Sierra Valley, CA –

A White Paper on the Opportunities and Challenges for Management of Groundwater under SGMA

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Acronyms and Abbreviations

AF	Acre-Feet
BGS	Below ground surface
CASGEM	California Statewide Groundwater Elevation Monitoring Program
CDEC	California Department of Water Resources California Data Exchange Center.
CGS	California Geological Society
DWR	California Department of Water Resources
ET	Evapotranspiration
FRLT	Feather River Land Trust
Ft	feet
GSA	Groundwater Sustainability Agency
GSP	Groundwater Sustainability Plan
GVF	Grizzly Valley Fault
GVEF	Grizzly Valley East Fault
GVWF	Grizzly Valley West Fault
IWFM	DWR's Integrated Water Flow Model
INSAR	Interferometric synthetic-aperture radar
JPL	NASA Jet Propulsion Lab
LESA	Low Energy Spray Application
PLSS	Public Land Survey System
SGMA	2014 Sustainable Groundwater Management Act
SOP	Standard Operating Procedures
SVGMD	Sierra Valley Groundwater Management District
SWE	Snow water equivalent
SWRCB	State Water Resources Control Board
TNC	The Nature Conservancy
USFS	U.S. Forest Service
USGS	United States Geological Survey
WEHY	Watershed Environmental Hydrology model
WQCC	Water quality constituent of concern

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Opportunities and challenges for management of groundwater under SGMA in intermontane basin, Sierra Valley, CA

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Executive Summary

This paper discusses groundwater sustainability in California's Sierra Valley based upon review of various hydrologic and geologic data sets and publications and presents our findings in the context of the 2014 Sustainable Groundwater Management Act (SGMA) (DWR 2016). The discussion related to SGMA is based upon our current understanding of the legislation. As this legislation is implemented, its interpretation may evolve. The paper provides potential next steps and mitigation strategies as Sierra Valley works to move toward sustainable groundwater management.

The Sierra Valley groundwater basin is an intermontane trough, created by seismic and geologic activity and subsequently filled by fine and coarse sediments. Faults running northwest across the valley impede lateral flow across the basin and fine-grained sediment layers impede vertical flow. Thus, the groundwater basin consists of 1) shallow groundwater and deeper groundwater generally with poor connectivity and low hydraulic conductivity[1] between the groundwater layers; and 2) groundwater disconnected laterally across the valley because of faulting.

The 120,000-acre intermontane Sierra Valley sits at an elevation of 5000 ft. Precipitation in the valley averages between 19 – 23 inches per year in the western and southwestern valley and about 13 – 15 inches annually in the eastern valley, resulting in a wetter to drier gradient as one moves easterly and northerly across the valley. The valley is rich in wildlife dependent upon wetlands, creeks and streams. An approximately 20,000-acre wetland complex and a 30,000-acre montane meadow complex are both the largest in the Sierra Nevada (FRLT 2019). Approximately 300 bird species, of which 25 are special status bird species, and over 1200 plant species, representing 18% of California's flora, are found in Sierra Valley (FRLT 2019). Several efforts and organizations have identified Sierra Valley as a top conservation priority (TNC 1999, Audubon 2008, NRCS 2016). Much of the valley is used for livestock grazing and hay production. During summer, appropriative and riparian water rights[2] holders divert nearly all available stream flows to irrigate area ranches. Frenchman Dam, in the northeast of the watershed, releases impounded water through Little Last Chance Creek to the eastern valley throughout the summer. Some ranchers supplement surface water irrigation with groundwater pumping.

Since the 1960s, groundwater levels[3] in groundwater monitoring wells, particularly for deeper groundwater (more than 300 feet below ground), have generally declined. Groundwater levels within an aquifer are measured by installing a groundwater monitoring well within the aquifer and measuring the hydrostatic head[4]. These drops in groundwater levels and their associated hydrostatic head have been attributed to groundwater pumping and overdraft, predominantly from a small number of irrigation wells primarily in four eastern townships. DWR (1983)

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[1] Hydraulic conductivity is a defined as a constant that reflects the rate water moves through porous sediments and fractures under a hydraulic gradient.
[2] California law allows surface water to be diverted at one point and used (appropriated) beneficially at a separate point, defining this water right as **appropriative**. This is in contrast to a **riparian** right, which is based on ownership of the property adjacent to the water.
[3] Groundwater level is used interchangeably with groundwater elevation in this document. Groundwater elevation refers to the water level in a well standardized against sea level, whereas groundwater level does not use a standard elevation datum. All groundwater data presented has been standardized to the NAVD88 Datum.
[4] Hydrostatic head is the potential elevation groundwater would rise to if no restricting layers were present. Unconfined aquifers typically have the hydrostatic head below the ground surface. Deeper confined aquifers can have hydrostatic head above the top of the restrictive layer and even above ground surface, depending upon the groundwater sources and flow paths.

reported over 10,000 AF of overdraft in 1981 during a drought year in which 14,500 AF were pumped. Artesian wells and springs historically flowed through the valley (DWR 1983, DWR 2003, Schmidt 2017), but groundwater overdraft has also been linked to the loss of artesian[5] wells and springs (DWR 1983, DWR 2003). Deep groundwater elevations[3] in the drier eastern valley have currently fallen 30 – 40 ft below ground elevations, and over 70 ft below the surface in some eastern wells. Sustainable yield[6] in the eastern valley has been estimated at 6000 AF annually (Schmidt, 2017) and our study similarly estimates a range of 5000 – 6000 AF annually. Periods of declining groundwater are associated with median[7] groundwater pumping rates of about 6500 AF annually and periods of increasing GW associated with median rates of 4000 AF annually. To achieve a sustainable yield of 6000 AF annually in the eastern valley would require a 50% reduction in groundwater pumping below the average of annual pumping for the last few years.

Climate change is expected to exacerbate water resources management in Sierra Valley. Greater variance in climate such as longer droughts, more frequent wet years, and greater flooding as well as a general reduction in average snowpack and earlier spring runoff are now expressing themselves in the Sierra Nevada and those trends are expected to continue. These changes will challenge reservoir managers to efficiently manage reservoirs under increasing variance in the timing, frequency and magnitude of weather events, seasonal precipitation totals and the distribution between rain and snow. Moreover, earlier runoff and reduced snowpack may reduce groundwater recharge (Stewart et al. 2004, Freeman 2012, Huang et al. 2018).

Under SGMA, six sustainability indicators have been developed as measures of groundwater sustainability:

- Groundwater level,
- Groundwater storage,
- Land subsidence,
- Water quality,
- Seawater intrusion, and
- Maintaining interconnected surface water beneficial uses.

The Basin Prioritization (DWR 2019) for Sierra Valley prioritizes the sustainability indicators of groundwater level and storage, land subsidence and interconnected surface water beneficial uses, while also identifying water quality. DWR (2019) concludes from their review of area data that Sierra Valley is at risk for the following undesirable results:

- significant and unreasonable groundwater declines,
- significant and unreasonable groundwater storage reduction,
- significant and unreasonable land subsidence interfering with surface land uses,
- significant and unreasonable reductions in surface water beneficial uses such as to groundwater dependent ecosystems[8], and
- significant and unreasonable water quality degradation.

[5] Artesian water flows from groundwater to the land because of high underground pressure in the aquifer force it to the surface. Water can be delivered through a well or spring. Water levels in artesian wells are above ground surface elevation.

[6] Sustainable yield is defined as the average groundwater pumping rate that can be maintained that enables long-term stable groundwater elevations and does not negatively affect any other SGMA sustainability indicator.

[7] Median represents the middle value represented for a set of data and does not make any statistical assumptions regarding data distribution. Mean represents an average rate and assumes a normal statistical distribution.

[8] Groundwater dependent ecosystems are ecosystems supported by groundwater (e.g., springs, seeps, caves, deep-rooted plant communities). In many cases, rivers, wetlands, and lakes are also groundwater dependent ecosystems. These ecosystems are home to many rare, threatened, and endangered species.

Based upon their assessment, DWR (2019) has identified the Sierra Valley sub-basin as a medium priority basin. Sierra Valley Groundwater Management District (SVGMD) serves as the Groundwater Sustainability Agency (GSA) for Sierra Valley. The first step for SGMA compliance will be development of a Groundwater Sustainability Plan (GSP), due by January 31, 2022. Success for the GSP will be measured against January 1, 2015 baseline conditions for the relevant sustainability indicators.

Our review of the current data provides insight into groundwater sustainability challenges for Sierra Valley. Aside from declines in groundwater levels as discussed above, subsidence rates of up to several inches a year and several feet per decade have been measured in Sierra Valley, generally corresponding with areas of groundwater overdraft (DWR 1983, Farr et al. 2017). Dropping groundwater levels may also have reduced surface flows in local streams and creeks through reduced groundwater contributions. Declining shallow groundwater would reduce stream flows as stream reaches shift from "gaining" to "losing" conditions[9] and loss of artesian waters have reduced contributions from deep groundwater. These stream flow effects could impact local wildlife by changing habitat availability. Sierra Valley has the largest wetland and meadow complex in the Sierra Nevada, and these waters support a wide variety of flora and fauna (NRCS, 2016). Increasing groundwater pumping has begun to affect shallow groundwater in some areas of the western and southwestern valley. In those areas, the wetlands and meadows represent groundwater dependent ecosystems that are sensitive to even small water level changes.

Finally, groundwater quality is an important consideration basin wide. In Sierra Valley, groundwater quality data is limited, though the existing data indicates potential concerns with boron, nitrate, and primary and secondary organics (DWR 2003, Schmidt 2003, Bohm 2016b, UFRRWMG 2016). SGMA aims to ensure sustainable groundwater management does not degrade water quality below the January 1, 2015 baseline conditions, providing GSAs power to address water quality problems deemed significant and unreasonable through water treatment and replacement (California Water Boards 2019a). Moreover, basin water quality management will need to meet local, state and federal water quality standards (Moran and Belin 2019, California Water Boards 2019a). During the GSP process, SVGMD will need to engage with the Counties and the Central Valley Regional Water Quality Control Board to develop a strategy consistent with the standards.

Moving forward under SGMA, Sierra Valley will undoubtedly require reductions in agricultural pumping. In developing the GSP, SVGMD will need to develop a robust and defensible dataset that –

- can be used to assess the success of actions taken to achieve groundwater sustainability,
- can engage and be of value to SGMA beneficial users and stakeholders, and
- can be used to adaptively manage the basin and develop informed and cost-effective strategies toward sustainability.

Adaptive management is a process in which operational goals are set; success, outcomes and shortcomings are determined from collected data; and policies and operations are adjusted iteratively based on what is learned. A successful process depends upon stakeholder input throughout.

To advance groundwater management in Sierra Valley, we make eight recommendations:

1. **Create Management Areas that Correspond to Differing Conditions in Sierra Valley.** Sierra Valley has a west to east and south to north climate gradient and is intersected by geologic faults throughout. These factors create broadly different environmental, hydrologic and ecological conditions in Sierra Valley. Separating Sierra Valley into management areas will enable data collection and management strategies tailored to the priorities and needs of each management area.

[9] Losing stream reaches are lengths of streams in which local groundwater elevations are below stream water levels causing water loss from the stream through seepage to groundwater. Gaining streams are streams in which local groundwater elevation are higher than stream water levels resulting in groundwater seeping into the streams.

2. **Develop More Robust Monitoring Networks.** Sierra Valley lacks sufficient data to fully understand groundwater impacts of current watershed management. A more robust monitoring network should be designed to provide sufficient coverage within each management area and to target sustainability indicators (e.g. groundwater level, subsidence) deemed to be at risk of becoming significant and unreasonable in that area. The GSA will define what constitutes significant and unreasonable subject to final approval by DWR. These monitoring networks should leverage available data (e.g. California Statewide Groundwater Elevation Monitoring Program (CASGEM) wells, Interferometric Synthetic-Aperture Radar (INSAR) land surface deformation data, regulatory water quality programs currently in place).
3. **Improve Groundwater Level and Pumping Data.** Currently, groundwater well and water level data is collected with uneven quality assurance and quality control, and uneven frequency. Synchronous data collected more frequently and with more standard quality control protocols will provide more useful information for understanding the linkages between climate, groundwater level changes and pumping, and thus enable a more flexible and robust operational approach and management response.
4. **Implement More Consistent Surface Water Sampling.** Data could include flow measurements at key surface water inputs to the valley and/or paired stream water level and shallow groundwater level measurements (using piezometers[10]). This data would help with understanding area hydrology (e.g., climatic effects on stream inputs, areas of gaining and losing streams as related to groundwater dependent ecosystems).
5. **Standardize Data Sampling and Reporting.** SGMA will require defensible data. Procedures for data sampling, reporting, quality control and management will need to be standardized.
6. **Implement an Adaptive Management Approach for Sustainable Groundwater Management.** In Sierra Valley, geologic, hydrologic and climatic uncertainty will likely make a comprehensive water budget[11] and numerical modeling poor management tools. An Adaptive Management approach using high quality data and implemented across distinct management areas will likely provide the best outcomes and opportunities for achieving sustainable groundwater management.
7. **Investigate Promising Mitigation Strategies.** A number of mitigation strategies could help with groundwater management in Sierra Valley: e.g., 1) improving irrigation efficiency to decrease groundwater pumping; 2) altering land management to enhance regional recharge; 3) conducting local infiltration-based recharge in the valley to benefit groundwater dependent ecosystems; and 4) increasing water use efficiencies through reservoir re-operation.
8. **Broaden Stakeholder Participation.** Sierra Valley groundwater management would benefit from collaboration with the many stakeholders in the watershed. Sierra Valley has several factors outside the GSA's control that affect groundwater conditions (e.g. the Feather River's integral part of the State Water Project, Frenchman Dam operation, variable and changing hydrology). Moreover, Sierra Valley has high environmental and cultural value with many organizations active in conserving its natural heritage. Public outreach could increase stakeholder prioritization of groundwater sustainability and promote the development of tools, resources and actions that facilitate groundwater management. For instance, managing public land to reduce forest fuels, restore forests and streams, and eliminate roads would benefit both GSA and USFS objectives. SGMA provides a legal framework for defining agreements between GSAs and governmental bodies if there are shared interests in groundwater sustainability.

[10] A piezometer is an open pipe set in the ground to enable monitoring of shallow groundwater elevations. The bottom of the pipe is open so that the water level in the pipe represents the static water pressure of groundwater.
[11] A water budget is an accounting of water inflows, outflows and storage within a defined area (e.g., agricultural field, wetland, watershed, basin, state) and includes surface water and groundwater.

