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Groundwater relationships to pumping, precipitation and geology in high-elevation basin, Sierra Valley, CA

P.A.M. Bachand[1], K.S. Burt[1], S. Carlton[2] and S.M. Bachand[1]

[1]Bachand & Associates, [2]Carlton Hydrology

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Written by:

P.A.M. Bachand[1], K.S. Burt[1], S. Carlton[2], and S.M. Bachand[1]

[1]Bachand & Associates, Davis, CA; [2]Carlton Hydrology, Grass Valley, CA

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For more information, please contact Philip Bachand, Ph.D., President, Bachand & Associates, 231 G Street Ste 28, Davis, CA 95616, 530-574-3376. philip@bachandassociates.com

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1.3 Acronyms and Abbreviations

AF	Acre-feet, volume measurement
AMSL	Above mean sea level
BGS	Below ground surface
CASGEM	California Statewide Groundwater Elevation Monitoring Program
CDEC	California Department of Water Resources California Data Exchange Center
CFS	Cubic feet per second, flow measurement
CGS	California Geological Society
DWR	California Department of Water Resources
ETo	Reference evapotranspiration
FloodMAR	Flood-managed aquifer recharge
Ft	Feet
GSA	Groundwater Sustainability Agency, SGMA
GSP	Groundwater Sustainability Plan, SGMA
GVE	Grizzly Valley east fault
GVW	Grizzly Valley west fault
GWE	Groundwater elevations
INSAR	Interferometric Synthetic Aperture Radar
JPL	NASA Jet Propulsion Lab
LESA	Low elevation spray application irrigation system
MFFR	Middle Fork Feather River
OFR	On-farm recharge
PLSS	Public Land Survey System
QAQC	Quality assurance / quality control
SGMA	2014 Sustainable Groundwater Management Act
SJV	San Joaquin Valley
SOP	Standard Operating Procedures
SVGMD	Sierra Valley Groundwater Management District
SWE	Snow water equivalent
SWRCB	State Water Resources Control Board
UCCE	University of California Cooperative Extension
USFS	U.S. Forest Service
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
WQCC	Water quality constituents of concern, typically regulated

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Bachand & Associates, Carlton Hydrology

2 Abstract

Sierra Valley, located in the northern Sierra Nevada, California, serves as the Middle Fork Feather River headwaters and provides surface water to Oroville Dam of the California State Water Project (SWP). Under California's Sustainable Groundwater Management Act (SGMA), the Sierra Valley sub-basin has been designated a medium-priority basin, due to chronic groundwater declines and the valley's high ecological value as the largest freshwater marsh and meadow system in the Sierra Nevada. The Sierra Valley Groundwater Management District (SVGMD) serves as the Groundwater Sustainability Agency (GSA) for the Sierra Valley sub-basin. As such, SVGMD is tasked through SMGA with achieving sustainable groundwater management over an approximate 20-y timeframe. The first step is the development of a Groundwater Sustainability Plan (GSP) (to be completed by January 2022) that 1) hydrologically assesses the basin, 2) identifies methods and protocols to track groundwater trends, and 3) develops an initial suite of actions to move the basin towards groundwater sustainability.

Agricultural groundwater pumping in Sierra Valley, primarily occurring in the eastern half of the valley, averages around 8600 acre-feet (AF) (10.6M m^3) annually over the last 20 years and exceeded 10,000 AF y^{-1} (12.3M m^3 y^{-1}) from 2013 – 2016. We estimate sustainable yield for the eastern valley to be about 6000 AF y^{-1} (7.4M m^3 y^{-1}). Thus, groundwater has been overdrafted most years in the last two decades, resulting in shallow and deep groundwater declines, loss of artesian wells and springs, and subsidence in the overdrafted area. Shallow groundwater in the wetter western valley is showing some signs of groundwater pumping pressure, potentially impacting the valley's wetland habitat. These issues, among others, are common throughout California and are identified in SGMA as sustainability indicators – metrics for groundwater conditions that will be used to measure the progress of GSP implementation.

Our investigation builds on previous watershed studies and further establishes the Sierra Valley watershed as a highly complex hydrologic system. These complexities include: large variation in precipitation phase and quantity throughout the watershed; geologic features that restrict both vertical and lateral groundwater flow; many water inflow pathways, both surface and sub-surface, that are logistically impossible to quantify by conventional monitoring means. Prior attempts at developing accurate water budgets and numerical models of the watershed have been hindered by the uncertainty these factors present. Thus, though a hydrologic budget is required by SGMA for the development of the GSP, numerical models will be of limited utility as either tools to derive hydrologic budgets or to help determine the efficacy management actions to achieve sustainable groundwater conditions.

