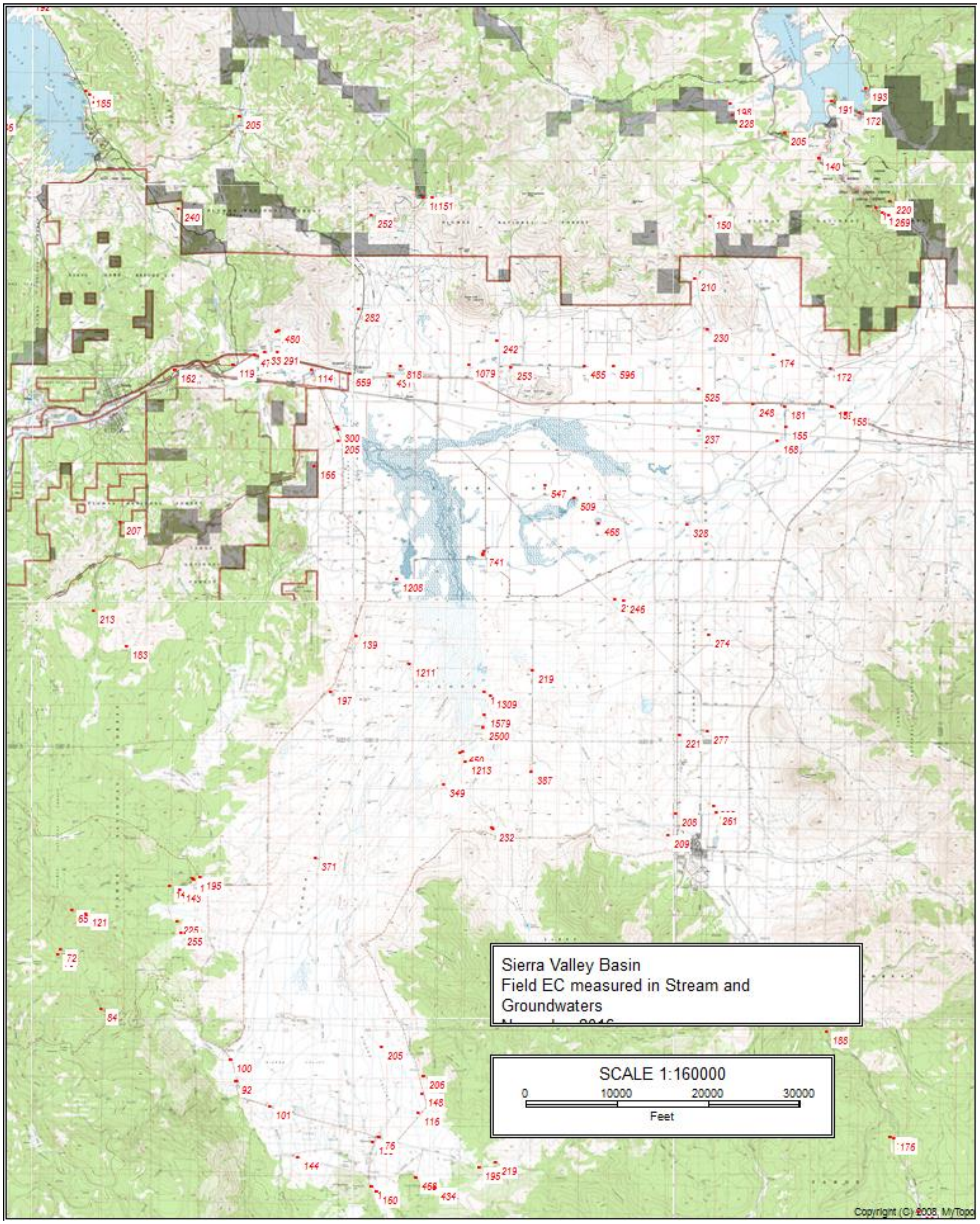
A few comments are worth sharing about the boiling well (AV-03) on the Filipini Ranch. This well which is reportedly 1200 ft deep, and plots outside the linear trends of either type A or B, for one of several reasons:

1. When sampling the boiling well may have been affected by an oxygen-18 shift to the right, which is a characteristic of geothermal waters.
2. The isotope composition was affected by steam separation and evaporation.

On the other hand its chemical composition with a TDS of 1410 mg/L (see Chart 4-7) compared to 400 and 357 mg/L in nearby wells AV-4 and 5 differs significantly from the other wells plotting in this corner, which indicates that the t type B waters are not geothermal waters, although most type B wells have had elevated temperatures during sample collection.

Indications of groundwater mixing in the central valley floor wells

In Chart 4-7 both groups show plotting patterns that can be interpreted as mixing, tempting one to conclude that a great deal of the variability in SVB groundwater chemistry can be



Map 4-3 Field EC values of Sierra Valley groundwaters. The data include also a few stream waters.

explained by mixing in the subsurface. Indications of mixing in the basin aquifers carry important implications as to how well the aquifer formations are hydraulically connected. This raises the question which source waters (end-members) are involved in Chart 4-7:

- The Group A plotting pattern can be explained by mixing between two end-members with similar TDS but unequal oxygen-18 (and D).
- The Group B plotting pattern can be explained by mixing between two end-members with unequal TDS and unequal oxygen-18 (and D).

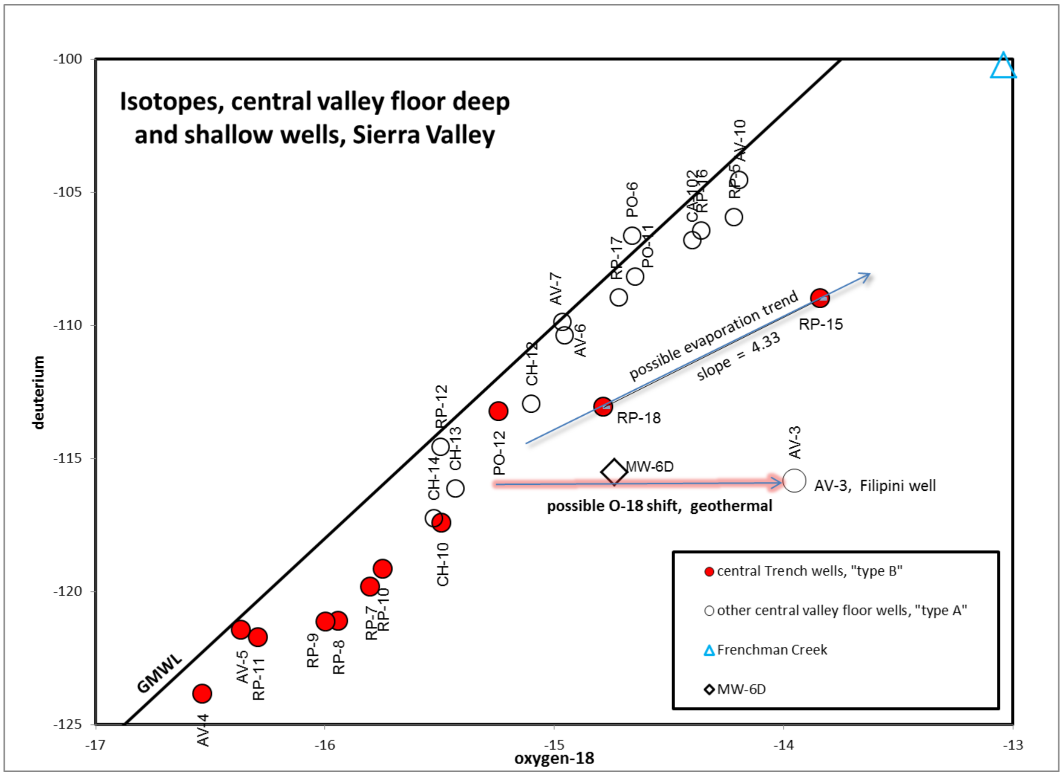


Chart 4-8 Oxygen-18 and deuterium in central valley floor wells.

Mixing among type A waters

A likely type A mixing endmember could be a groundwater source associated with the Frenchman Lake Sub-basin (recharged in the Dixie Mountain volcanic complex). A sample deemed as representative, collected in Frenchman Creek (FL-1, above the lake) is plotted in Chart 4-7. Mixing can be inferred in this group, assuming either Frenchman Creek representing groundwater flowing out of the Frenchman Basin along the Vinton-Calpine fault-zone. This is deemed a reasonable choice given the topographic and geologic setting.