Overview

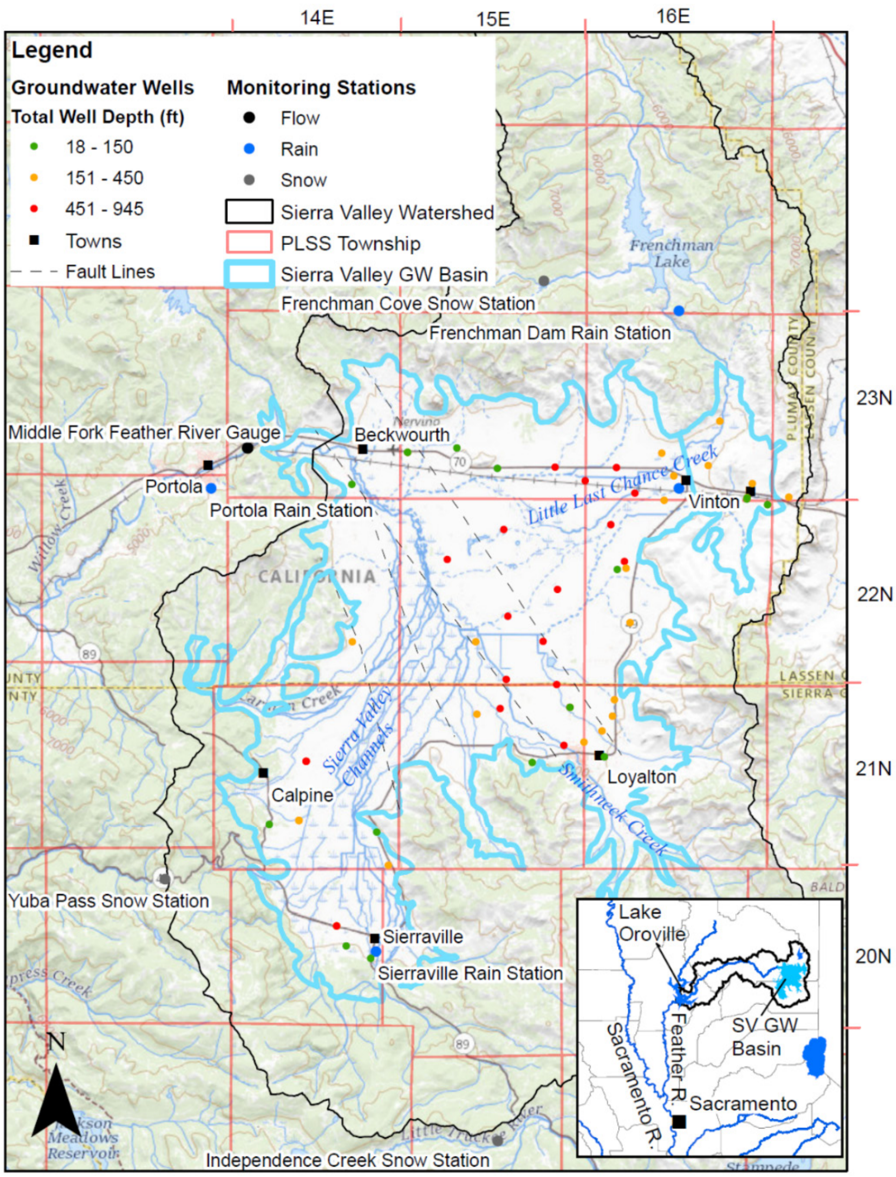

Figure 1. Map of Sierra Valley groundwater basin, streams and watershed boundaries, monitoring stations, and groundwater wells.

Public Land Survey System (PLSS) Township-Range divisions are outlined in red, with township and range labels on the right and top of the figure, respectively. Wells shown are wells with sufficient measurement accuracy to be used in our groundwater analysis. Wells are categorized into three depth zones. The collection of perennial and ephemeral surface water channels is generally ascribed to three drainages – the Sierra Valley Channels, Smithneck Creek and Little Last Chance Creek. The Chilcoot sub-basin is the eastern most portion of Sierra Valley, separated from the Sierra Valley sub-basin by a shallow bedrock shelf situated beneath Vinton.

This White Paper discusses groundwater sustainability in California's Sierra Valley (Figure 1) based upon review of various hydrologic and geologic data sets and publications. This discussion is in the context of the 2014 Sustainable Groundwater Management Act (SGMA) (DWR 2016). The discussion related to SGMA is based upon our current understanding of the legislation. This legislation is in its early stages, with submittal of Groundwater Sustainability Plans (GSPs) due on January 31, 2020 for critically overdrafted hydrologic basins and January 31, 2022 for non-critical basins, including Sierra Valley. As this legislation is implemented, its interpretation may evolve. The paper presents potential next steps and mitigation strategies.

Geology and Hydrology

The Sierra Valley groundwater basin is an intermontane trough created by the faulting and pulling apart of mountain blocks, which subsequently filled with water and sediments over 30 million years (Bohm 2016a). Up to 1,500 feet deep in places, the basin is layered with fine-grained lacustrine[12] silts and clays generated by one or more lakes, and with fine and coarse alluvial[13] sediments deposited from upland runoff (Bohm 2016a, Schmidt 2003). This sediment blend has resulted in zones of deep and shallow groundwater, separated by fine-grained sediment layers which impede vertical hydrologic connectivity and therefore, vertical groundwater flow (Schmidt 2005). The California Geological Society has identified several fault lines in the valley (Figure 1). Though some uncertainty remains regarding the exact locations of the fault lines – Bohm (2016a) used imagery to map the fault lines and obtained slightly different results – Bachand et al. (2019) identified the Grizzly Valley Fault as a potential barrier to lateral groundwater flow. Throughout this document, we will use the Grizzly Valley Fault to divide the valley into areas <u>east</u> and <u>west of the fault</u>, and use the terms western, southwestern, northern, northeastern and eastern to refer more specifically to portions of the valley (Figure 2).

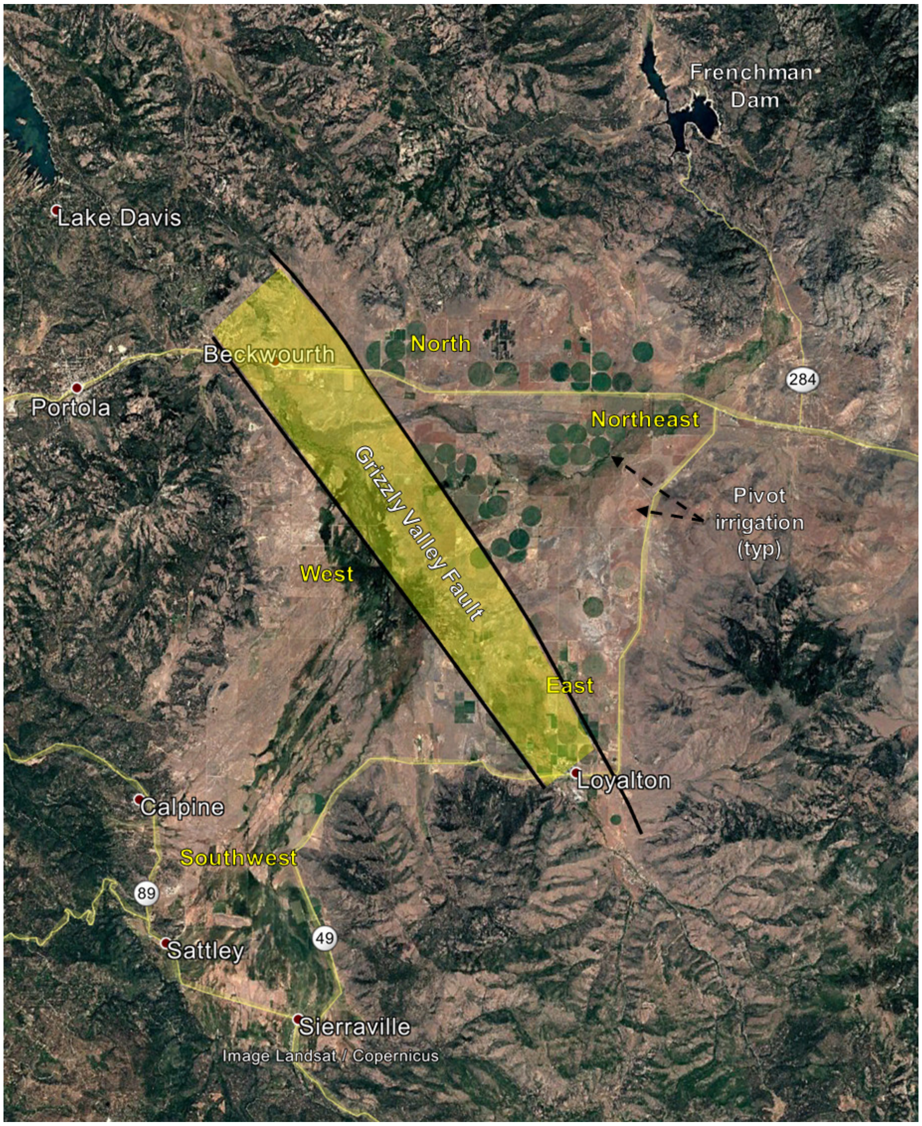

Figure 2. Landsat (Google Earth) image of Sierra Valley, December 2016.
Aerial photo shows the location of the Grizzly Valley Fault (yellow shaded area), and its western and eastern fault lines. The image also shows pivot irrigation fields. We use the fault to divide the Sierra Valley basin into two halves east and west of the fault, and subdivided those areas with the yellow labels shown.

[12] Relating to or associated with lakes.
[13] Deposited by rivers, streams and creeks consisting of silt, sand, clay and gravel.

The 120,000-acre Sierra Valley sits 5000 ft above sea level. (Figure 1, Figure 2). The valley is surrounded by mountains and fed by snowpack and rainfall. It is wetter west of the fault, with annual rainfall averaging 19 to 23 inches, and drier east of the fault, where annual rainfall averages between 13 and 15 inches (Vestra 2005).

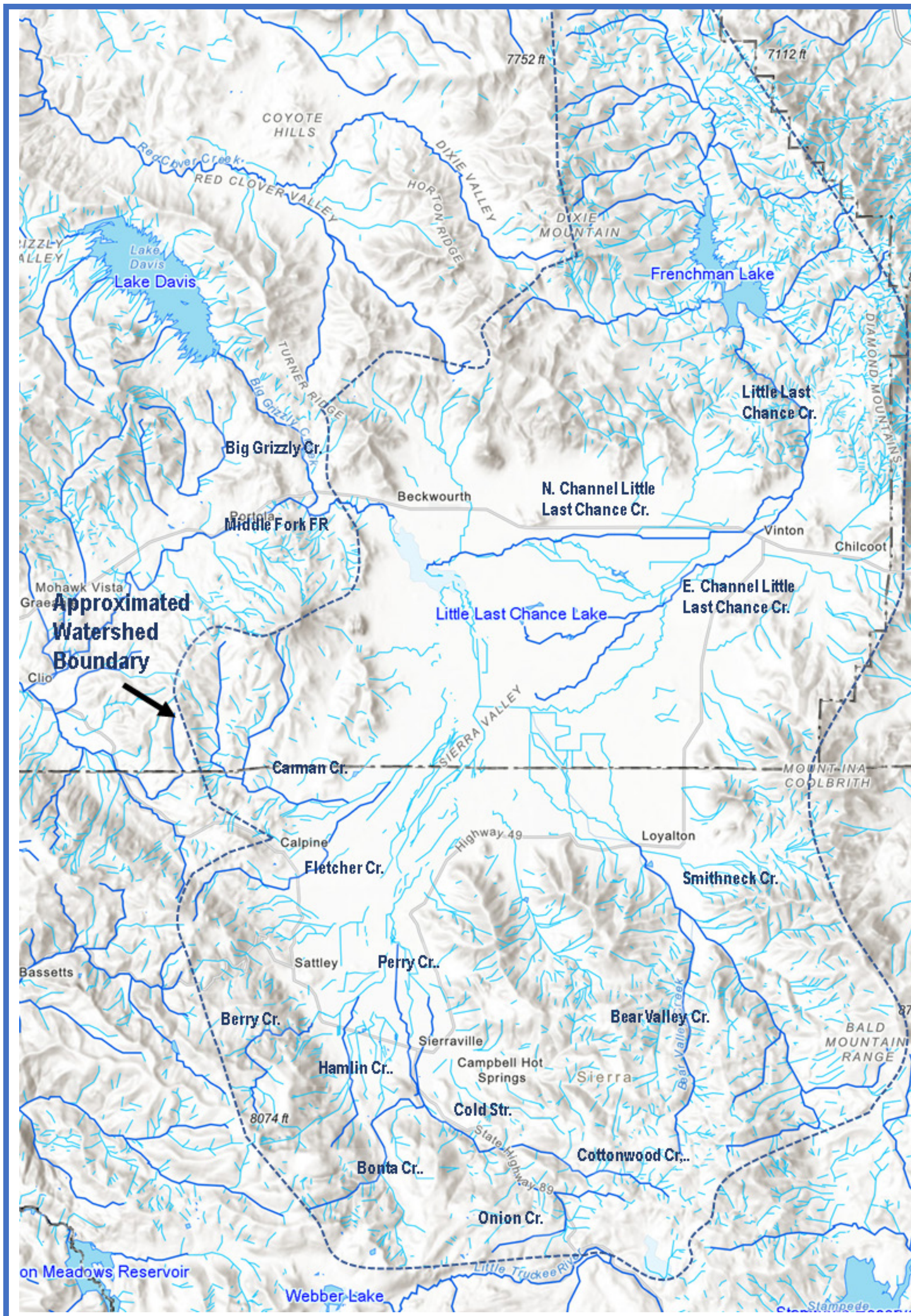

Figure 3. Sierra Valley watershed streams and creeks.
Several named creeks and streams feed Sierra Valley with the majority providing surface flow to the southwestern valley. A large number of small, unnamed streams also provide surface water to Sierra Valley around its entire perimeter.

A large number of named and unnamed streams and creeks enter the valley (Figure 1, Figure 3). The main creeks feeding the portion of the valley east of the fault are Little Last Chance Creek (which flows from Frenchman Lake) and Smithneck Creek. The west and southwestern valley is fed by nine named creeks and their tributaries, with the largest drainage area being the Cold Stream watershed. This area is home to a braided network of streams and has a rich history of wildlife dependence upon wetlands and surface creeks and streams, with an approximate 20,000-acre wetlands complex and an approximate 30,000-acre montane meadow complex, the largest in the Sierra Nevada (FRLT 2019). Approximately 300 bird species, of which 25 are special status bird species, and over 1200 plant species, which represent 18% of

California's flora, are found in Sierra Valley (FRLT 2019). Several efforts and organizations have identified Sierra Valley as a top conservation priority (TNC 1999, Audubon 2008, NRCS 2016).

The eastern half (right of the fault) is drier and has more agricultural irrigation – the many pivot irrigation plots are evident in satellite imagery (Figure 2). The two aforementioned tributaries – Little Last Chance Creek, which flows out of Frenchman Lake in the northeast and Smithneck Creek, which enters the valley from the east – flow perennially from the eastern uplands (Vestra 2005).

Much of Sierra Valley is used for livestock grazing. During the summer, appropriative and riparian water right holders divert nearly all of available stream flows to irrigate surrounding ranches (Vestra 2005, Bohm 2016a). Frenchman Dam releases water into Little Last Chance Creek throughout the summer for irrigated agriculture in the lands east of the fault such that the downstream stretch is seasonally ephemeral and usually dries out completely before its confluence with the western channels (Vestra 2005).

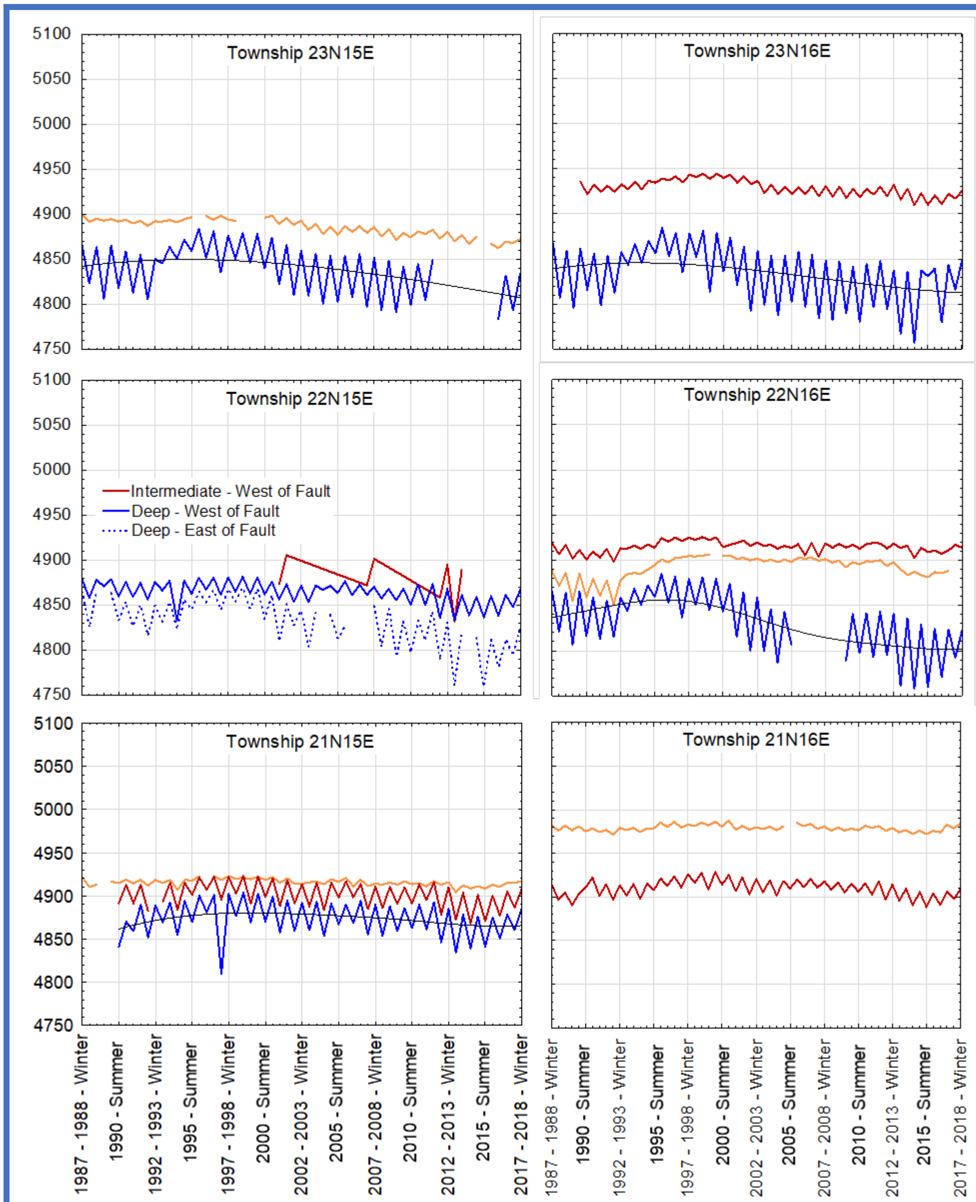

Figure 4. Average groundwater elevations since 1987 for three depths.
Shallow groundwater elevations (well depths ≤150 ft) are shown in orange; Intermediate groundwater elevations, (well depths between 150ft and 400ft), are shown in red; deep groundwater elevations (well depths ≥400 ft) are shown in blue. Inverse distance weighted fit lines are shown in black.

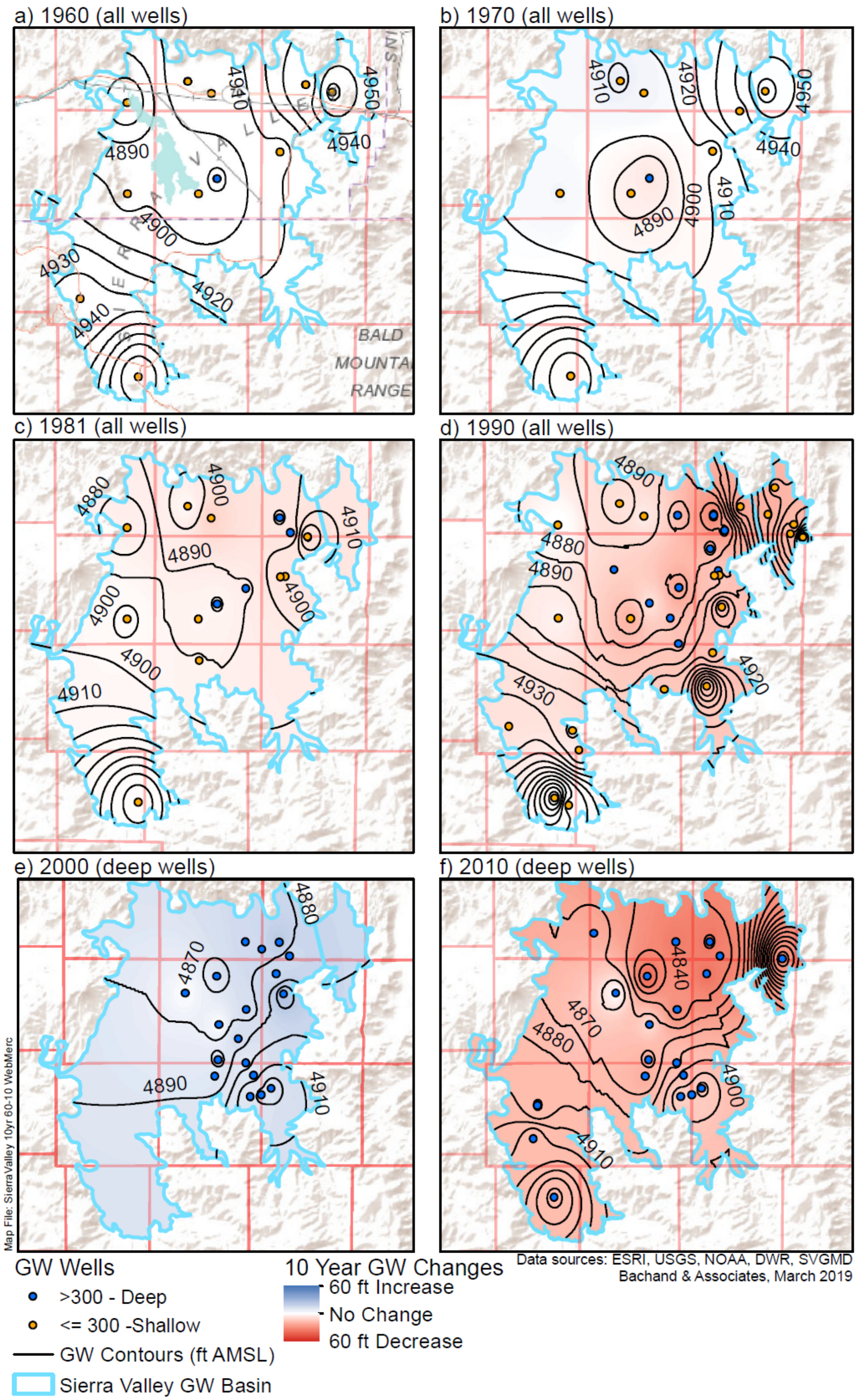

Figure 5. Spring groundwater contours at 10 ft intervals on a decadal frequency.

Contour maps show groundwater elevations for the given year. Heat maps show decadal groundwater elevation changes standardized against 1960 and ending in the year labeled. Elevation changes ranges are for a 60 ft increase (dark blue) to a 60 ft decrease (dark red), with white indicating stable water elevations during the preceding decade. Well coloration indicates depth.

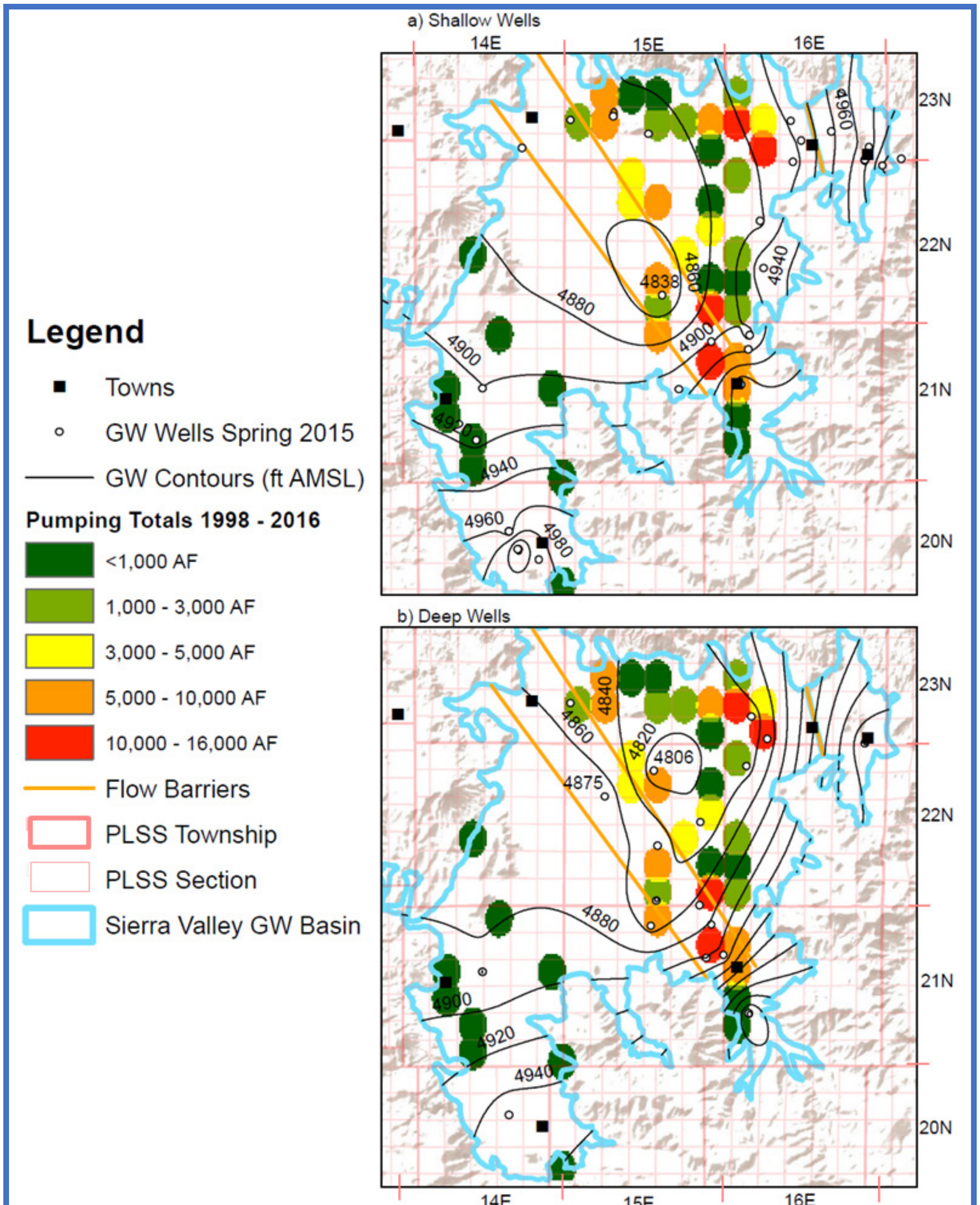

Figure 6. Pumping totals from 1998 – 2006 overlaying Spring 2015 groundwater elevations. Contours at 20 ft intervals for deep and shallow wells. Shallow elevation contours (wells ≤ 300 ft) indicate different areas of concern from deep wells (>300 ft). Pumping data is irrespective of depth.

Some ranchers supplement surface water supplies with groundwater to meet irrigation needs (Figure 6), and center-pivot fields (examples identified in Figure 2) rely on pumped groundwater for irrigation. Most pumping comes from a small number of irrigation wells located east of the fault.

Eleven Public Land Survey System (PLSS)[14] townships cover the majority of the Sierra Valley basin, most with 36 one-square mile PLSS sections. Only four PLSS sections in the Sierra Valley sub-basin have had cumulative withdrawals of more than 10,000 AF of groundwater during the last 20 years (red circles, Figure 6). Irrigation wells are typically drilled into the deeper portion of the aquifer. Because low permeability layers limit downward flow, the deep zone is most heavily affected by overdraft.

[14] The PLSS is a way to subdivide and describe land in the U.S. All lands in the public domain are subject to subdivision by this rectangular system of surveys, regulated by the U.S. Department of the Interior, Bureau of Land Management (BLM). More information on this system can be found at https://nationalmap.gov/small_scale/a_plss.html.

Groundwater level declines, mostly associated with deep groundwater wells[15], began in the mid-1960s and steepened in the 1980s (Figure 4, Figure 5). A series of very wet years was partially responsible for lower pumping volumes during the 1990s, resulting in nearly a decade of groundwater recovery (Figure 4). Groundwater pumping has increased steadily since 2000, and groundwater, primarily deeper, has experienced elevation declines through 2015. Though recent wet year recharge has increased groundwater levels above record lows observed in 2015, a clear history of chronic groundwater declines, most notably deeper groundwater, exists in Sierra Valley. As a result of groundwater pumping, deep groundwater elevations (as measured as hydrostatic head[4]) are commonly 30 feet or more below the ground surface in the area east of the fault where they were historically near or above ground surface (Figure 7). The Sierra Valley Groundwater Management District (SVGMD) was formed in 1980 and has recently taken steps toward active management (i.e. metering pumping, restricting installation of new pumping wells).

Climate Change Considerations

Snowpack is currently California's largest wintertime reservoir system (CNAP 2019). DWR (2014) climate models predict by the end of this century snowpack will have decreased by 48 – 65% due to climatic effects caused by human-generated greenhouse gas and aerosol emissions (DWR 2014) (Figure 8), supported by Dib et al (2016). These changes are now becoming evident in river flows. Climate change will also result in periods of higher-intensity surface runoff and stream flows over a compressed time period in spring (Stewart et al. 2004, Huang et al. 2018, Freeman 2012). These hydrologic changes could decrease groundwater recharge by increasing the percentage of snowmelt and rainfall that leaves the basin as runoff, rather than entering the aquifer system as infiltration (Stewart et al. 2004, Godsey et al. 2014). These changes to the water cycle need to be considered in long-term management plans for the basin, as their effects will confound and counteract some of the progress toward the sustainability of both surface water and groundwater resources. Climate change effects specific to the Sierra Valley watershed include loss of much of the deep snowpack by 2100 (Dib et al. 2016). With more rain and less snow, peak runoffs will be greater in magnitude and summer dry periods will be longer (Stewart et al. 2004). Runoff timing has shifted forward in the Sierra Nevada with runoff historically occurring in April now occurring in March (Freeman 2012). Increased dry periods consisting of successive, low precipitation years as predicted (Huang et al. 2018) are now occurring. In Sierra Valley, 2015 saw the lowest precipitation on record following several dry years 2012 – 2014 and then was followed by a historically wet year in 2017.

These climate change effects will challenge water resources management throughout California (DWR 2017a,b, CEC 2018, Dib et al. 2016) as well as in Sierra Valley. Lessened snowmelt is expected to decrease reservoir storage in Lake Davis (Dib et al. 2016), and likely also Frenchman Dam, potentially limiting late-summer water availability (Stewart et al. 2004). Earlier snowmelt and extreme flood events will further challenge reservoir management, potentially resulting in earlier flood releases. Decreases in snow will also likely decrease groundwater flows from the upland watershed due to less high-elevation infiltration (Huntington and Niswonger 2012). Increasing competition for a shorter window of surface water supplies, coupled with temperature-related increases in evaporative crop demand, will likely increase groundwater demand throughout the summer (Stewart et al. 2004, Dib et al. 2016). Dib et al. (2016) forecasts groundwater pumping would need to increase up to 25% by 2100 to maintain the equivalent agricultural production.