Mixing among type B waters

The group B plotting pattern observed in Chart 4-7 is an anomaly in terms of a typical groundwater flow systems. Usually the higher TDS levels are associated with the smaller isotope values (more isotopically depleted), and vice versa. However, in this case the pattern is reversed, with the higher TDS end-member plotting in the upper right corner of Chart 4-7.

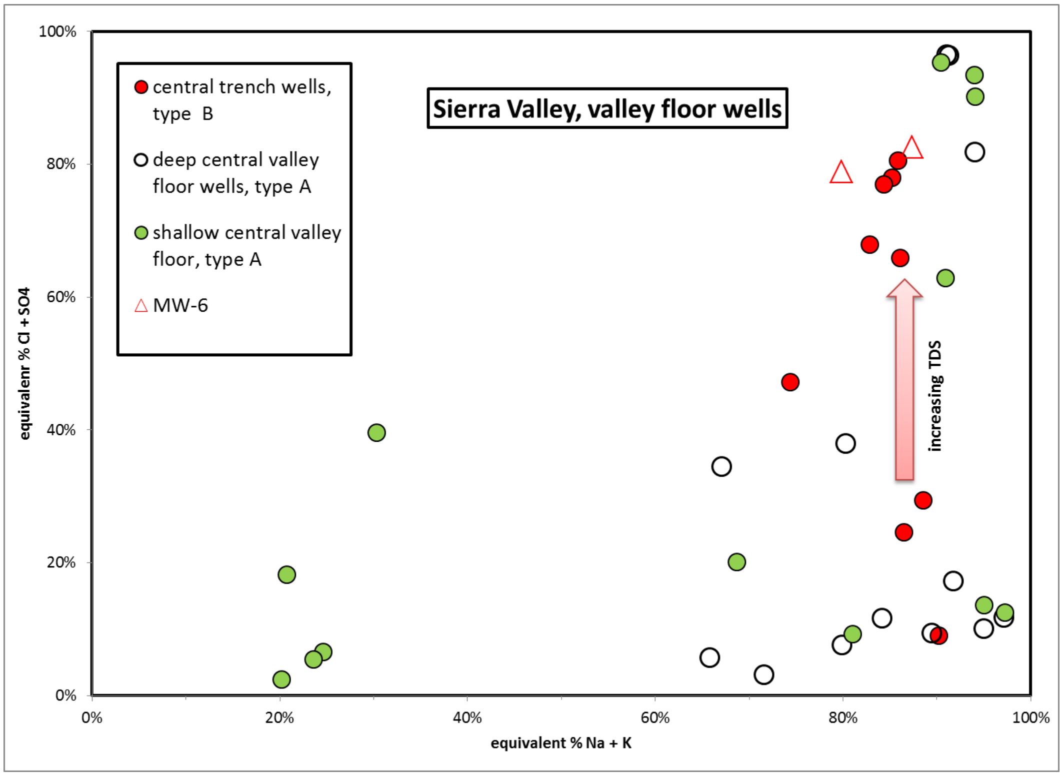


Chart 4-9 Cation and anion equivalent percentages, Sierra Valley

There are two parts in the group of type B waters plotted in Chart 4-7. Wells PO-12, RP-18, MW-6S, and RP-18 plot on a linear trend of increasing TDS with increasing oxygen-18. These wells are located north of HWY 70, near Beckworth, an area where high TDS waters would be least expected, given the close proximity to the northern uplands. If this is indeed a mixing trend, the inevitable question is: what is the source of this high TDS water in these wells? It is probably not geothermal since the temperatures in these wells are all less than 20^{o}C. The possibility of evaporation is explored in the next section.

On the other hand, as is typical, the temperatures are the highest in the isotopically most depleted waters.

Evaporation and irrigation return flow

The occurrence of high TDS water in two wells, RP-15 and RP-18, located near Beckworth is conspicuous. One possibility is irrigation return flow affecting the shallow aquifer. To prevent salinization of the soils, irrigation has to be sufficient to flush out salts which accumulate in the soils due to evapotranspiration. , Under favorable conditions the resulting irrigation return flow can be noticeable in the shallow aquifer chemistry and isotope data.

However, in only two wells, RP-15 and RP-18, the plotting position can be interpreted as an evaporation trend (see Chart 4-8). This would imply the possibility of a gradual increase of shallow aquifer TDS in this area.

Recommendation: Given the management implications, a better understanding of this potential TDS trend is warranted.

Summary of central and northern valley floor well chemistry

As summarized in Chart 4-9 the groundwater chemistry under the central and northern valley floor is highly variable, in part the result of subsurface mixing between two high TDS waters (type B) of predominantly deep origin and the inflow of a low TDS water (type A) from the Northeast, possibly originating in the Frenchman Lake Basin (recharged on Dixie Mountain). For so far unknown reasons these two types apparently do not mix, possibly indicating a physical barrier between central trench "type B" groundwater and "type A" groundwater flowing SW in the Vinton-Calpine fault zone. The chemical characteristics of the two types featured in Chart 4-9 are:

- Shallow Type A waters (green dots) probably recharged along the basin periphery, evolving from dilute calcium-bicarbonate waters into sodium-bicarbonate and then sodium-chloride-sulfate waters, with TDS less than 300 mg/l.
- Type B waters the source of which so far is not known, evolving from sodium-bicarbonate to sodium-chloride-sulfate waters. TDS ranges from about 300 mg/L to more than 700 mg/L. The wide TDS range is attributed to mixing with high TDS water exemplified by two wells near Beckwourth (RP-15 and RP-18).

Geothermal effects on groundwater chemistry

As in the other groundwater basins in NE California elevated groundwater temperatures are typical in most valley floor wells (VFWs), indicating high heat flow. This has led to at least two geothermal exploration efforts in Sierra Valley:

- Under a State grant Sierra County drilled five geothermal gradient holes and two test wells in southern Sierra Valley in 1988 (Geothermex 1989; HLA, 1989). The gradient hole locations are indicated on Map 3-1.
- A deep geothermal exploration hole was drilled by Philips Petroleum, Inc. in December 1973, reportedly to a depth of more than 2000 ft.

Unfortunately, except for one exploration well ("SCGP-1", Map 3-1) located north of HWY 49 about 4 miles west of Loyalton), no water chemistry and isotope data are available from these efforts. In spite of the elevated temperatures, none of the groundwater sampled in Sierra Valley show the oxygen-18 shift that is so characteristic of geothermal waters. In other words under the prevailing temperatures and subsurface residence times none of the Sierra Valley groundwater's subsurface residence time was long enough to permit oxygen-18 exchange between groundwater and aquifer rock material to shift the oxygen-18 composition to the right from the GMWL. Even the waters sampled at Campbell Hot Springs east of Sierraville do not show an oxygen-18-shift.

The one exception among all waters sampled in Sierra Valley is the boiling well (AV-3) on the Filipini Ranch, which was reportedly drilled in the early 1900s to 1200 ft). In Chart 4-8 this well plots outside and to the right of the linear isotope trend of the trench wells for one of several reasons:

1. It may have been affected by an O-18 shift away from the GMWL, characteristic of geothermal waters.
2. The isotope composition has been affected by steam separation and evaporation during sample collection. If that is so its actual isotope composition would be on the trend of trench wells, below and left of AV-4.

Given its chemical composition with a TDS of 1410 mg/L compared to the TDS-trend of the trench wells (type B) in Chart 4-7 it differs significantly from the other wells plotting in this corner. Therefore it's plotting position in Chart 4-8 is probably due to an oxygen-18 shift.

Stream waters of northern Sierra Valley

Stream water flows out of Sierra Valley as the MFFR through Rocky Point Canyon about 1.5 miles NE of Portola. Within a short distance upstream of Rocky Point, Little Last Chance Creek (LLCC), Big Grizzly Creek (BGC), and whatever surface water flows from southern Sierra Valley merge to add up to the flow of the MFFR.

Since both BGC and LLCC are fed by outflow from Lake Davis and Frenchman Lake, respectively, the isotope signal of water released from these two reservoirs is very much affected by evaporation. This effect is evident in Chart 4-10 , where LLCC and BGC plot on an evaporation slope of 4.6, deviating from the 8.0-slope of the GMWL.