[15] A depth > 300 feet below ground surface (BGS) is generally defined in this work as deep groundwater and a depth of < 300 ft BGS is defined as shallow groundwater. This definition is consistent with others (Bohm 2016, Schmidt 2003). Where three groundwater elevations were considered, shallow groundwater was defined as < 150 ft BGS, intermediate groundwater was defined as > 150 ft BGS and < 400 ft BGS, and deep groundwater was defined as < 400 ft BGS (See Figure 4).

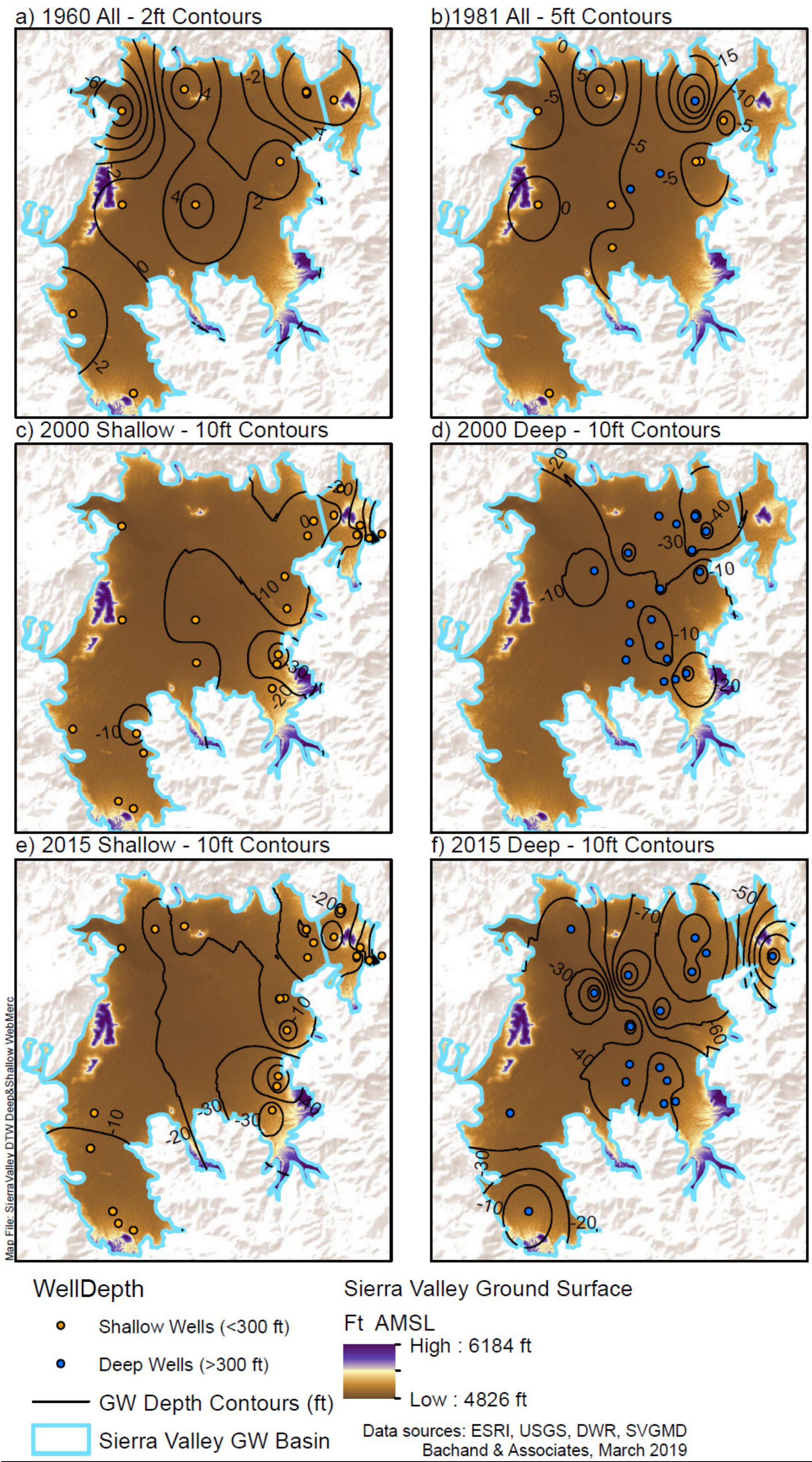

Figure 7. GW level contours relative to ground surface for shallow wells. Negative numbers indicate depth of groundwater below ground surface; positive numbers indicate groundwater levels above ground surface (only occurs in 1960). A digital elevation model is displayed for the Sierra Valley GW basin, with purple colors indicating higher elevations and brown lower.

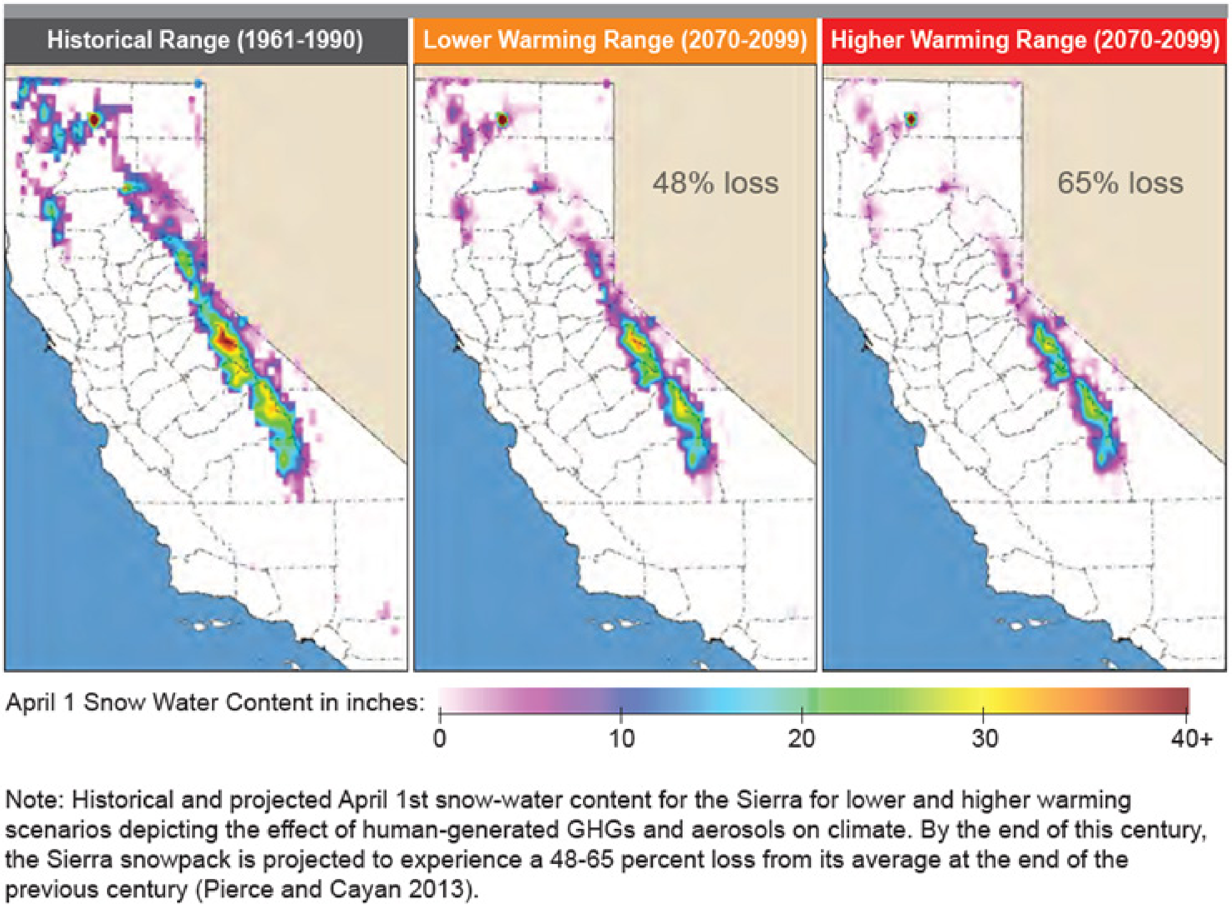

Figure 8. DWR Sierra Nevada snowpack projections

SGMA and Sierra Valley

The Sustainable Groundwater Management Act (SGMA) provides a four-phase process to move toward groundwater sustainability over 20+ years (Figure 11):

1. Groundwater Sustainability Agency (GSA) Formation and Coordination.
2. Groundwater Sustainability Plan (GSP) Preparation and Submission,
3. GSP Review and Evaluation, and
4. Implementation and Reporting.

SGMA Best Management Practices (DWR 2016a) introduce and discuss sustainable yield as a level of pumping that does not cause any undesirable results as measured for six sustainability indicators. Addressing overdraft will include estimating and achieving sustainable yield.

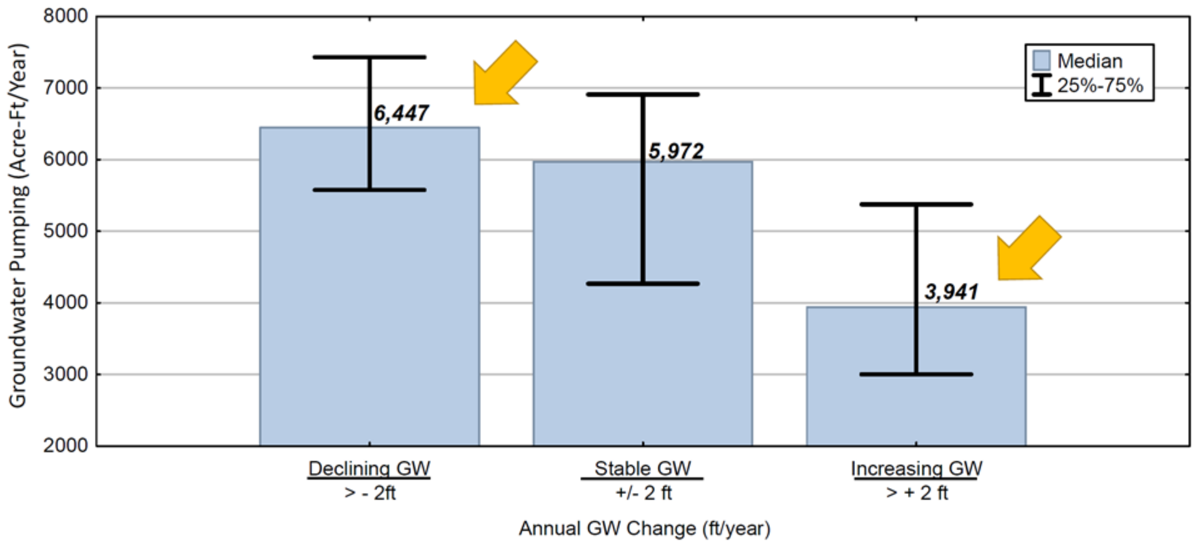

Figure 9. Pumping values categorized by average deep groundwater change groupings for wells east of the fault.
The stable GW years have median annual pumping at roughly 6000 AF, matching the sustainable yield value Schmidt has estimated for the area east of the fault. Pumping rates during periods of declining deep groundwater levels and increasing groundwater levels were significantly different using the Kruskal-Wallis statistical test[16]. These two conditions are shown with arrows. Pumping data obtained from Schmidt reports (2012,2015).

Sustainable Yield Estimates

Schmidt (2017) estimated sustainable yield at 6,000 AF per year for the "part of the valley now tapped by large-capacity wells" (i.e. the area east of the fault) but refrained from estimating sustainable yield for the entire valley. We grouped groundwater pumping data for the area east of the fault based on periods of declining, stable and increasing elevations in the deep groundwater (Figure 9). Periods of declining groundwater were defined as any year with a decrease in average deep groundwater exceeding 2 ft. Periods of rising groundwater were defined as any year with an increase in average deep groundwater exceeding 2 ft for the same areas. Periods of relatively stable groundwater were any year with an average deep groundwater change of less than 2 ft.

In our comparison of these groupings, we found statistical differences (Kruskal-Wallis statistical test) in median pumping volumes between periods of increasing groundwater and decreasing groundwater, evidence that pumping rates affect annual changes in groundwater levels (Figure 9). Groundwater overdraft was occurring at median pumping levels of 6400 AF/year, and groundwater elevation gains were occurring at median pumping levels of 4000 AF/year. Groundwater elevation remained relatively stable at median pumping levels of roughly 6000 AF/year. Thus, sustainable yield for the eastern valley appears to be less than 6400 AF annually, consistent with the estimate by Schmidt (2017). Other analyses for this study suggest sustainable yield could be slightly lower, in the 5000 – 6000 AF/year range (Bachand et al. 2019). Assuming sustainable yield is within this range, a pumping reduction of 58% is necessary from the 2016 pumping withdrawals of 14,300 AF from the area east of the fault.

Sustainability Indicators and Undesirable Results

SGMA mandates active monitoring and management of a groundwater basin's water resources. The regulation's goal is to achieve sustainability in a basin by preventing the significant and unreasonable occurrence of any of the six sustainability indicators (SGMA 2014, DWR 2016):

[16] The Kruskal-Wallis test is used to compare to populations and determine if they are statistically different. The test is a "nonparametric" test, meaning it does not assume a normal distribution within the populations and compare the mean of the populations, but rather ranks the values and compares the means of the ranks.

- Groundwater level,
- Groundwater storage,
- Seawater intrusion,
- Water quality,
- Land subsidence, and
- Surface water and its beneficial uses depletions.

The GSP will define *minimum thresholds* for each indicator, for which *significant and unreasonable* exceedance will represent unsustainable groundwater management, defined by SGMA as *undesirable effects*. Adjustments in basin management through an *Adaptive Management process* will continue over a 20-year period, in response to greater knowledge, new opportunities or changing basin conditions (DWR 2016b).

Under SGMA, the California Department of Water Resources (DWR 2019) has given all 515 groundwater basins in California a priority status, using four categories from very low to high based on California Water Code Section 10933(b) components, and has defined an overdraft status, designated critical or non-critical (DWR 2016b, DWR 2019). California's most critically overdrafted groundwater basins are in the Sacramento and San Joaquin Valleys. Groundwater basins in mountainous regions of California are mostly designated as non-critical but face groundwater sustainability challenges because of their complex geology and hydrology.

DWR (2019) has designated the Sierra Valley subbasin (DWR Basin 5-12.01) as a medium priority basin, primarily due to declining groundwater levels, subsidence, and habitat loss risks from surface water loss (DWR 2019). The complexity of the basin's hydrology and management challenges outside the subbasin's control also contributed to the designation (DWR 2019). SVGMD, which includes representation from Sierra and Plumas Counties, is the GSA for the subbasin and will develop the GSP. For medium priority basins, GSPs are due January 31, 2022 and groundwater sustainability needs to be achieved by 2042, with milestones along the way.

The prioritized sustainability indicators are discussed below.

Groundwater level and storage

Both groundwater level decline and groundwater storage reduction are relevant for Sierra Valley. With groundwater level declines, the total water volume of storage in the basin has decreased. DWR (1983) estimated a loss of 11,000 AF of storage in the aquifer for a single year, 1981, in which pumping exceeded 14,000 AF. Recent dry years 2015 and 2016 have seen similar levels of pumping, and a total of 237,000 AF have been withdrawn from the basin over the last 20 years. These two indicators will need management to prevent significant and unreasonable effects under SGMA.

Water quality

Groundwater quality for Sierra Valley is particularly important as the entire valley is designated a Disadvantaged Area (DA), based upon low median incomes. These areas are often characterized by dependence on small community and private wells. Several factors make assessing current water quality in Sierra Valley groundwater difficult:

- Inconsistent monitoring methods have been used for sampling water quality constituents of concern (WQCC);
- The aquifer has complex geologic and sediment layering likely making water quality non-uniform; and
- Water quality data is from multiple data sources for different programs with different goals.