In a typical water-year the flow out of the LLCC branch of the MFFR ends after mid-summer, and water flowing past the USGS gauge (PO-4) is made entirely of Lake Davis discharge from BGC (evident in the isotope data). On the other hand in the winter months MFFR water flowing past the HWY A-23 Bridge does not indicate the evaporation signal coming from LLCC, perhaps because it receives only stream and groundwater from the wetlands S and SE of Beckwourth, which in turn is fed by stream water from southern Sierra Valley (Cold Creek and others).

Since the evaporation signal in LLCC water is not showing in the isotope signal of wells pumping nearby, the aquifers in this area are apparently not recharged by channel infiltration from LLCC (although hyporheic exchange between channel and the very shallow unconfined aquifer is still a possibility. This will be further examined later in this report.

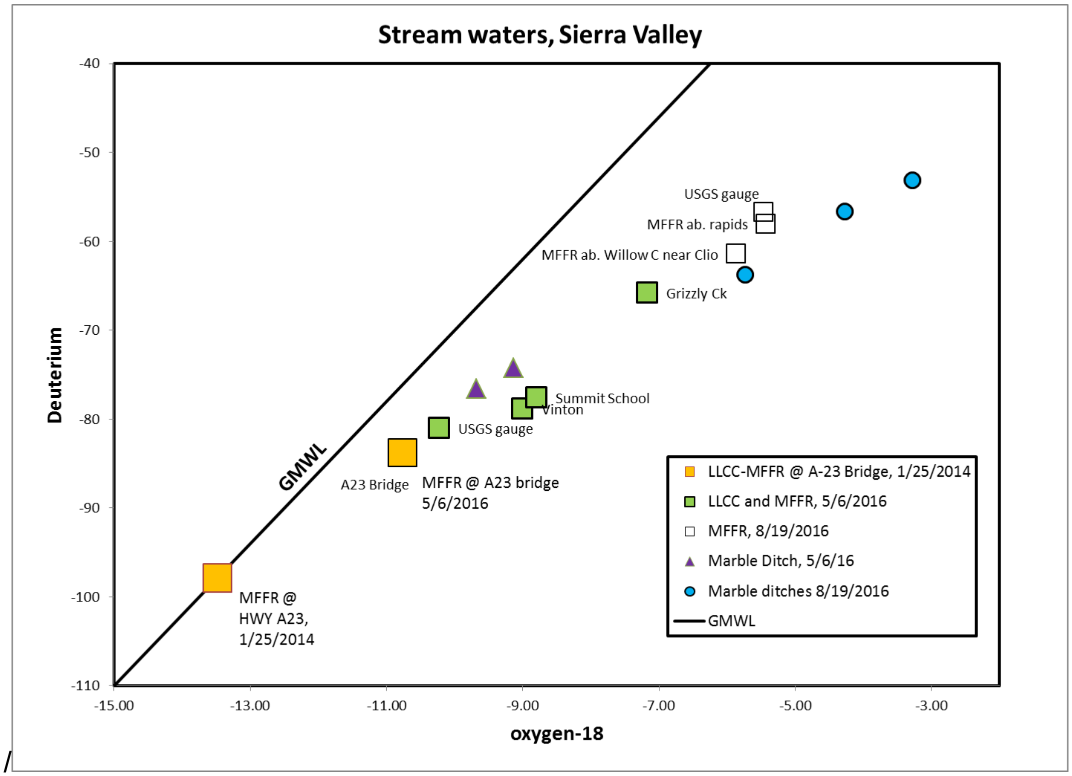


Chart 4-10 Stable light isotopes in northern Sierra Valley stream waters.

Streams and groundwater recharge in southern Sierra Valley

Streamflow

Several streams enter the basin in southern SV, the most prominent of which are Turner, Berry, Hamlin, Lemmon, and Cold Creek. Among all these groundwater and streams inflow from the Cold Creek watershed most profoundly affects the hydrology of southern SV. Isotope data from these streams are plotted in Chart 4-11. Also included are data from Smithneck Creek and several springs sampled in Smithneck Canyon and Sardine Valley. Furthermore several high elevation springs and streams from the area near Yuba Pass are plotted (open triangles).

It is striking that in Chart 4-11 these data are aligned in the same sequence as in their geographical distribution, from SW to NE – approximately. As is to be expected the isotope signals in these areas are affected by the rain-out effect and site-specific recharge conditions (elevation, temperature, and precipitation history as the storms migrate from SW to NE).

Cold Creek was sampled at several elevations, from its origin in Onion Valley below Little Truckee Pass to Sierraville, with isotope data plotting over a wide range due to the elevation effect (between 4950 and 6485 ft ab. msl). The isotopically most depleted stream waters were sampled at the highest elevations. In other words isotope composition in this stream correlates inversely with elevation. Similar observations were made in Smithneck Creek and the streams draining from the Yuba Pass area.

The close cluster of the Yuba Pass waters with Turner, Berry, and Hamlin Creek comes as no surprise given the source areas of each of these streams.

Most prominently plot the data from the two PUD springs used as a water-supply by the Sierraville community (red squares), representative of an average composition of groundwater discharging as baseflow into Cold Creek in lower channel reach. The source of this groundwater is the glacial moraine formation that constitutes the north facing slopes south of Sierraville.

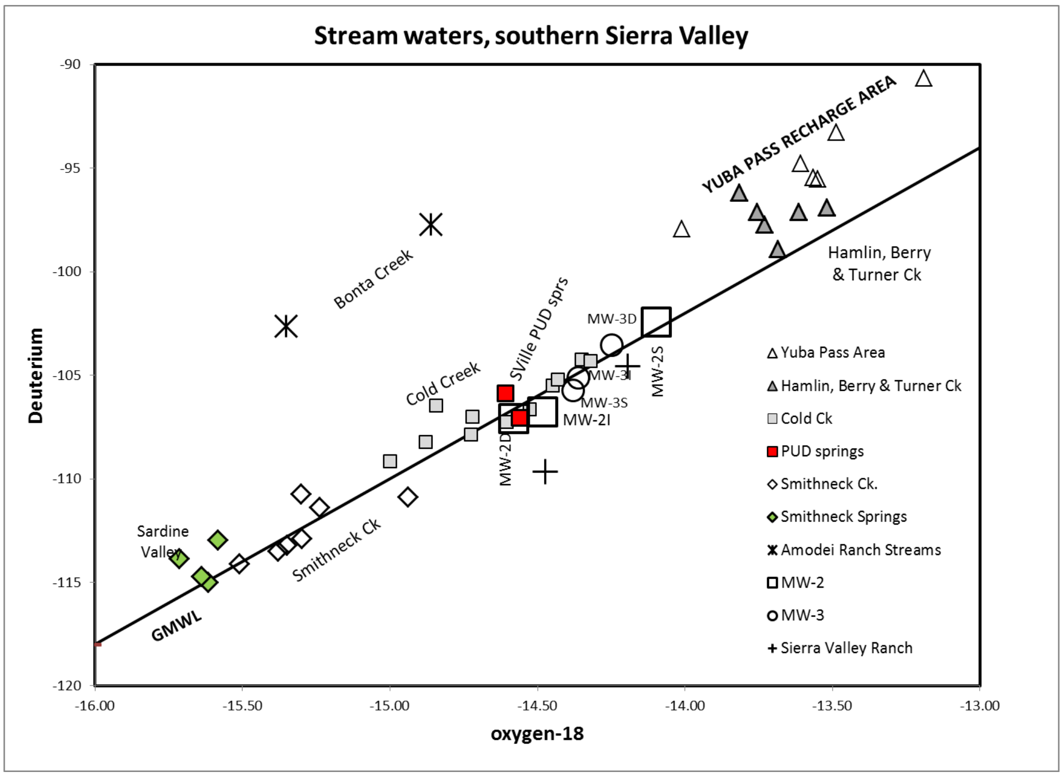


Chart 4-11 isotopes in southern Sierra Valley stream and groundwaters

Groundwater recharge

Apparently the southern Sierra Valley basin aquifer is recharged not only by stream water but also (probably mostly) by subsurface flow from the moraine deposits to the south, assuming the isotope composition of the two PUD springs is representative of groundwater flowing out of the uplands to the south. In support of this hypothesis, the composition of the deeper waters from nested piezometer MW-2 (2I and 2D) almost perfectly matches the PUD spring water composition.