Sierra Valley data in general shows some potential for concern. In limited well sampling for major WQCC (e.g., pesticides, nitrates, primary and secondary organics; 1994 – 2000), DWR (2003) concluded one well (of 10 measured) had a WQCC above the federal maximum contaminant level (MCL). Studies by others (Schmidt 2003, Bohm 2016b, UFRRWMG 2016) report wells in the western and southwestern valley have high levels of total dissolved solids and other WQCCs (e.g., boron, iron, manganese and arsenic) from geothermal waters. For these wells, only boron exceeded federal MCLs. Portola recently installed an arsenic filtration facility to reduce high arsenic levels in their municipal supply wells (UFRRWMG 2016), raising concerns about individual domestic wells not regulated by a water services district. Bohm (2016b) reviewed Sierra Valley wells sampled from 1981 – 2002 and found high nitrate levels, concluding elevated nitrate levels were from organic deposits within the lacustrine sediments rather than to septic system leaks or fertilizer use.

SGMA aims to ensure that basin operations do not unreasonably or significantly degrade water quality, though the GSA has the authority to improve groundwater quality (California Water Boards 2019a). Under SGMA, the GSA can address significant and unreasonable water quality in many different ways including 1) acquisition and transport of surface water or groundwater; and 2) reclamation, treatment and use of other waters including polluted water or wastewater (California Water Boards 2019a). In developing a basin's water budget, water of insufficient quality should not be included as a water budget source (California Water Boards 2019a). Minimum thresholds set by GSPs for WQCC's will need to be consistent with local, state, and federal water quality standards unless scientific and legal justifications support less stringent requirements (Moran and Belin 2019, California Water Boards 2019a). Sierra and Plumas Counties regulate groundwater for individual domestic wells, community water systems (up to 14 connections) and public water suppliers such as restaurants and gas stations with bathrooms, and the counties' regulatory actions include issuing permits, enforcing regulations, assessing water quality data and reporting violations to the State Water Resources Control Boards. The Central Valley Regional Water Quality Control Board regulates groundwater as related to agriculture through the Irrigated Lands Regulatory Program. During development of the GSP, the GSA will need to develop strategies to address degraded water quality, leveraging these regulatory programs. The GSA should coordinate with the Central Valley Regional Water Quality Control Board (Region 5) during GSP development (California Water Boards 2019a). The State has compiled groundwater water quality data from throughout California (including Sierra Valley) in the GAMA[17] system which is available through an online public portal (California Water Boards 2019b).

Subsidence

Sierra Valley subsidence rates have been up to several feet per decade (DWR 1983) and up to several inches annually (Farr et al. 2016) and have corresponded with areas of overdraft (DWR 1983). Farr et al. (2017) report land subsidence of up to six inches from 2015 to 2016 during the recent drought in the northeastern regions of Sierra Valley, corresponding to areas of greater deep groundwater overdraft. DWR (1983) reported several feet of subsidence and damage to pumping well infrastructure in Sierra Valley. A Caltrans survey of roads in Sierra Valley indicated up to 2 ft of subsidence between 2012 and 2016 (Unpublished Caltrans Data).

Potential impacts from subsidence are often identified as interference with regional infrastructure – railroad tracks, highways, water conveyance structures and canals (DWR 1983, USGS 2017). Damage to infrastructure and other subsidence risks have not been systematically evaluated in Sierra Valley. Under SGMA, a determination will need to be made by stakeholders what constitutes significant and unreasonable effects related to land subsidence. From that determination, strategies for management will need to follow.

Surface water depletion and beneficial uses

For Sierra Valley, DWR (2019) identified in the Basin Prioritization that groundwater pumping could affect surface water beneficial uses, particularly for groundwater dependent ecosystems. Potentially, this issue could relate to both shallow and deep groundwater.

Shallow groundwater levels may not be a SGMA concern east of the fault. Smithneck Creek appears to be primarily a losing stream, contributing flow to groundwater, and Little Last Chance Creek is suggested to have little connection with groundwater at all (Bohm 2016a, DWR 1983). However, shallow groundwater is a concern west of

[17] California's Ground-Water Ambient Monitoring and Assessment program includes local, state and federal partners to collect groundwater information throughout California. Online tools are available to available to present and analyze the data. https://www.waterboards.ca.gov/water_issues/programs/gama/online_tools.html

the fault, where most of the wetlands and wet meadows are located. Sierra Valley has high wildlife value as the largest meadow and wetlands complex in the Sierra Nevada, with rich and diverse flora and fauna. The wetlands provide habitat for many species of migratory birds and several rare or endangered plant species (Vestra 2005, NRCS 2016). Wetlands and meadows are sensitive to small water level and elevation changes (Hunsaker et al. 2015).

During the last decade, groundwater wells near Calpine, located in the southwestern valley, have experienced increased seasonal variation in groundwater elevations that suggest increased stress on shallow groundwater. These increased variations have occurred across all groundwater depths. Moreover, some areas have also shown groundwater declines. These two trends are incongruous with historical groundwater elevation trends that have been shown at nearby wells (Bachand et al. 2019a).

Deep groundwater may also be contributing to surface water beneficial uses. Artesian waters have historically been a groundwater source for creeks, streams and wetlands in Sierra Valley. Schmidt (2015, 2017) tracked the changes in groundwater elevations and pumping since the 1990s and noted specific wells that have stopped flowing due to groundwater elevation declines.

Adaptive Management

SGMA discusses using an adaptive management approach to learn from data and to adjust sustainability strategies. This approach will be especially important in Sierra Valley given the hydrologic, geologic and climatic complexity and uncertainty.

Adaptive management requires a robust, legally and scientifically defensible and informative data set to support and guide decision making. Successfully implementing adaptive management requires understanding its definition. Adaptive management is defined by the National Research Council (2004):

"Adaptive management [is a decision process that] promotes <u>flexible decision making</u> that can be adjusted in the <u>face of uncertainties</u> as outcomes from management actions and other events become better understood. <u>Careful monitoring</u> of these outcomes both advances scientific <u>understanding</u> and helps <u>adjust policies or operations as part of an iterative learning process</u>. Adaptive management also recognizes the importance of <u>natural variability</u> in contributing to ecological resilience and productivity. It is not a 'trial and error' process, but rather <u>emphasizes learning while doing</u>. Adaptive management does not represent an end in itself, but rather a <u>means to more effective decisions and enhanced benefits</u>. Its true measure is in how well it helps <u>meet environmental, social, and economic goals, increases scientific knowledge, and reduces tensions among stakeholders</u>."

Key points in the definition of adaptive management:

- Acknowledge uncertainty in natural resources systems,
- Seek to improve system understanding in order to achieve management objectives, and
- Allow management adjustments and interventions to improve both system understanding and subsequent decision making (Atkinson et al. 2004, Williams et al. 2009).

Adaptive management success depends upon many factors as identified by Rist et al. (2013) and listed below. At the planning and decision-making scales, decision makers need to:

1. Understand the need for adaptive management and the process,
2. Make long-term resource commitments to the process,
3. Understand Business-As-Usual is not sustainable,
4. Accept risks,
5. Build shared understanding and appropriate, stakeholder-engaged governance,
6. Develop realistic expectations for monitoring and experimental programs, and
7. Avoid conflicts of interest (Rist et al. 2013).

Implementation can be challenged by:

1. Difficulties in developing appropriate experiments,
2. Costs and commitment,
3. Learning not effectively informing policy and management decisions,
4. Institutional fragmentation confusing or hampering management responsibilities,
5. Lack of leadership and trust, and
6. Poor stakeholder engagement.

Evaluation and reflection can be limited by:

1. Not realizing the full range of management options,
2. Suppressing surprises, and
3. Not continuing to value learning but focusing on actions alone.

In implementing adaptive management to address an environmental or ecological challenge, decision makers and stakeholders need to recognize adaptive management will occur within a broader social, political and institutional framework, in which management and governance involve trade-offs as related to stakeholder objectives, risks and short-term vs. long-term goals and objectives (Rist et al. 2013). The success or failure of an adaptive management approach will depend upon the social framework, commitment and enforcement under which it is implemented (Figure 10).

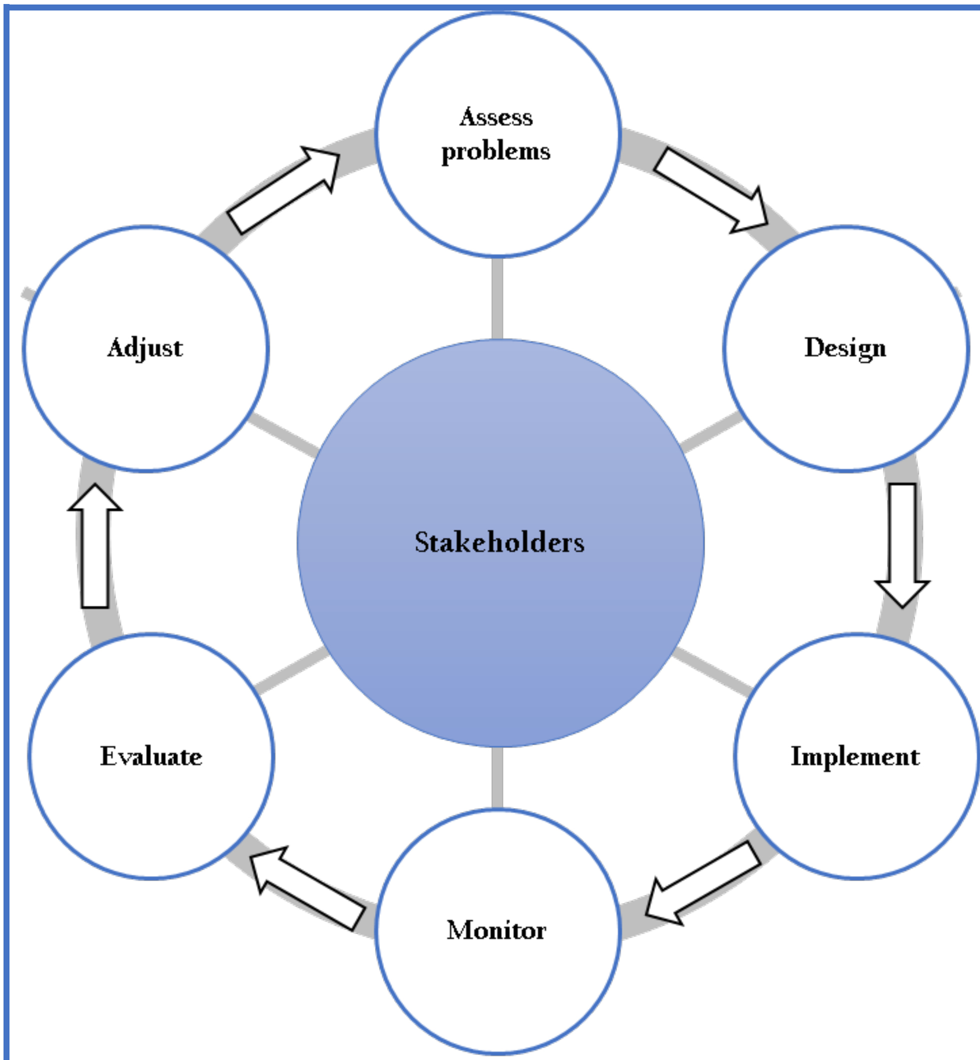

Figure 10. The adaptive management process for resource management.
Stakeholders play a central role in the learning based process that continually cycles through a process of 1) assessing the problem; 2) drawing upon best available information and data; 3) identifying uncertainties; 4) implementing policies, strategies and practices; 5) monitoring; 6) evaluating outcomes; and then starting over. Modified from Rist et al. (2013).

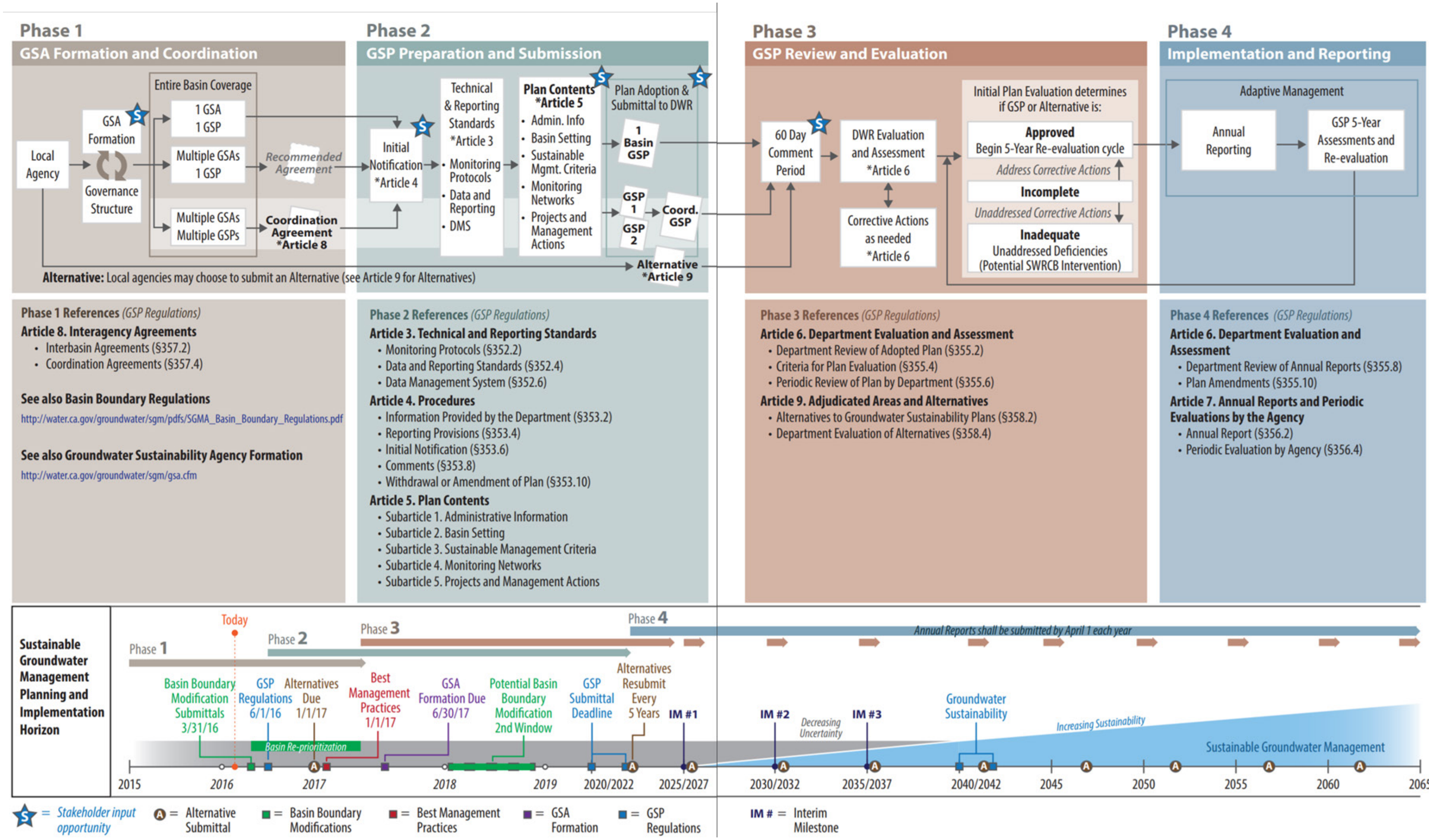

Figure 11. The SGMA Compliance Process.
Phase 1 and 2 represent the periods of GSA formation and preparation and submission of the GSP. Phase 4 represents a 20-year period of compliance in which adjustments are made in basin management to ensure the basin is moving toward sustainability. From DWR (2016).