Several further observations made in Chart 4-11 also point to the origins of groundwater in southern SV. The shallow samples from nested piezometers MW-2S (about 1 mile

NW of Sierraville) and MW-3 (about 2.5 miles north of Sattley) are shifted closer to the low elevation samples from Cold Creek, and even further towards the stream water composition of Hamlin, Turner and Berry Creek. This suggests that groundwater in the lacustrine aquifer formations south of Calpine and around Sattley and Sierraville are recharged not only by stream and groundwater entering the Basin from the south but also increasingly from the uplands to the west, with increasing distance to the north.

However, the shallow water composition in MW-2S (screened 85 – 100 ft bel. TOC) can also be interpreted as the effect of shallow recharge by water imported from the Little Truckee River (see next section). On the other hand the deep water sampled in MW-3 (screened 340 – 355 ft bel. TOC) is also shifted closer to the Yuba pass data, indicating that the lacustrine aquifer north of Sattley receives inflow from the uplands to the west.

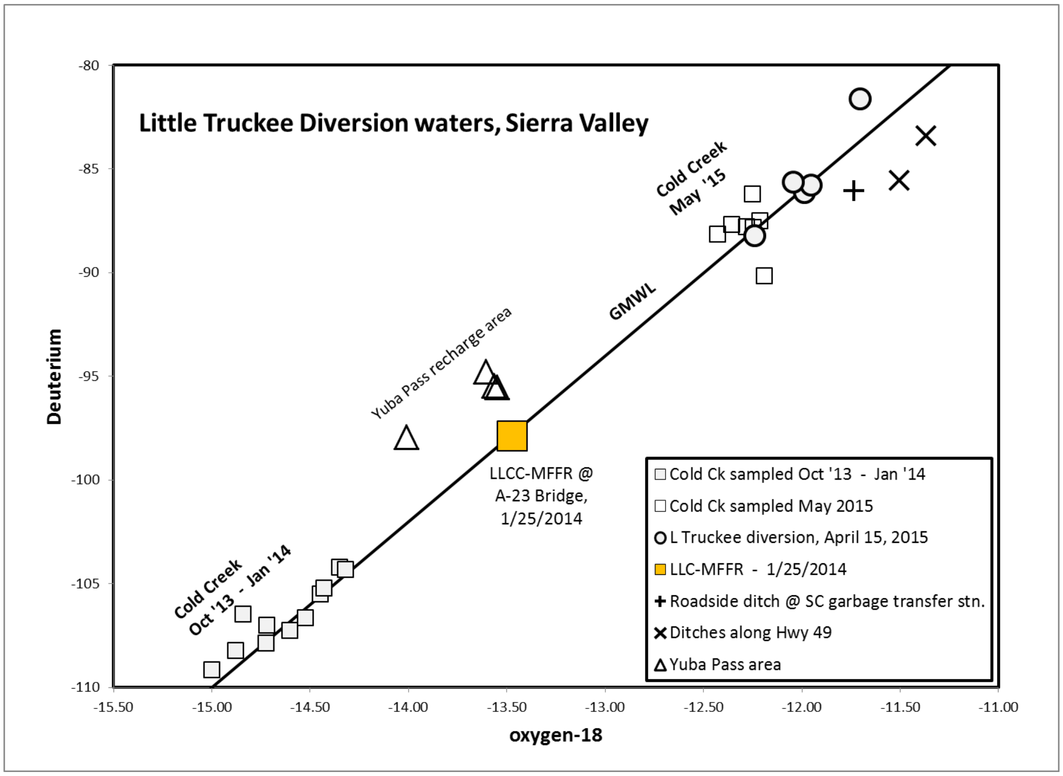


Chart 4-12 Effects of the Little Truckee River Diversion on southern Sierra Valley stream waters.

The Little Truckee River Diversion

The Little Truckee River Canal reportedly diverts about 6,000 ac-ft water annually into southern SV. This is a significant addition to the basin water balance and ought to be noticeable in the tracer data.

Isotope data from Cold Creek (squares) and the Little Truckee River (open circles) are plotted in Chart 4-12. The Little Truckee River flows out of Webber Lake, located several miles SW of the Sierra Valley watershed, at more than 8770 ft elevation. Its isotope signal differs significantly from any other waters in SV. Indeed the Cold Creek samples collected in May 2015 plot next to the Little Truckee River and the diversion canal waters. The difference between the late spring and late summer or fall Cold Creek data is significant enough to detect diversion water as far as it is distributed north of Sierraville. Using this rationale, LTR water was identified in conveyance ditches along HWY 89 (more than 2.5 miles north of Sattley) and HWY 49 (more than 2 miles north of Sierraville.

Diversion water apparently also recharges shallow groundwater as indicated in the preceding section's discussion. Probably the Little Truckee diversion at certain times of the year significantly impacts southern Sierra Valley hydrology. In the months of May through June southern Sierra Valley is in many areas like a 'swamp', with so many irrigation channels presumably used for pasture irrigation.

The isotope composition of the MFFR at the highway A-23 Bridge was included in Chart 4-12 (compare also with Chart 4-10). Since it plots next to recharge from the Yuba Pass area (and about midway between Cold Creek and Little Truckee Diversion water), presumably during the winter and spring months surface water discharge from southern Sierra Valley flows all the way north to discharge into the MFFR (which probably occurred year-round under pre-development, or natural conditions).

Recharge areas – a preliminary assessment

Isotopic provenances and recharge areas

All upland waters were plotted in Chart 4-13, and the following observations are made:

1. The upland isotope data occupy certain provenances, some of which plot as elongated groups and arranged roughly parallel to the GMWL:
2. The southern recharge areas, listed from west to east are the Yuba Pass area, the Cold Creek area, and the Sardine Peak area.
3. In the north and northwest are Crocker Mountain and Grizzly Valley (Lake Davis). Dixie Mountain, Diamond Range and the Chilcoot sub-basin.
4. The Frenchman Sub-basin receives groundwater flow from Dixie Mountain, since these two areas plot practically as one group.
5. Very little data is at this stage available from the western uplands, and no data are available from the uplands to the east.

It is remarkable that each of the recharge areas identified in Chapter 2 by means of topography, geographic location and geologic substratum is represented by distinct isotope data provenances in Chart 4-13. The alignment of the three southern recharge areas is probably determined by the migration path of the prevailing winter storms indicating the rain-out effect that leads to gradual isotopical depletion of atmospheric moisture as it travels from west to east.

In other words, isotope plotting patterns in the upland waters are an indication of precipitation patterns that are controlled by topography (orographic effect). The unmistakable indication of the rain-out effect hints that waters (samples) originating from the same recharge area can be expected to plot in the same elongated plotting pattern. An example is the group of stream waters associated with the Yuba Pass area.

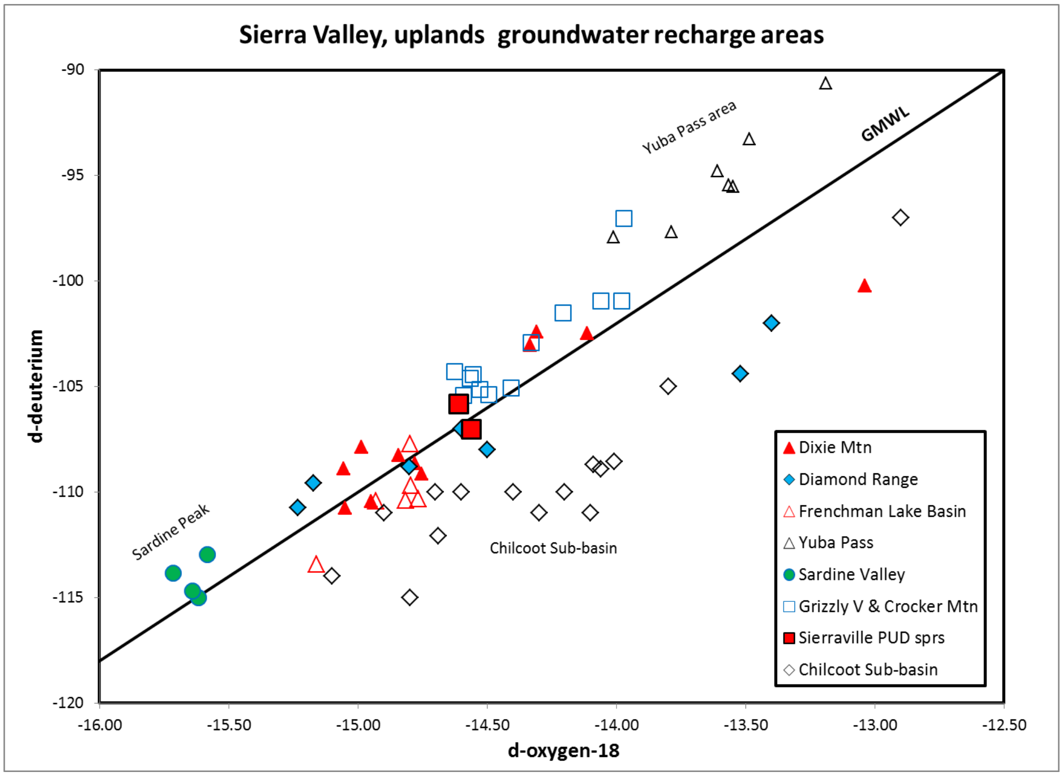


Chart 4-13 Isotope provenances in Sierra Valley upland recharge waters.