Data Gaps, Recommendations and Next Steps

Below, we identify eight priorities for the SGMA planning effort in Sierra Valley based on our assessment of current knowledge, resources and level of public engagement.

1. Create Management Areas to Optimize Results from Decisions Made

Creation of management areas would facilitate adaptive management efforts in Sierra Valley to address the prevention of undesirable effects from groundwater usage. The GSA will prioritize sustainability indicators and minimum thresholds for different areas in Sierra Valley based upon groundwater sustainability challenges. For instance, deep groundwater declines, loss of deep aquifer storage and land subsidence are likely the primary indicators relevant in the area east of the fault. In contrast, the area west of the fault does not have long-term deep or shallow groundwater declines nor reports of subsidence, though recent well data is limited. However, because of the importance of shallow groundwater as a water supply for meadows and wetlands, pumping in the area west of the fault poses a greater risk to groundwater dependent ecosystems. As noted earlier, these systems are sensitive to even small water level changes (Hunsaker et al. 2015) which will occur with changes in water supply, whether surface or shallow groundwater. Precipitation gradients, geologic differences, data collection needs and existing regulations in the valley may also be considered when delineating management areas.

Some priorities will likely be important throughout the basin. For instance, the entire Sierra Valley is a DA. These rural communities often depend upon shallower wells for their drinking water. Thus, protecting water quality will be a priority throughout Sierra Valley.

2. Develop and Implement More Robust and Higher Density Monitoring Networks

Monitoring networks should be developed and monitored to specifically gauge success in meeting sustainability indicators and to effectively inform management decisions.

Data and results from monitored wells will form the basis for groundwater interpretation and will be particularly important in assessing the significance of groundwater level and groundwater storage decline, subsidence and loss of supply to groundwater dependent ecosystems. Currently, SVGMD has about a dozen groundwater monitoring locations, typically monitored on a monthly basis. Additionally, the California Statewide Groundwater Elevation Monitoring Program (CASGEM) has roughly 130 additional groundwater monitoring locations in Sierra Valley. Actively monitored CASGEM wells are typically monitored twice yearly and these wells can be residential, observational, for irrigation or for stock water. However, because these wells (and their monitoring protocols) are not standardized, these wells provide inconsistent groundwater data and introduce error into groundwater measurements. CASGEM wells could potentially and cost-effectively be incorporated into the monitoring network through improving associated metadata (e.g., elevation, screening interval) and selecting a suitable subset that meet quality control standards and fill spatial data gaps.

Adding new wells to the SVGMD monitoring network would allow better characterization of groundwater in this geologically complex system. Groundwater level contour maps depend upon data accuracy, data density and the underlying geologic assumptions. Figure 12 presents groundwater elevation contour results based on the SVGMD wells and a large set of wells supplementing the SVGMD with a screened set of CASGEM wells. As shown in this figure, less groundwater elevation data throughout the valley gives very different contour results. Less dense and lower spatially resolved groundwater data produces less accurately modeled groundwater contours to define areas of decreasing or increasing groundwater elevations, to identify potential groundwater flow paths, and to characterize groundwater elevation responses to natural (e.g., precipitation, climate change) and anthropogenic (e.g. land management, groundwater pumping) drivers. This incomplete data set is more likely to result in less effective, less efficient and less equitable management decisions. Poor management decisions based on incomplete data will waste human and economic resources. Adding wells to the SVGMD system could be through construction of new monitoring wells or through the addition of a subset of CASGEM wells determined suitable for inclusion in the groundwater monitoring system.

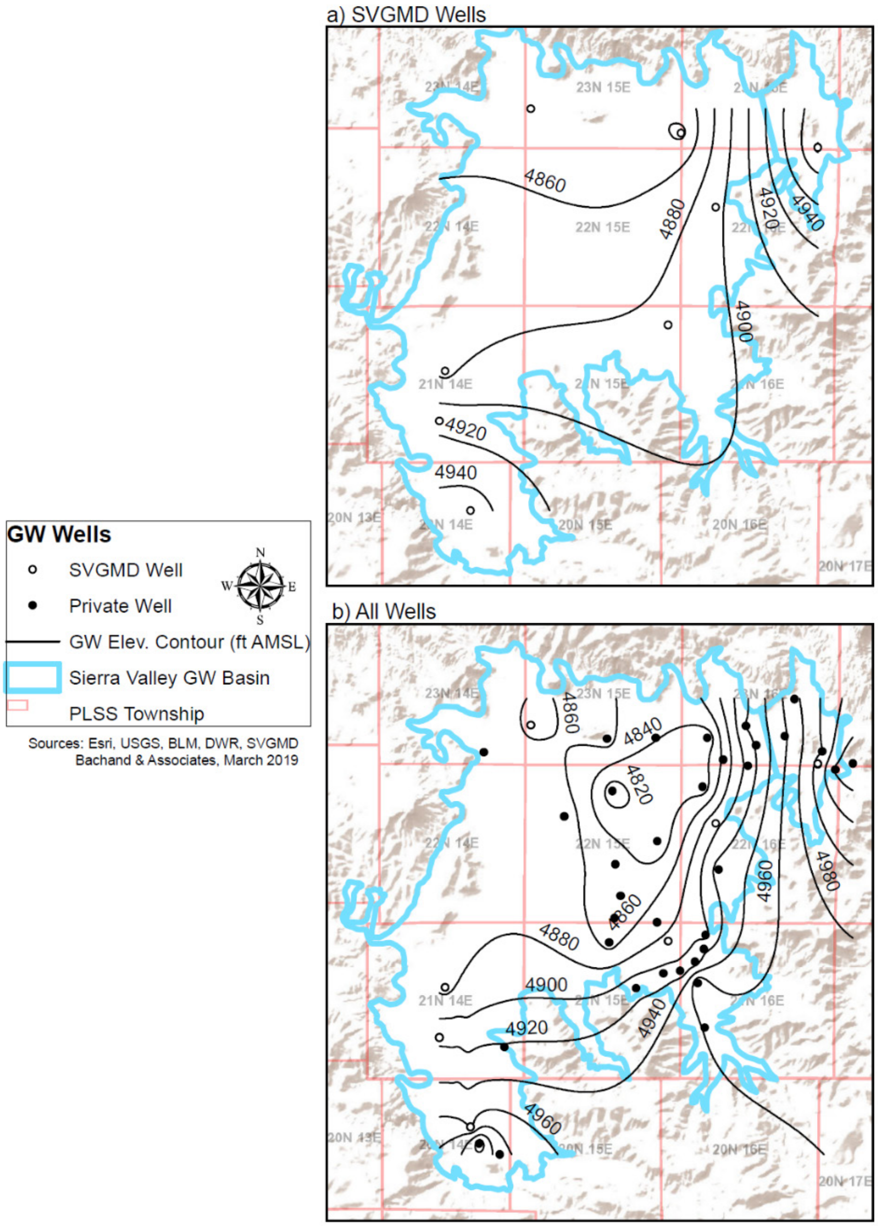

Figure 12. Contours at 20 ft intervals generated using differing selection of wells
Well selections are (a) high accuracy, cluster wells monitored by SVGMD and (b) lower accuracy CASGEM wells monitored by DWR. Wells are shown irrespective of depth.

Additionally, having a reasonable geologic model is important in considering and assessing data. Assumptions on effects of faults (e.g. impediments to flow along hydraulic gradients) will affect contour results as well (Figure 13). Not properly considering faults and other geologic boundaries can lead to misunderstanding zones of influence for pumping and lateral connectivity across the aquifer, again introducing inefficiencies and potentially inaccurate information into the decision-making process. Since geologic effects are not homogenous between depths nor along the length of the faults, insufficient monitoring wells near these geologic barriers will reduce the value of groundwater elevation contour maps.

The groundwater well network could also be leveraged for groundwater quality and subsidence monitoring. A regular and defensible water quality sampling program is required by SGMA. Past water quality sampling can be used to aid development of the GSP, but sampling plans, methods, and locations may need to be adjusted. The groundwater well network could provide water quality sampling locations paired with hydrologic monitoring.

Wells may also be used for subsidence monitoring by co-locating some land subsidence monitoring points with well monitoring to tighten the linkage between subsidence and groundwater level declines. The GSP will need to define what constitutes significant and unreasonable effects from subsidence and develop methods for monitoring and adaptively managing these risks. Groundwater levels can be used as surrogate data if a ratio of water level decline to land subsidence can be determined, potentially linking to recent (Farr et al. 2016) and future InSAR data.[18]

3. Improve Groundwater Pumping Data to Support Sustainable Yield Efforts

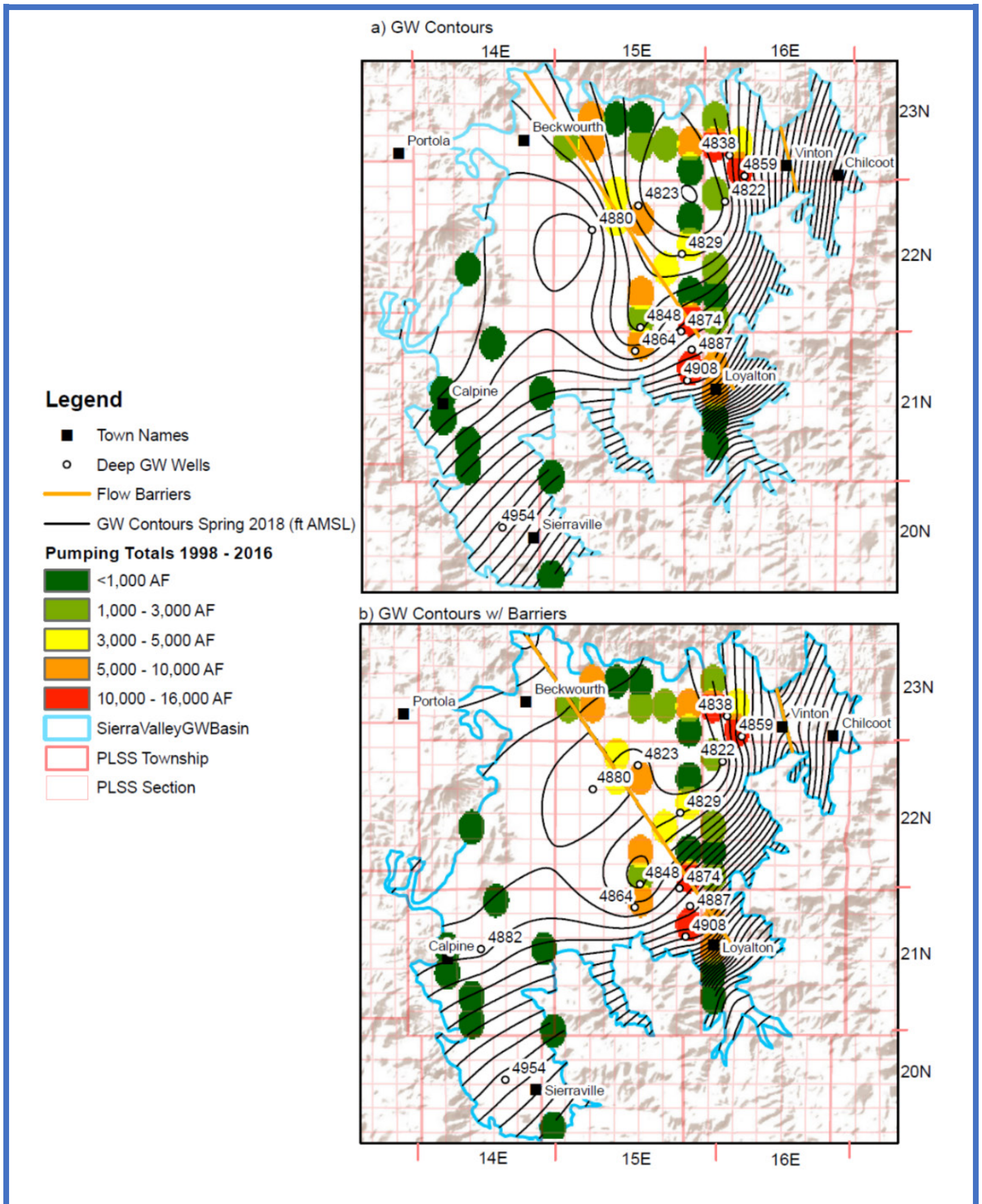

Figure 13. Sierra Valley groundwater contours below 300 ft and 20-yr totals.
Contours are generated: a) without consideration of the flow barriers and b) with consideration of the east fault line of GVF, showing discontinuity of groundwater bodies on either side of the fault.

Better groundwater pumping data with better quality control is needed to accurately quantify pumping, develop more accurate relationships between pumping and groundwater elevation trends, and provide more useful data for management decisions. Useful metadata[19] for wells would include more complete and accurate data on well screen intervals, meter installations, and elevations. Good rapport between the GSA and well owners will facilitate the collection of this information. Finer spatial and temporal resolution pumping data would help in developing 1) relationships between pumping volumes and groundwater levels; 2) relationships with precipitation; 3) sustainable yield estimates; and 4) zones of

[18] DWR is planning implementation of INSAR data collection in support of SGMA.

[19] Metadata is a set of data that provides background data and information.

influence for irrigation wells[20]. These data could enable the implementation of a more flexible or adaptive strategy to manage groundwater pumping.

4. Implement More Consistent and Informative Surface Water Sampling

Understanding shallow groundwater effects on groundwater dependent ecosystems (e.g., marshes, meadows) is a priority for Sierra Valley under SGMA. SGMA requires GSAs to develop GSPs that consider the impacts of groundwater on surface water beneficial uses including to groundwater dependent ecosystems. For groundwater dependent ecosystems, achieving this objective requires understanding the connection between groundwater and surface water supplies.

Surface water monitoring is limited in Sierra Valley. Current data sampling consists of:

- River level and flow monitoring at the Middle Fork of the Feather River at Portola,
- Rain at Sierraville, Vinton and Portola,
- River level, reservoir storage, and rain at Frenchman Dam and Lake Davis,
- Snow at Yuba Pass, Frenchman Cove and Lake Davis, and
- Monthly diversions from the Truckee River (CDEC 2019).

Other locations have been historically monitored for flow (i.e., Smithneck Creek, Bonta Creek, Berry Creek, Little Last Chance Creek, Big Grizzly Creek, Little Truckee Diversion) by the USGS and by DWR, though most have been inactive for decades. Based upon historical records, their total inflows into Sierra Valley account for approximately half the outflow from the Middle Fork Feather River (Bachand et al. 2019).

Several main creeks and streams feed Sierra Valley (Figure 3):

- The portion of the valley east of the fault is fed by Little Last Chance Creek and Smithneck Creek, and
- The area west of the fault is fed by nine creeks and their tributaries, the largest drainage being the Cold Stream watershed.

Quantifying total surface flows into Sierra Valley would require creek and stream monitoring at several locations within or immediately upstream of Sierra Valley (e.g., Little Last Chance Cr., Smithneck Cr., Cold Str., Berry Cr., Hamlin Cr., Fletcher Cr., Carman Cr.) as well as monitoring, surveying, or modeling the many unnamed or smaller creeks and streams that feed Sierra Valley.