The approach to determine which recharge area contributes groundwater recharge to which region in the Sierra Valley Basin can be by comparing associations on the standard isotope plots. The underlying assumption is that the isotope signal of the uplands springs is representative of the recharge that eventually emerges in the basin. The dilemma is that most of the upland spring waters have probably been recharged at a slightly lower elevation than the water that has migrated deepest and far enough to discharge into the basin.

The separation of the Dixie Mountain data into two separate clusters is due to the geographic locations of the sample points. The left group is located on the northern slope of the Dixie Mountain complex, including a number of springs discharging north into Ramelli Creek. The second cluster is from a number of springs on the east slope (see Map 4-1).

The elongated plotting pattern of the groundwaters sampled in the Chilcoot Basin (including a few data points from the far northern sub-basin, part of the Diamond Range) seems to be an indication of how localized recharge mixes into the shallow aquifer water which has been recharged at higher elevations. The physical process that leads to this effect is indicated in the schematic cross-section of a typical groundwater flow system in Chart 4-1, and has been observed elsewhere in the MFFR Basin (for example in Mohawk Valley). A complete analysis of these elongated isotope plotting patterns exceeds the resources available for this project. In other words the following discussion of the isotope hydrology in the recharge areas is incomplete, and must be accepted only as preliminary.

Recommendation: Complete the interpretation of isotope data collected in recharge areas and tie them into the isotope data collected from the valley floor wells.

Recharge in the N and NW basin periphery

The northern valley floor wells north and east of Beckwourth are recharged by a source similar `to the Dota Saddle springs (Chart 4-14). But the northwestern VFWs sampled on the south facing slope north of Ross Meadow (PO-6, PO-10.1) and the Caltrans rest-area well (PO-7) may be affected by recharge from the Lake Davis uplands (compare Chart 4-14).

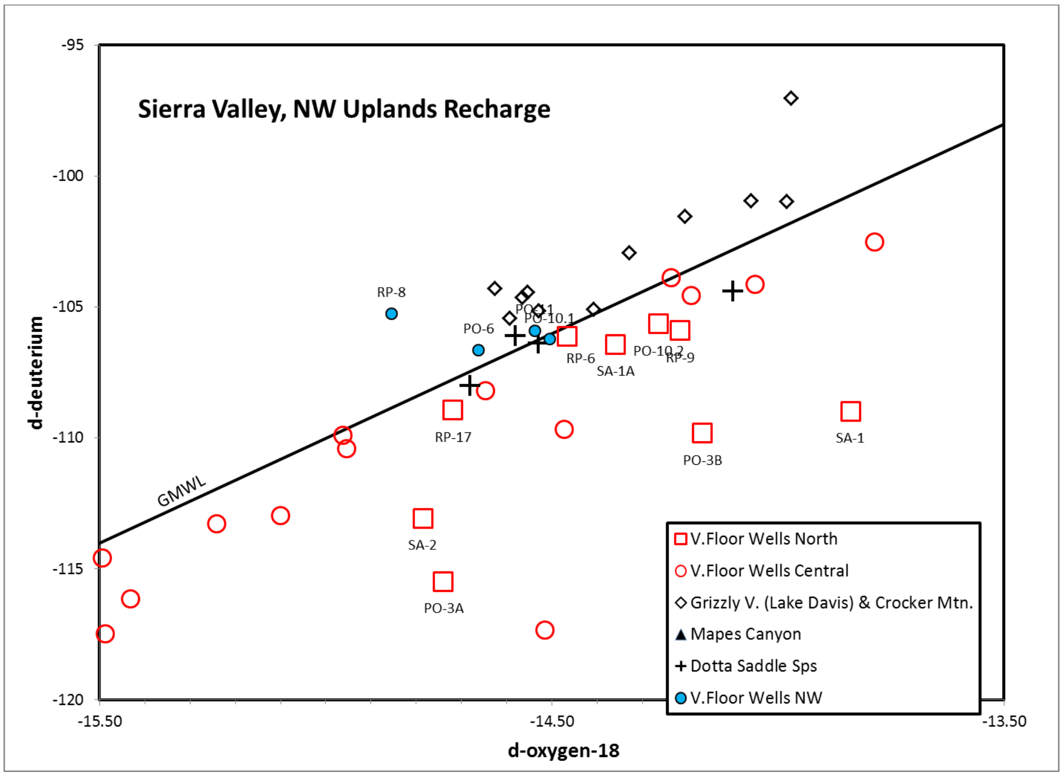


Chart 4-14 Isotopes in NW Sierra Valley well and spring waters.

The sampling points in question are located in the western part of a small south-facing sub-watershed (compare Map 4-1). Based on drilling records and aerial photo mapping the local groundwater hydrology is dominated by two faults, one striking NE and one striking NNW (Bohm, 1992). A huge spring at the intersection of these two faults indicates enhanced groundwater flow associated with these faults. Unfortunately no isotope data are available from this spring (dry due to drought).

One argument raised against the Hot Springs fault as a significant groundwater flow conduit, is that it is a strike-slip and dip-slip fault, whereas typically the most favorable bedrock well drilling sites are near the intersection of NNW and NE striking faults.

Chart 4-15 shows again the Dota Saddle springs (black "+"), plotting in a linear group with Dixie Mountain waters (red triangles), and northern VFWs (red squares). This can be interpreted as an indication that source of the northern VFWs and the Dota Saddle springs is associated with the Dixie Mountain complex.

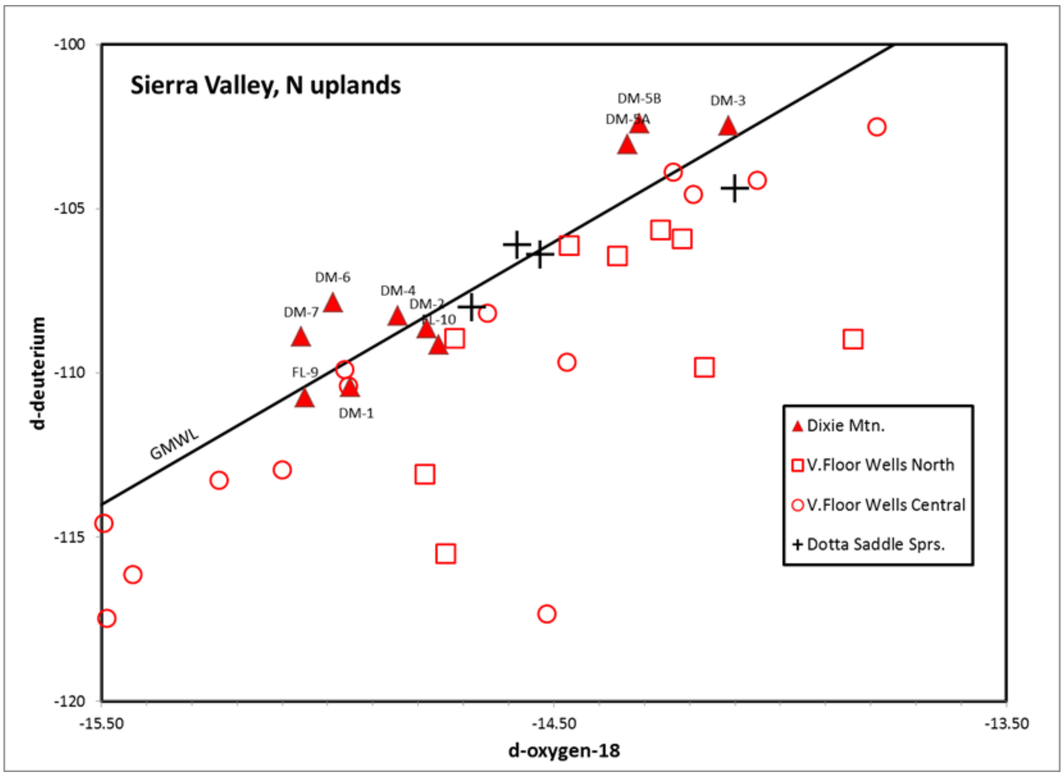


Chart 4-15 Isotopes in northern Sierra Valley upland waters (Dixie Mountain region).

Recharge in the NE periphery

The isotope plot in Chart 4-16 provides an overview of the central VFWs, Dixie Mountain, and the Chilcoot Sub-basin. The northern VFWs plot in a linear pattern in line with about the type A central VFWs, indicating that at least that group of VFWs originates from the north. The linear pattern of the 'trench" wells (less than -15 per mil oxygen-18), is offset such that it is aligned more with the Chilcoot Sub-basin groundwaters. Whether this means that the deep central trench waters (Type B) are mixing with water entering the Basin from the NE and/or the Chilcoot Sub-basin remains to be determined.

Recommendation: Conduct further sampling to characterize mixing dynamics in the trench and adjacent areas.

Discussion and Conclusions

The preceding interpretation of groundwater flow based on groundwater chemistry and isotope data is by no means complete. Due to time constraints it is not possible to complete this analysis which should be completed given the information content of these tracer data.

Comparing the Sierra Valley groundwater chemistry with the topography leads to a few interesting observations which may have implications for future groundwater flow characterization and further developing the hydrologic balance for the SVB.

While the lowest EC values (equivalent to TDS) are observed in the wells near Sierraville and Calpine, the highest EC values in wells occur at a point in the valley with the lowest elevation. This point is located in the region where the Hot Springs fault intersects the Vinton-Calpine fault zone.

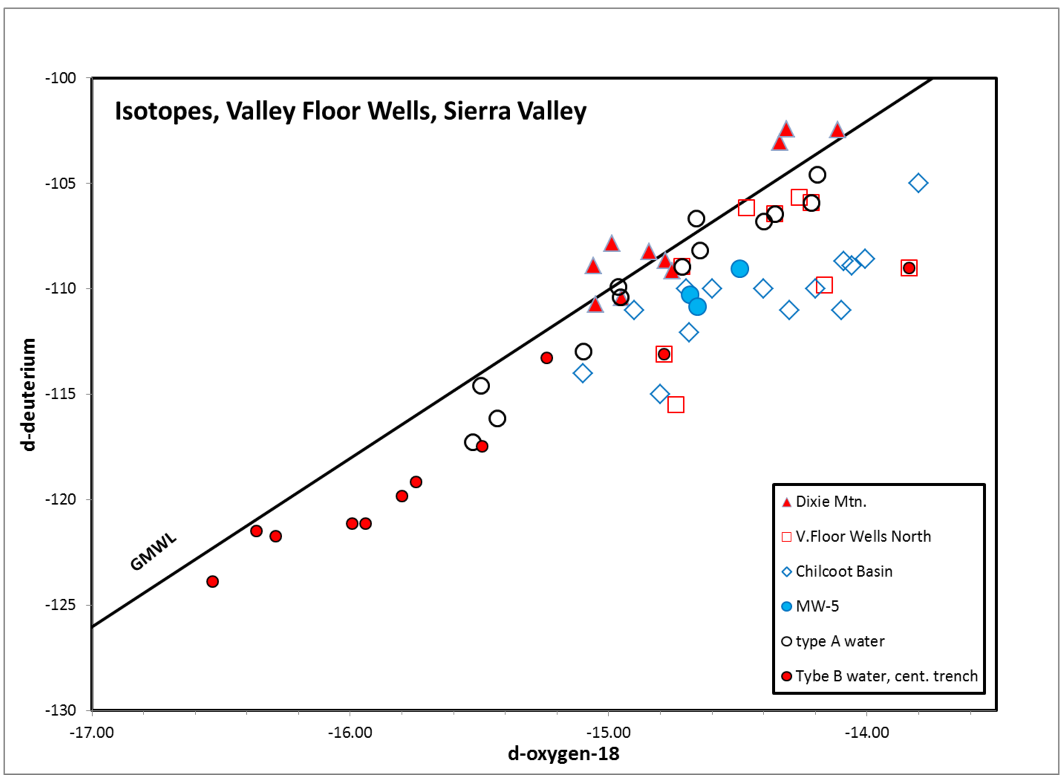


Chart 4-16 Isotopes in NE Sierra Valley aquifers and relations to central valley floor groundwaters.

In the interim, the preceding discussion permits the following initial conclusions and recommendations:

1. To ease the interpretation of uplands isotope data, it should be preceded by interpretation of the valley floor data, and a better understanding of the basin hydrogeochemistry.
2. The comparison between northern and central valley floor waters indicates that the aquifers on the northern valley periphery are generally recharged by groundwater migrating from the northern uplands.
3. The central valley aquifers are a blend of groundwater recharged in the surrounding uplands and water migrating from great depth**.**
4. Elevated groundwater temperatures are prevailing in wells throughout the central and northern valley. Truly geothermal waters, however, are rare and were found in only one well in the central valley, suggesting that the geothermal resource is deeper than the deepest irrigation wells and isolated by a low permeability barrier.
5. The fraction of geothermal water contained in the central valley aquifer portion can at this point not be estimated. However given the overall abundance of high quality low TDS groundwater, the fraction of geothermal water is probably small.

Further Recommendations:

1. Determine spring density, by counting the number of springs per area (i.e. area of rock formation on the geologic map or by sub watershed area), in order to help identify the most 'productive' groundwater recharge areas.
2. Classify the Sierra Valley Basin well waters by chemistry and isotope composition, tied into the 3-dimenional framework of the basin, which will require linking each chemical/isotopic data set to its corresponding well driller's log. To accomplish this task it will require release of crucial well data from State agencies and well owners.

5. The Sierra Valley Water Balance

Introduction

The water balance is an important means to help cross-check the validity of our conceptual models of the SVB. Under natural conditions the water balance can be conceptualized with the following equation:

Outflow = inflow + precipitation - evaporation - transpiration

The last two terms are lumped into a single term “evapotranspiration” or simply ET. Then the equation becomes:

Outflow = inflow + precipitation - ET

The Sierra Valley groundwater basin has only one outflow, but several sources of inflow. The outflow for Sierra Valley is the MFFR through the canyon at Rocky Point.

Since Sierra Valley has no streamflow entering from outside the watershed, the only way that water is added is by precipitation minus evapotranspiration. Whatever precipitation water is left after ET is available for groundwater recharge. Depending on the geologic setting a certain portion of recharge discharges into stream channels. Groundwater discharging after short time periods is called “interflow”, whereas groundwater that has migrated deeper and farther before discharging into a channel becomes “runoff”.

Most precipitation occurs in uplands at elevations between 6000 and 8500 ft, much higher than the Basin floor at about 5000 ft. since precipitation increases with increasing elevation the uplands receive much more moisture than the valley floor. This difference is exacerbated by the inverse correlation between ET and elevation.

Therefore the water balance equation for Sierra Valley becomes upland groundwater recharge which is the amount of precipitation left after ET. In other words

recharge = precipitation - ET.

Precipitation and ET vary by location, elevation and the kind of geologic formation underlying the landforms.

Uplands groundwater recharge percolates into the underlying fractured bedrock, and depending on geologic conditions one of two situations can occur:

1. If the bedrock is well fractured to great depth, recharge ends up discharging into the basin trough, hidden in the subsurface, as “mountain-block recharge” (MBR).

2. If the bedrock is comparatively poorly fractured and/or only to moderate depth, then a portion or all of the high elevation groundwater will emerge in an upland stream channel, and eventually flow past the uplands mountain front into the valley, to percolate into the basin's alluvial deposits, recharging the shallow aquifer as "mountain-front recharge" (MFR).

In other words uplands groundwater recharge will either end up as deep percolation in the deep bedrock formations that constitute the Sierra Valley bedrock trough or it will emerge as uplands streamflow to recharge the shallow aquifer in the basin periphery. However, all modes of groundwater recharge will eventually end up as streamflow on the valley floor or will be returned to the atmosphere as ET, or will leave the Basin as groundwater flow.