Rather than attempting to quantify total valley surface inflows, more focused studies of a select number of stations representing the sub watersheds of the basin (Figure 3) could be undertaken to characterize changes in surface hydrology over time resulting from management actions and from climate change. In those areas, developing paired stream level and shallow groundwater level monitoring could provide data to track and better understand surface water and groundwater connectivity and potential challenges in their supply and management.

5. Standardize Data Sampling and Reporting

SGMA will require defensible and standardized data methods. These methods will cut across all data activities (e.g., collection, quality control, management, analyses, reporting) and will need to be documented, transparent and reproducible. Sampling errors or incomplete records will affect data utility and value (DWR 2010). In our analyses, we found most well elevation measurements in Sierra Valley appear to have an accuracy of +/- 5 ft as compared to the +/- 0.1 ft recommended by DWR (2016) for the GSP. Surveying the top of well casings and ground surface elevation of all wells included in the groundwater monitoring network to an established elevation benchmark would improve groundwater elevation data quality and its utility. Data errors, whether related to groundwater elevation changes or to land elevation changes, will mislead decision making.

[20] The zone of influence for groundwater pumping is the area in which a depression in groundwater elevations is occurring. Depressions can vary in the short-term by the groundwater pumping rates or in the long-term by natural groundwater flows replenishing groundwater and raising groundwater elevations.

Sampling frequency also will affect data utility and value. For instance, well information gathered twice per year, as required under CASGEM, or monthly, as generally implemented by the SVGMD, provides limited data regarding groundwater response to groundwater pumping, effects on groundwater flows from climate, and other potential drivers. Increased data frequency, such as data regularly collected (e.g., hourly, daily) via automated sensors, would provide better information for groundwater management decision making.

6. Implement an Adaptive Management Approach for Sustainable Groundwater Management.

Under SGMA, each GSP requires a water budget to reasonably estimate total annual groundwater and surface water inflow and outflow volumes by water sources and water use sector (e.g., agriculture, municipal) and to quantify aquifer storage change (DWR 2016a). This information, developed for "historical, current and projected water budget conditions," can be quantified through direct measurements or estimates based on data (DWR 2016a). GSP regulations do not provide specific methods for quantifying water budget components but lay out best management practices in the suite of SGMA guidance documents (DWR 2016a).

Portions of a basin-wide water budget using analytical measurements have been developed by various agencies and researchers. For instance, DWR (1983) estimated aquifer storage loss of 11,000 AF in 1981, though no other water budget component was given. Vestra (2005) quantified components of the water budget for the entire Sierra Valley watershed but assumed steady state conditions in groundwater and thus did not account for long-term declines in groundwater levels. Bohm (2016a) has detailed several distinct methods for estimating the groundwater inflows and outflows for Sierra Valley and outlined the necessary components and data sources for developing a water budget but did not provide quantifications for these components.

A recent numerical model computer program combined the privately-developed Watershed Environmental Hydrology (WEHY) and DWR's Integrated Water Flow Model (IWFM) models to simulate historical and projected hydrologic components for the Sierra Valley groundwater basin, including precipitation, evapotranspiration (ET), streamflow, deep percolation (groundwater recharge from the valley floor), crop demand and water use (pumping and surface water diversions) (Dib et al. 2016). The simulated data were used to generate values for the average of water budget components during water years 2000 – 2010 and to provide monthly values for each component (Dib et al. 2016). Dib et al. (2016) estimated the basin's budget to be about 223,000 AF per year. Water budget assumptions and specifics are not always clear in this model as some components are combined. For instance, pumping and surface water diversion are combined into "prime water" (total applied irrigation water). The budget is also missing components required by the GSP regulation (DWR 2016b), most notably groundwater inflow volumes from the surrounding uplands and annual groundwater storage changes (Dib et al. 2016). The model's results suggest groundwater recharge occurs exclusively from water percolating from the surface within the groundwater basin, potentially accounting for upwards of 20% of the annual total water availability (Dib et al. 2016). That mechanism is not supported by Bachand et al. (2019) which concludes that direct recharge to deeper groundwater is limited due to fine-grained layers restricting deep percolation throughout most the valley floor, nor by Bohm (2016a) which suggests that the surrounding fractured granite or volcanic bedrock is an important flow path for groundwater.

Of note, modeling Sierra Valley hydrology by Dib et al. (2016) and others is challenged by uncertainties in input data: e.g.,

- ET is the primary pathway for water loss from Sierra Valley, but no direct measurements of ET are made in Sierra Valley.
- Precipitation is the major water source to the watershed. Basin estimates of precipitation rely upon limited monitoring stations. Precipitation varies spatially across the valley and widely from year to year.
- Total basin storage has been estimated only roughly, and the amount of subsurface flow entering and leaving the basin is very difficult to quantify.

- Surface flows entering the valley are largely not monitored and there exists a large number of smaller, unnamed creeks and streams (Figure 3).

The model by Dib et al. (2016) has a roughly 20% difference between observed and simulated streamflow volumes. Uncertainties of other model components are not clearly quantified.

This limited data availability, combined with high spatial variance in the climatic conditions and complex aquifer structure and boundaries, creates uncertainty and error in even simple water budget calculations. Increased data coverage can reduce the uncertainty. However, it is unlikely uncertainty can be decreased sufficiently to for models to accurately define a sustainable yield or provide sufficient information to make management decisions to achieve sustainable yield. With an annual water budget in the Sierra Valley basin of approximately 223,000 AF (Dib et al. 2016) and with sustainable yield in the 5000 – 6000 AF range, a 2 – 3% error in the total water budget will preclude accurate assessment of sustainable yield. Given uncertainties related to geology, precipitation, evaporation and surface flows, uncertainty associated with the water budget exceeds 2 -3%.

Thus, existing water budgets, hydrologic data, and geologic information for Sierra Valley provide a good starting point for developing a water budget for the GSP. However, for managing hydrology and groundwater levels in Sierra Valley, an adaptive management approach will be needed that relies on data collection and its interpretation for decision-making.

7. Investigate Promising Mitigation Strategies

Strategies exist that may help mitigate groundwater overdraft and achieve sustainability with regard to declining elevations of deep groundwater and declining groundwater storage: e.g.,

- Reducing water use through improved irrigation efficiencies or changes in land use;
- Increasing regional recharge by altering land management practices;
- Conducting local recharge in the valley to benefit groundwater dependent ecosystems; and
- Increasing groundwater recharge through reservoir re-operation.

We discuss each of these below.

<u>Improving sprinkler system efficiencies to decrease groundwater pumping.</u> Center-pivot and linear sprinklers systems used for hay irrigation in Sierra Valley predominantly rely upon groundwater. Low Elevation Spray Application (LESA) systems have been studied to assess improvements in irrigation efficiencies (Kisekka et al. 2017, Zhu et al. 2016). Kisekka et al. (2017) found 10 – 20% better irrigation efficiencies when using LESA sprinklers because of reduced water losses to wind and evaporation. Zhu et al. (2016) found improved soil moisture distribution under LESA systems. A study is currently underway (Bachand & Associates, UCCE) to analyze the effects of LESA systems in Sierra Valley on water use efficiencies and hay yield. Further studies could be conducted to better understand the efficiencies that could be achieved by adopting sprinkler technologies or changing the management of current systems.

Soil amendments are another potential method to improve irrigation use efficiencies. For instance, increasing soil organic carbon content can improve irrigation efficiency by increasing water-holding capacity on sandy soils and by improving infiltration on clay soils (Li et al. 2017, Yu et al. 2017).

<u>Altering regional land management to promote groundwater recharge.</u> The Upper Feather River Integrated Regional Water Management Plan (UFRWMG 2016) proposes various projects to improve forest management:

- USFS road improvements for Plumas Co (UF-7)
- Upper Feather River Cooperative regional forest thinning (UF-12)
- Sierra County road improvements (MS-33)
- Management of upland livestock grazing to reduce impacts on stream systems (FMW-18 and ALS-3)
- Infrastructure improvements to increase water quality and conservation (ALS-2 & ALS-6).

These projects could potentially improve groundwater conditions as well. Thinning overstocked forests reduces forest fuels (North et al. 2009) and ET losses (Bohm 2015, Smerdon et al. 2009, Wyatt et al. 2011), potentially increasing subsurface flow to groundwater. Conklin et al. (2015) reports vegetation density is more tightly linked to ET in forests that are more limited by precipitation. Forest thinning practices should be designed based upon the forest stand structure and density, topography, aspect and local climate (North et al. 2009). In addition to UFRIRWMP proposed projects, Grismer and Hogan (2005) showed adding organic matter to forest soils can reduce runoff energy and rates. Hunsaker et al. (2015) showed restoring creeks and streams can reconnect them to wetlands and local floodplains, raising local water tables and potentially increasing groundwater recharge. Furthermore, Bachand et al. (2019a) suggested existing groundwater flow paths from upland alluvial areas to deeper groundwater (Bohm 2016a) could be bolstered by recharge or restoration efforts in these upland areas. Thus, more coordinated and active upland management could improve valley groundwater conditions over the long term.

<u>Conducting local recharge in the valley to benefit groundwater dependent ecosystems.</u> Flooding agricultural lands with excess surface water can be a cost-effective method to improve groundwater conditions in places with appropriate needs and conditions (Bachand et al. 2016, Maliva 2011, DWR 2018). In Sierra Valley, these methods are unlikely to recharge deeper groundwater because fine sediment layering associated with lacustrine deposits block deep percolation (Bachand et al. 2019a). However, these approaches in the southwestern and western valley or along Last Chance Creek could potentially increase local shallow groundwater levels and promote gaining conditions in local stream stretches (Bachand et al. 2019a). Flooding agricultural lands adjacent to targeted streams or restoring channels to improve connection between streams and their local floodplains are potential approaches to benefit groundwater dependent ecosystem streams.

<u>Increasing groundwater recharge through reservoir re-operation.</u> Frenchman Dam is owned and operated by DWR and was originally designated for irrigation and recreation. Little Last Chance Creek Water District has the majority of senior water rights for Frenchman Dam water. Non-allocated waters, such as the overtopping of Frenchman Dam in wet years, potentially present recharge opportunities. Reservoir spill, which is relatively infrequent, could increase under climate change (DWR 2019a,b) as discussed earlier. DWR has begun investigating changing reservoir operations throughout California to improve surface water and groundwater management under climate change (DWR 2017). Potentially, operational changes in Frenchman Dam could benefit Sierra Valley groundwater and surface water management by 1) improving the connection between Little Last Chance Creek and its floodplain upstream of the valley to promote deep aquifer recharge, or 2) promoting recharge in the valley to support groundwater dependent ecosystems.

8. Broaden Stakeholder Participation

Agricultural well owners are currently the most involved stakeholders in the SGMA process. SGMA defines beneficial users as agricultural users, domestic and municipal well owners, public water systems, local land use planning agencies, environmental users of groundwater, surface water users, the federal government, California Native American tribes, disadvantaged communities and groundwater monitoring agencies (SGMA 2016).

The federal government (e.g. US Forest Service, Bureau of Land Management) can voluntarily enter into an agreement with local agencies in the basin if they have a shared interest in groundwater sustainability (SGMA 2016). In Sierra Valley, public and private land and resource uses are tightly linked. For instance, the Sierra Valley watershed is 291,500 acres but only 125,100 of these acres are private. The U.S. Forest Service, Bureau of Land Management, and California Department of Fish & Wildlife (CDFW) hold the other 57%. Public land management likely affects watershed hydrology and basin groundwater sustainability. Sierra Valley residents and beneficial users should seek to form agreements with federal agencies given the shared interest in groundwater sustainability and the interconnectedness between land uses and hydrology. These agreements could seek to collaborate on multi-benefit sustainable resource management programs, policies or strategies.

Frenchman Dam was installed in the early 1960s and has fundamentally changed the region's hydrology in terms of the timing, duration and volume of outflows from the Little Last Chance Creek watershed. By constructing Frenchman Dam, DWR promoted greater water usage by capturing spring runoff and supplying inexpensive surface water for irrigation later in the season. The SGMA basin prioritization for Sierra Valley acknowledges that reservoir operations are beyond the control of local water managers (DWR 2019), suggesting some shared responsibility for the condition of groundwater in Sierra Valley. Furthermore, Sierra Valley is at the headwaters of the Middle Fork Feather River, a federally-designated Wild and Scenic river that feeds Oroville Dam, a major reservoir in the State Water Project. Over the last half century, Sierra Valley hydrology has departed from historic conditions in part due to DWR's involvement and activities in Sierra Valley, with positive and negative impacts for local and State stakeholders. SVGMD should collaborate with DWR in their groundwater sustainability efforts.

Conclusion

Since the 1960s, groundwater levels, particularly for deeper groundwater (approximately 300 feet or more below ground surface), have been in general decline in Sierra Valley due to pumping and overdraft. Aside from decreasing groundwater levels, groundwater overdraft has been linked to subsidence and loss of artesian wells. Dropping groundwater levels may also be reducing surface flows in local streams and impacting the rich local flora and fauna by altering habitat availability. Furthermore, declining groundwater levels could threaten local communities by decreasing water supply or quality in residential wells. All these problems are likely to be exacerbated as climate change alters watershed hydrology.

SGMA is launching a two-decade process for basins with unsustainable groundwater management to achieve sustainability. Six indicators are used to measure groundwater sustainability: groundwater levels, aquifer storage, water quality, land subsidence, surface water beneficial uses that depend upon groundwater and seawater intrusion. For basins like Sierra Valley designated as medium priority or higher, SGMA places responsibility on local GSAs to develop GSPs that present defensible paths to groundwater sustainability.

For Sierra Valley, the SVGMD, as the GSA, will need to address five potential undesirable results identified in the basin prioritization (DWR 2019): groundwater level declines, aquifer storage loss, water quality degradation, land subsidence, and negative impacts to beneficial surface water uses, including damage to groundwater dependent ecosystems. The GSP will identify a strategy to avoid and mitigate unreasonable and significant progression of these results. The GSP will define what constitutes "unreasonable and significant" relative to minimum thresholds for each indicator, and will monitor progress toward measurable objectives with regular updates to DWR. The GSP will require approval by DWR, and failure to prevent or mitigate undesirable results may lead to intervention by the State Water Resources Control Board.

As a first step, SGMA requires the GSP to provide background information characterizing the basin, including a water budget and hydrologic conceptual model. Conceptual models, water budgets and numerical models can then potentially be used to help determine corrective actions and to gauge the effectiveness of those actions. However, Sierra Valley in not an appropriate place to rely heavily on these types of tools. Sierra Valley is near the snowline and experiences variations in precipitation, both in magnitude and type (i.e., rain, snow), that appear to be increasing, attributed in part to climate change. The Sierra Valley basin is an ancient glacial lakebed with fine-grained lacustrine silt and clay layers that impede infiltration of surface water to deep groundwater. Faults running diagonally across the valley in a northwest direction impede groundwater flow. All these factors increase uncertainties and reduce the ability of water budgets and numerical models to accurately quantify sustainable yield or other hydrologic metrics. Rather, these factors point to the need to develop a robust adaptive management approach that efficiently develops the data needed to inform progress toward sustainable groundwater management.

Currently, surface hydrologic data is limited in the Sierra Valley watershed, with flow monitoring only at the Middle Fork Feather River at Portola as the river leaves the basin, three rain and two snow stations within the basin and reservoir level measurements at Frenchman Dam and Lake Davis. Groundwater monitoring is more extensive with about a dozen SVGMD wells and a CASGEM network of about 130 wells. Hydrologic data will need to be improved to provide sufficient and actionable information given the basin's complexity and uncertainty related to geology, hydrology and climate. Sierra Valley groundwater managers will need to develop a more robust and defensible dataset that –

- can be used to assess the success of actions taken to achieve groundwater sustainability,
- can be used to adaptively manage the basin and develop informed and more cost-effective strategies toward sustainability, and
- can engage and be of value to SGMA beneficial users and to stakeholders.