This conceptual distinction is important in the water balance calculations, since recharge is the sum-total of Mountain Block Recharge (MBR) and Mountain Front Recharge (MFR). Therefore estimating "inflow" into Sierra Valley by measuring streamflow (MFR) will be at best a minimum estimate since it does not include the MBR component.

Sierra Valley Waterbudget				1 = good	
at USGS gauging station, Rocky Point				2 = poor	
			3 = uncertain		
			4 = use substitute data		
		data sources	**data available?**	**data quality**	**Comments**
INFLOW					
natural recharge, precipitation					
	valley floor	CDEC	yes	1	
	uplands	none	4	3	minimum values, estimated from valley floor data
groundwater inflow, MBR		none			probably no GW inflow
canal diversions					
	L. Truckee Div.	SVGMD, DWR	yes	1	
streamflow					
	L. Grizzly Ck., Lake Davis	CDEC	yes	1	LGC flow is not part of the SV water balance
	MFR				but is measured due to the location of the gauge
	Little Truckee River diversion	CDEC			
irrigation return flow		literature			
OUTFLOW					
surface water outflow					
	MFFR at Rocky Point	CDEC, DWR	yes	1	
groundwater outflow to Mohawk Valley		none	no	4	may be able to estimate w/env. Tracer data
evapotranspiration, ET					
	croplands	literature			
	net lake and stream surface evaporation	literature			
	wetlands	literature			
	native drylands vegetation	literature			
pumping					
	irrigation	SVGMD			under current law these data are proprietory
	residential, indiv. wells	DWR well logs			can be estimated
	consumptive, community wells	City of Loyalton			data can be obtained from City of Loyalton

The components of the water balance

The outflow at Rocky Point is determined by the sum total of recharge that eventually emerged on the valley floor as streamflow, minus ET. ET constitutes all processes whereby water is diverted or consumed from valley floor streamflow. This includes both natural and man-made processes. A listing of these processes is given in the table below.

A substantial number of the water balance components cannot be supported by data. Therefore at best, this table provides an overview of the data gaps. However, most of the inflow components can be lumped into the term “groundwater recharge”. Unfortunately, measuring groundwater recharge is one of the most challenging subject matters in groundwater hydrology. However, there are several methods that can yield at least certain ranges of groundwater recharge volumes for specific upland areas.

Recharge areas

Instead of preparing one bulk recharge estimate for the valley it is better to partition the valley into specific groundwater recharge areas, each according to geographic location, topography, elevation range and geology. Applying these criteria the following recharge areas have been identified:

A. Dixie Mountain recharge center.

B. Crocker Mountain

C. Beckworth Peak (Carman Valley).

D. Yuba Pass area.

E. Truckee Summit area, H89 (Cold Creek etc.).

F. Sardine Peak recharge center

G. Antelope Valley watershed.

H. Mount Ina Coolbrith recharge center.

I. Diamond Mountains recharge center.

J. Chilcoot sub-basin.

The total valley wide average annual recharge estimate can be made adding up each of these areas’ recharge estimates.

Methods to prepare preliminary recharge estimates

Preliminary recharge estimates can be made with the following methods:

1. Hydrologic balance discharge method
2. Chloride mass balance method
3. Refined Maxey-Eakin method

These methods have been applied to the Chilcoot Sub-basin in a preliminary study, and the results have been surprisingly consistent when subjected to a sensitivity analysis.

Hydrologic balance discharge method

The total annual ETo at a specific location is much higher than the total annual precipitation. For example in eastern Sierra Valley Eto is 42 inches (Pruitt et al., 1987), whereas the annual precipitation at the Vinton Station (the station with the lowest recorded precipitation in SV) is only 13.5 inches (data obtained from the California Department of Water Resources). Yet, ground water recharge occurs every year as documented in the rising and falling well water levels. The reason is that most precipitation occurs during the winter and spring when evapotranspiration is minimal (Chart 4-1). Thus when subtracting monthly ETo from the mean monthly precipitation, the average annual amount of precipitation available for runoff and infiltration is 4.37 inches per year. This estimate is conservative, since the total estimated evapotranspiration is assumed to be the sum total of every day of the year, even when precipitation is not occurring.

Since most streams in Sierra Valley are not gauged a substitute for gauging data is needed. One way could be to estimate average annual runoff from stream channel dimensions

The amount of groundwater recharge can be estimated by the monthly difference between precipitation and ET, and multiplied by the recharge area, and then subtracting runoff estimated from stream channel dimensions. This would be a minimum estimate of groundwater recharge, since it is based on precipitation and ET measured at valley floor elevation (precipitation increases with elevation, and ET decreases with elevation).

Chloride mass balance method

The chloride mass balance method relies on the chloride ion as a conservative tracer, which gradually accumulates in the ground water system, starting with precipitation, infiltration, recharge, and finally discharge in wells and springs. First applied by Eriksson and Khunakasem (1969) to estimate ground water recharge the method has been successfully applied to many other ground water systems (Allison, 1988; Dettinger, 1998).

Knowing the chloride concentration in precipitation and ground water, one can estimate the amount of water that is lost by evapotranspiration, before recharge enters the aquifer. Multiplying the average amount of precipitation by the hydrologic basin area, the amount of recharge can be estimated. The concentrations Cg and Cp of chloride in ground water and precipitation and the volumes (per year), Qg and Qp ground water recharge and precipitation, can be related in the following equation, to estimate ground water recharge:

$$Qg = Qp \times Cp/Cg$$

Therefore the higher the ground water chloride concentration, relative to precipitation chloride, the higher the loss to evapotranspiration, and vice versa. Although this approach looks strikingly simple, it requires careful examination of the data which are used in the above equation.

The method is based on several assumptions, which deserve some in-depth discussion:

1. The only (significant) source of chloride in ground water is from precipitation.
2. Chloride concentrations in the aquifer, when compared to those of precipitation, reflect the degree to which evaporation has concentrated chloride before ground water recharge.
3. The ratio of chloride concentration, relative to precipitation is proportional to the amount of actual recharge occurring in the system.
4. The aquifers in the sub-basin are open to recharge, i.e. they are not confined.
5. The aquifers do not receive their ground water flow from adjacent basins.
6. Chloride concentrations in precipitation have not changed over time, since the ground water was recharged (steady state chloride input).
7. Chloride input is spatially evenly distributed, i.e. chloride concentrations in precipitation are similar everywhere in the watershed.
8. No chloride is added to ground water after water has recharged the aquifer system.

The first assumption does apply in Sierra Valley as indicated by the annual well water level changes, i.e. the aquifers are well fractured, and are accessible to recharge every year. There is no evidence of underflow from or to adjacent aquifer systems in SV, and assumption two is assumed valid (though the presence of large NNE faults suggest that this maybe a possibility).

The third and fourth assumptions are assumed applicable, within the range of variability in the snow chemistry data available. The fifth assumption is probably violated, as the chloride and O-18 data suggest.

Given, therefore the ranges of possibility, the estimates will provide minimum and maximum values, the range between which can be further narrowed down with a sensitivity analysis.

Chloride in precipitation

Precipitation chloride data can be obtained from a study by Feth et al. (1964), who studied major and minor ion chemistry of various areas in the Sierra Nevada. Their data for the eastern Sierras indicate an average snow chloride concentration of 0.47 mg/l, ranging between 0.4 and 1.2 mg/l. These numbers seem to agree with snow chemistry data collected more recently by the Desert Research Institute in Reno (R. Stone, personal communication). Snow cores obtained from the Lake Almanor area about 30 miles west of the Chilcoot Basin suggest an average snow chloride content of 0.13 mg/l. For the purpose of this study an average snow chloride concentration of 0.13 mg/l would be assumed.

Ground water chloride data

Chloride concentrations in upland groundwaters need to be obtained by sampling selected upland springs.

Refined Maxey-Eakin method

The refined Maxey-Eakin method developed by Watson, et al. (1976), takes into account increasing precipitation with elevation. Ground water recharge is estimated by multiplying annual precipitation with elevation specific recharge coefficients. These coefficients were derived from correlations between elevation and ground water recharge obtained from 63 ground water basins in the Great Basin.

Although Sierra Valley is not part of the Great Basin it is located adjacent to the same. It may be worthwhile to apply this method to SV, and see how the results compare with the results from other methods.