Moving forward, we have identified eight priorities for the GSP development and implementation process in Sierra Valley:

1. Create management areas that correspond to differing conditions in Sierra Valley;
2. Develop more robust monitoring networks;
3. Improve groundwater level and pumping data;
4. Implement more consistent surface water sampling;
5. Standardize data sampling and reporting;
6. Implement an adaptive management approach for sustainable groundwater management;
7. Investigate promising mitigation strategies; and
8. Broaden stakeholder participation.

Cited Works

Allen, R., Irmak, A., Trezza, R. Hendrick, J., Bastiaanssen, W., Kjaersgaard, J., 2011. Satellite-based ET estimation in agriculture using SEBAL and METRIC. *Hydrological Processes,* 25, pp.4011-4027.

Atkinson, A.J., P.C. Trenham, R.N. Fisher, S.A. Hathaway, B.S. Johnson, S.G. Torres, and Y.C. Moore. 2004. Designing monitoring programs in an Adaptive Management context for regional multiple species conservation plans. U.S. Geological Survey Technical Report, USGS Western Ecological Research Center, Sacramento, CA.

Salafsky, N., R. Margoluis, and K. Redford. 2001. Adaptive Management: A Tool for Conservation Practitioners. Biodiversity Support Program, Washington, DC. Available on www.worldwildlife.org/bsp/.

Audubon. 2008. Important Bird Areas: Sierra Valley, California. Plumas Audubon. https://www.audubon.org/important-bird-areas/sierra-valley. Accessed August 28, 2019.

Bachand P., Roy S., Stern N., Choperena J., Cameron D., Horwath W., 2016. On-Farm flood capture could reduce groundwater overdraft in Kings River Basin. *California Agriculture,* 70(4), pp.200-207.

Bachand P.A.M, Burt, K.S., Cartlon, S., Bachand, S.M., 2019a. Groundwater relationships to pumping, precipitation and geology in intermontane basin, Sierra Valley, CA. In preparation.

Bachand, P.A.M., Hossner, R., Carlton, Bachand, S.M., Kajiwara, S., Wasem, C., 2019b. Increased shallow groundwater levels from Irrigation-For-Recharge (IFR) provides a potential strategy to improve salmonid habitat in Mark West Creek while benefiting growers. In preparation.

Bohm, B., 2015. Groundwater recharge and forest canopy thinning. Plumas Geo-hydrology.

Bohm, B. 2016a. Sierra Valley Aquifer Delineation and Ground Water Flow. Plumas Geo-hydrology. December 2016.

Bohm, B. 2016b. Inventory of Sierra Valley Wells and Groundwater Quality Conditions. Plumas Geo-hydrology. December 2016.

Bohm, B. 2016c. Forest and Water Balances, an Exploratory Study: Concepts of the Upper Feather River Basin Uplands Hydrology. Draft, June 29, 2016. Appendix 3-2. UFRRWMG, IRMW.

CA Senate & Assembly Legislature, 2014. Sustainable Groundwater Management Act. Senate Bill No. 1168, Senate Bill No. 1319, Assembly Bill No. 1739.

California Water Boards. 2019a. Sustainable Groundwater Management Act, Water Quality Frequently Asked Questions. Posted October 10, 2019. https://www.waterboards.ca.gov/water_issues/programs/gmp/docs/sgma/sgma_wtr_qual.pdf

California Water Boards. 2019b. GAMA – Groundwater Information System. https://gamagroundwater.waterboards.ca.gov/gama/gamamap/public/Default.asp

CDEC, 2019. DWR California Data Exchange Center. http://cdec.water.ca.gov/cdecstation2/. Accessed 8/26/2019.

CEC. 2018. Climate Change Risk Faced by the California Central Valley Water Resource System. A report for California Fourth Climate Change Assessment. California Energy Commission and California Natural Resources Agency. August 2018. CCCA4-EXT-2018-001.

CNAP, 2019. Water Storage Tracking in California. California-Nevada Climate Applications Program. Web. Accessed 2/27/2019. https://scripps.ucsd.edu/programs/cnap/water-storage-tracking-in-california/

CNRA, 2019. California Natural Resources Agency, California Streams. ArcGIS map for Sierra Valley. https://arcg.is/5Svjq. Accessed 8/26/2019.

Conklin, M., R. Bales, P. Saksa, S. Martin and R. Ray. 2015. Appendix E: Water Team Final Report. Sierra Nevada Adaptive Management Project. December 15, 2015.

Dahlke, H., Brown, A., Orloff, S., Putnam, D., O'Geen, T., 2018. Managed winter flooding of alfalfa recharges groundwater with minimal crop damage. *California Agriculture,* 72(1), pp.65-75.

Dettinger, M., Anderson, M., 2015. Storage in California's Reservoirs and Snowpack in This Time of Drought. *San Francisco Estuary and Watershed Science*, 13(2). June 2015.

Dobbin, K., Clary, J., Firestone, L., Christian-Smith, J., 2015. Collaborating for Success: Stakeholder Engagement for Sustainable Groundwater Management Act Implementation. Community Water Center, Clean Water Fund, Union of Concerned Scientists. July 2015. https://www.cleanwateraction.org/files/publications/ca/SGMA_Stakeholder_Engagement_White_Paper.pdf

DWR, 1983. Sierra Valley Ground Water Study 1983. California Department of Water Resources, Northern District. Memorandum Report. June 1983.

DWR, 2003. Sierra Valley Groundwater Basin, Sierra Valley Groundwater Sub-basin. Bulletin 118, Basin Boundary Description. California Department of Water Resources. October 2003. https://water.ca.gov/-/media/DWR-Website/Web-Pages/Programs/Groundwater-Management/Bulletin-118/Files/2003-B118-Basin-Descriptions/B118-Basin-Boundary-Description-2003---5_012_01.pdf

DWR, 2010. Groundwater Elevation Monitoring Guidelines. California Statewide Groundwater Elevation Monitoring Program. Department of Water Resources. December 2010.

DWR, 2014. California Water Plan, Update 2013, Volume 1: The Strategic Plan. California Department of Water Resources. October 2014. https://water.ca.gov/-/media/DWR-Website/Web-Pages/Programs/California-Water-Plan/Water-Plan-Updates/Files/Update-2013/Water-Plan-Update-2013-Volume-1.pdf

DWR, 2016a. Best Management Practices for the Sustainable Management of Groundwater. California Department of Water Resources. December 2016. https://water.ca.gov/Programs/Groundwater-Management/SGMA-Groundwater-Management/Best-Management-Practices-and-Guidance-Documents

DWR, 2016b. GSP Emergency Regulation. California Water Code. Department of Water Resources. May 2016. https://water.ca.gov/LegacyFiles/groundwater/sgm/pdfs/GSP_Emergency_Regulations.pdf

DWR, 2017a. System Reoperation Study, Phase III Report: Assessment of Reoperation Strategies. Department of Water Resources. August 2017.

DWR. 2017b. 2017 CVFPP Update – Climate Change Analysis Technical Memorandum. CVFPP 2017 Update. Technical Series. State of California, Natural Resources Agency, Department of Water Resources. March 2017.

DWR, 2018. Flood-MAR: Using Flood Water for Managed Aquifer Recharge to Support Sustainable Water Resources. California Department of Water Resources. June 2018.

DWR, 2019. Basin Prioritization. https://water.ca.gov/Programs/Groundwater-Management/Basin-Prioritization. Accessed August 23, 2019.

Dib, A., Ceyhan, S., Kavvas, M.L., Ishida, K., Jang S., Ohara N., 2016. Final Report on The Upper Middle Fork Project. Hydrologic Research Laboratory, Department of Civil and Environmental Engineering, University of California, Davis. Report to Plumas County. December 2016.

Farr, T.G., Jones C.E., Liu, Z., 2016. Progress Report: Subsidence in California, March 2015 – September 2016. Jet Propulsion Laboratory, California Institute of Technology.

Rist, L., Felton, A., Samuelsson, L., Sandström, C., Rosvall, O. (2013), A new paradigm for adaptive management. Ecology & society, 18(4): 63http://dx.doi.org/10.5751/ES-06183-18046

Freeman, G.J. 2012. Analyzing the impact of climate change on monthly river flows in California's Sierra Nevada and Southern Cascade Mountain Ranges. Power Generation Department, Pacific Gas &Electric Co., Mail Code N13A, P.O. Box 770000, San Francisco, CA 94177, GJF2@pge.com. Western Snow Conference 2012.

FRLT. 2019. Feather River Land Trust Personal communications.

GE. 2019. Google Earth Pro imagery.

Godsey, S.E., Kirchner, J.W. and Tague, C.L., 2014. Effects of changes in winter snowpacks on summer low flows: case studies in the Sierra Nevada, California, USA. *Hydrological Processes,* 28(19), pp.5048-5064.

Grismer, M.E., Hogan, M.P., 2005. Simulated Rainfall Evaluation of Revegetation/Mulch Erosion Control in the Lake Tahoe Basin. *Land Degrad. Develop.*, 16, pp.489-501

Huang, X., Hall, A. D., & Berg, N., 2018. Anthropogenic Warming Impacts on Today's Sierra Nevada Snowpack and Flood Risk. *Geophysical Research Letters*, 45 pp.6215 – 6222

Hunsaker, C., Swanson, S., McMahon, A., Viers, J., Hill, B., 2015. Effects of Meadow Erosion and Restoration on Groundwater Storage and Baseflow in National Forests in the Sierra Nevada, California. US Forest Service.

IPCC, 2018. Global Warming of 1.5 degrees C, An IPCC Special Report. Summary for Policymakers. Intergovernmental Panel on Climate Change.

Kisekka, I., Oker, T., Nguyen, G., Aguilar, J. and Rogers, D., 2017. Revisiting precision mobile drip irrigation under limited water. *Irrigation Science*, 35(6), pp.483-500.

Li, Z., Schneider, R., Morreale, S., Xie, Y., Li, C., Li, J., 2017. Woody organic amendments for retaining soil water, improving soil properties and enhancing plant growth in desertified soils of Ningxia, China. *Geoderma*, 310, pp.143 – 152.

Maliva, R. 2014. Economics of Managed Aquifer Recharge. *Water*, 6, pp.1257 – 1279. doi:10.3390/w6051257

Moran, T. and A. Belin. 2019. A Guide to Water Quality Requirements under the Sustainable Groundwater Management Act. Stanford, Water in the West. Spring 2019. https://stacks.stanford.edu/file/druid:dw122nb4780/A%20Guide%20to%20Water%20Quality%20Requirements%20under%20SGMA.pdf

National Research Council. 2004. Adaptive Management for Water Resources Planning, The National Academies Press. Washington, DC.

NRCS. 2016. Sierra Valley Conservation Partnership Project. Awarded 2016. https://www.nrcs.usda.gov/wps/portal/nrcs/detail/ca/programs/farmbill/rcpp/?cid=nrcseprd1295237

North, M., P. Stine, K. O'Hara, W. Zielinski and S. Stephens. 2009. An Ecosystem Management Strategy for Sierran Mixed-Conifer Forests. USDA Forest Service General Technical Report PSW-GTR-220 (Second printing with addendum). March 2009.

Pathak, T.B., Maskey, M.L., Dahlberg, J.A., Kearns, F., Bali, K.M., Zaccaria, D., 2018. Climate Change Trends and Impacts on California Agriculture: A Detailed Review. *Agronomy* 8(3).

Pierce, D.W. and D.R. Cayan, 2013: The Uneven Response of Different Snow Measures to Human-Induced Climate Warming. *J. Climate,* 26, 4148–4167, https://doi.org/10.1175/JCLI-D-12-00534.1

Salafsky, N., R. Margoluis, and K. Redford. 2001. Adaptive Management: A Tool for Conservation Practitioners. Biodiversity Support Program, Washington, DC. Available on www.worldwildlife.org/bsp/.

SBPSD, 2017. 2016 Consumer Confidence Report. Sierra Brooks Public Supply District. June 2017.

Schmidt, K.D., 2003. Hydrogeology and Groundwater Monitoring in Sierra Valley. Kenneth D. Schmidt and Associates. May 2003.

Schmidt, K.D., 2005. Sierra Valley Hydrogeologic Studies. Kenneth D. Schmidt and Associates. May 2005.

Schmidt, K.D., 2012. Hydrogeologic Evaluation for Sierra Valley. Kenneth D. Schmidt and Associates. May 2012.

Schmidt, K.D., 2015. Hydrogeologic Evaluation for Sierra Valley. Kenneth D. Schmidt and Associates. May 2015. http://www.sierravalleygmd.org/files/b3e5c94e6/2012-2014TechnicalReport.pdf

Schmidt, K.D., 2017. Hydrogeologic Evaluation for Sierra Valley. Kenneth D. Schmidt and Associates. July 2017.

SGMA. 2016. Sustainable Groundwater Management Act. https://water.ca.gov/-/media/DWR-Website/Web-Pages/Programs/Groundwater-Management/Sustainable-Groundwater-Management/Files/2014-Sustainable-Groundwater-Management-Legislation-with-2015-amends-1-15-2016.pdf

Smerdon, B.D., Redding T.E., and Beckers, J., 2009. An overview of the effects of forest management on groundwater hydrology. *BC Journal of Ecosystems and Management,* 10(1) pp.22-44.

Stewart, I.T., Cayan, D.R., Dettinger, M.D. 2004. Changes in snowmelt runoff timing in western North America under a 'business as usual' climate change scenario. *Climatic Change*, 63(3), 217 – 232.

TNC. 1999. Sierra Nevada Ecoregional Plan. The Nature Conservancy. https://www.conservationgateway.org/ConservationPlanning/SettingPriorities/EcoregionalReports/Documents/SierraNV_plan_LowRes.pdf. Assessed August 28, 2019.

UFRRWMG, 2016. Upper Feather River Integrated Regional Water Management Plan, Update 2016. Upper Feather River Regional Water Management Group; Uma Hinman Consulting. November 2016. http://featherriver.org/ufr-irwm-plan/

USGS, 2017. Land Subsidence: Cause & Effect. United States Geological Survey. Web. Accessed 2/28/2019. https://ca.water.usgs.gov/land_subsidence/california-subsidence-cause-effect.html

Vestra, 2005. Sierra Valley Watershed Assessment. Vestra Resources. April 2005.

Waechter, S.A. and T.E. Norton. 2002. Step Back in Time, Archaeology and Prehistory in Sierra Valley. Far Wester Anthropological Research Group, Inc. for the California Department of Transportation, District 2, Redding. http://caltrans2.info. http://farwestern.com/wordpress/wp-content/uploads/2014/05/Step_Back_In_Time.pdf. Accessed August 29, 2019.

Williams, B. K., R. C. Szaro, and C. D. Shapiro. 2009. Adaptive Management: The U.S. Department of the Interior Technical Guide. Adaptive Management Working Group, U.S. Department of the Interior, Washington, DC.

Wyatt, C., O'Donnell, F., Springer, A. 2015. Semi-Arid Aquifer Responses to Forest Restoration Treatments and Climate Change. *Groundwater*, 53(2), pp.207–216.

Yu, O., Harper, M., Hoepfl, M., Domermuth, D., 2017. Characterization of Biochar and Its Effects on the Water Holding Capacity of Loamy Sand Soil. *Environmental Progress & Sustainable Energy*, 36(5).

Zhu, X., Peters, T., Neibling, H. 2016. Hydraulic performance assessment of LESA at low pressure. *Irrigation and Drainage*, 65 pp.530 – 536.