6. Bibliography

Allison GB, 1988. A review of some of the physical, chemical and isotope techniques available for estimating groundwater recharge. In: Estimation of Natural Groundwater Recharge. Ed. by I. Simmers (pp. 49-72). D. Reidel Publishing Co., Dordrecht. 509 pp.

Bohm B and RW Juncal, 1986. Ground water resource evaluation for the Frenchman Lake Road Estates and Chilcoot Springs Ranches Subdivisions, Chilcoot, Plumas County, California. Technical summary report, Waterwork Corp. July 1986.

Bohm B and RW Juncal, 1989. Ground water resource evaluation: Rendezvous Highlands near Beckwourth Pass. Prepared for Lambdin and Lambdin, Inc., Reno, Nevada. Technical summary report, Waterwork Corp., April 1989.

Bohm B, 1992. Ground water resource evaluation for the Sierra View Subdivision, western Sierra Valley, Plumas County, CA. prepared for Ramelli Investment Group.

Bohm B, 1995, Isotope and hydrochemical hydrology, Chilcoot Sub-basin, Eastern Sierra Valley, California. (Including a Review of Current Ground Water Resource Estimates). Current Status of Investigations, prepared by Plumas Geo-Hydrology for Lambdin Development Group, Chilcoot, CA, September 1995.

Bohm B, 1998. Ground Water Resource Evaluation, Cedar Crest Development Project, Plumas County, California. Technical Summary Report. Plumas Geo-Hydrology prepared for QUAD Consultants, Sacramento. February 11, 1998.

Carling GT, AL Mayo, D Tingley, J Bruthans 2012. Mechanisms, timing, and rates of arid region mountain front recharge, Journal of Hydrology 428-429 (2012) 15-31.

Clark ID and P Fritz, 1997: Environmental isotopes in hydrogeology. Lewis Publishers. Boca Raton. 328 pages.

Davis, S.N. and DeWiest, R.J.M., 1966, Hydrogeology. John Wiley & Sons, New York, 1966.

Dettinger MD, 1989. Reconnaissance estimates of natural recharge to desert basins in Nevada, U.S.A., by using chloride-balance calculations: Journal of Hydrology, 106: 55-78.

Dunne, T. and Leopold, L.B., 1978, Water in environmental planning. 818 pages. W.H. Freeman and Company, New York.

Durrell C, 1987, Geologic History of the Feather River Country, California. Univ. California Press, Berkeley. 337 pages.

DWR, 1973. An interagency-multidisciplinary investigation of the Sierra Valley Study Area, Sierra and Plumas Counties. A cooperative study by Federal, State and Local Agencies. Report by California Dept. of Water Resources, Central District. October 1973.

DWR, 1983, Sierra Valley Ground Water Study. Memorandum Report. California Dept. of Water Resources. June 1983.

Feth, J.H., Rogers, S.M., Roberson, C.E., 1964, Chemical composition of snow in the northern Sierra Nevada and other areas. US Geol. Survey, Water Supply Paper, V. 1535-J.

Feth, JH, CE Roberson, WL Polzer, 1964, Sources of mineral constituents in water from granitic rocks, Sierra Nevada, California and Nevada. US Geol. Survey, Water Supply Paper, V. 1535-I.

Ford, et al., 1963, Northeastern Counties Ground Water Investigation. California Department of Water Resources.

Freeze A and J Cherry, 1979. Groundwater. Englewood Cliffs, N.J. 604 pages.

Grose, TLT and Mergner, M., 2000, Geologic map of the Chilcoot 15' quadrangle, Lassen and Plumas counties, California: California Division of Mines and Geology Open-File Report 2000-23, scale 1:62,500.

Grose, TLT and Mergner, M., 2000, Geologic map of the Chilcoot 15' quadrangle, Lassen and Plumas counties, California: California Division of Mines and Geology Open-File Report 2000-23, scale 1:62,500.

Grose, TLT, 1992, Abrupt change in tectonic style along the northeastern front of the Sierra Nevada uplift at Constantia, California: EOS, Transactions, American Geophysical Union, v. 73, n. 43, p. 549.

Grose, TLT, 2000a, Geologic map of the Portola 15' quadrangle, Plumas County, California: California Division of Mines and Geology Open-File Report 2000-22, scale 1:62,500.

Grose, TLT, 2000b, Geologic map of the Blairsden 15' quadrangle, Plumas County, California: California Division of Mines and Geology Open-File Report2000-21, scale 1:62,500.

Grose, TLT, 2000c, Geologic map of the Sierraville 15' quadrangle, Sierra and Plumas counties, California: California Division of Mines and Geology Open-File Report 2000-24, scale 1:62,500.

Grose, TLT, 2000d, Geologic map of the Loyalton 15' quadrangle, Lassen, Plumas and Sierra counties, California: California Division of Mines and Geology Open-File Report 2000-25, scale 1:62,500.

Hem JD, 1985. Study and interpretation of the chemical characteristics of natural water. Third edition. US Geol. Survey Water-Supply Paper 2254. 263 pages.

Kolterman, H., 1984, Hydrochemical and environmental isotope investigation of ground water recharge mechanisms in the Virginia City Highlands, Nevada. MS Thesis, Univ. of Nevada, Reno, December 1984.

Mariner R, TS Presser, WC Evans, 1983. Geochemistry of active geothermal systems in the Northern Basin and Range. In: geothermal resources Council, Special Report No. 13, pp. 95-121.

Oberdorfer J and D Hamilton, 1999. Reevaluation of the hydrogeology of the Lake Davis – Portola Region. Leland R. Gardner & Associates, Palo Alto, CA. for Plumas County Dept. of Public Works, Quincy, CA.

Piper, 1944, A graphic procedure in the geochemical interpretation of water analyses. Amer. Geophys. Union Trans., v. 25, 914-923.

Pruitt, W.O., Fereres, E., Snyder, R.L., 1987, Reference Evapotranspiration (Eto) for California. Agricultural Experiment Station, University of California. Bulletin 1922.

Schmidt, KD 2003. Hydrogeology and groundwater monitoring in Sierra Valley. Prepared by Kenneth D. Schmidt Associates for Sierra Valley Groundwater Management District, Sierraville, CA. May 1, 2003.

Schmidt, KD 2005. Sierra Valley Hydrogeologic Studies. Prepared by Kenneth D. Schmidt Associates for Sierra Valley Groundwater Management District, Sierraville, CA. May 2005.

Sinclair AJ, 1973, Selection of threshold values in geochemical data using probability plots, J. Geochem. Explor. V. 3, pp.129-149.

Thompson GA, LJ Meister, AT Herring, TE Smith, DB Burke, RL Kovach, RO Burford, IJ Salehi, MD Wood, 1967. Geophysical study of Basin-Range Structure, Dixie Valley Region, Nevada. Geophysics Dept., Stanford University, Stanford, California. Parts I-VIII. Prepared for Air Force Cambridge Research Laboratories, Bedford, Massachusetts. July 1967.

Wagner B, T Wilke, S Krastel, G Zanchetta, R Sulpizio, K Reicherter, M Leng, A Grahzdani, S Trajanovski, Z Levkov, J Reed, T Wonik, 2014. More than one million years of history in Lake Ohrid cores. EOS, Vol. 95, No. 3, 21 January 2014.

Walters Engineering, 1986, Ground water supply evaluation and completion report on Well no. 1 and Well no. 2. Prepared for Robert F. Carmody, Sierra View Subdivision, Chilcoot, Plumas County, CA. January 1986.

Watson Ph., P Sinclair, and R Waggoner. 1976. Quantitative evaluation of a method for estimating recharge to the desert basins of Nevada. J. Hydrol., 31: 335--357.

Winter TC, JW Harvey, OL Franke, WM Alley. 1998. Ground water and surface water, a single resource. US Geol. Survey Circular 1139.

Woodling JK, 1998. Ground water supply evaluation for the Cedar Crest Development Project, Plumas County, California. Administrative Draft Final Supplemental Environ. Impact Report, Planned Development Permit PD4-96/97-14, Cedar Crest. Prepared for Plumas County Planning Dept. for QUAD-KNOPF, Roseville CA. April 1998.

Wright L, 1976. Late Cenozoic fault patterns and stress fields in the Great Basin and westward displacement of the Sierra Nevada block. Geology, v. 4, p. 489-494.