In developing strategies to address undesirable groundwater conditions, we recommend an adaptive management approach paired with targeted and defensible data collection with standardized data collection, management and quality control procedures. This flexible decision-making process uses an increasingly well-developed understanding of outcomes from prior management actions to make more effective management decisions. For this approach, a monitoring network with sufficient temporal and spatial data density will be needed to assess progress towards sustainability across the different sustainability measures (e.g. groundwater elevation, groundwater pumping, subsidence). Direct or indirect hydrologic data gaps include 1) stream network monitoring to inform on area climate change effects and groundwater dependent ecosystems; 2) an improved groundwater network with sufficient temporal and spatial data density for water quality and well level trend assessment; and 3)

topographic surveys to increase well measurement accuracy, groundtruth DWR subsidence data and define subsidence-water level relationships.

We also identified a number of actions to potentially increase water supply and reduce water demand: improving irrigation system efficiencies; amending agricultural soils with organic amendments to improve water holding capacity; increasing multipurpose forest restoration programs to increase forest health, reduce fuels, reduce runoff and increase groundwater recharge; and making operational changes to Frenchman Dam to enhance recharge opportunities. With 57% of the watershed owned as public lands and outside of SVGMD's jurisdiction and control, SVGMD would benefit from the development and adoption of a collective vision with a broader stakeholder community that extends beyond the basin and represents the broader watershed.

3 Introduction

Sierra Valley is a 5000 ft elevation mountain basin at the Middle Fork Feather River (MFFR) headwaters, about fifty miles north of Lake Tahoe and draining the northern Sierra Nevada in California (Figure 1, Schmidt, 2017; DWR, 2003b). Originally formed by separating fault blocks, the basin is an ancient glacial lakebed filled with layers of lacustrine and upland sediments (Bohm, 2016a; Figure 2a). Much of Sierra Valley is private land used for livestock grazing and hay crops, while the surrounding watershed is primarily National Forest land (Vestra, 2005). In this manuscript, we distinguish between the eastern valley and the western valley due to the climatic and hydrologic differences east and west of the Grizzly Valley Fault (Figure 1).

Vestra (2005) estimated the watershed's total water budget at 643,000 acre-ft (AF) annually and Dib et al. (2017) estimated approximately 189,000 AF of that water directly falls on or flows into the groundwater basin (Dib et al., 2017). Between 70 and 80% of the total water budget is estimated to be lost to evapotranspiration. (Vestra 2005, Dib et al., 2017). Precipitation, falling as both rain and snow, is estimated to be twice as high in the west than in the east (Vestra, 2005). Two tributaries – Little Last Chance Cr., flowing out of Frenchman Lake in the northeast, and Smithneck Cr., entering the valley in the southeast – flow perennially from the eastern uplands, spread out across the valley, and feed the multitude of braided channels in the west during the winter (Figure 1, Vestra, 2005). Surface water also enters Sierra Valley from the western and southern periphery from nearly a dozen named creeks and many other unnamed creeks (Figure 1). These creeks and streams likely are the primary source of MFFR outflows based upon historic flow records and on a precipitation distribution that decreases along a west to east gradient (Vestra, 2005; DWR, 1983). During summer, appropriative and riparian water right holders in the eastern valley divert nearly all available stream flows to irrigate alfalfa and pastures (Vestra, 2005; Bohm, 2016). Frenchman Dam regulates Little Last Chance Creek flows throughout the summer for irrigated agriculture, generally drying out Little Last Chance Creek before its confluence with the western channels (Vestra, 2005). Increasing agricultural production has led to greater landowner competition for surface water rights and increased reliance on groundwater supply (Vestra, 2005).

Long term pumping has both lowered groundwater levels and caused land subsidence, primarily in the eastern valley (Schmidt, 2017; DWR, 1983, 2003b; Farr, 2016). Most pumping is from a small number of irrigation wells (Bohm, 2016b; Schmidt, 2017). Total municipal pumping for residential water supply in Sierra Brooks, Calpine and Loyalton averages 665 AF y^{-1}, likely insignificant to groundwater overdraft (SVGMD, 2019). Two main water producing aquifer zones exists in Sierra Valley: shallow and deep (Schmidt, 2005; Figure 2a). Parts of the deep aquifer zone may be pressurized, confined by low-permeability layers (Figure 2b; Bohm, 2016a). The vertical extent and isolation between these zones likely vary throughout the Sierra Valley sub-basin (Figure 2; Schmidt, 2005; Bohm, 2016a). Three geologic features potentially limit lateral groundwater flow from supply areas to the cone of depression: the eastern and western lineaments that make up the Grizzly Valley Fault, and the subsurface bedrock ridge dividing the Chilcoot and Sierra Valley sub-basins (DWR, 2003b; Bohm, 2016a).

The valley's groundwater levels follow an annual cycle with a spring peak corresponding with precipitation and a fall trough after summer irrigation pumping (Schmidt, 2017). Historically, this cycle had a small range, and flowing artesian wells were common in the valley (Schmidt, 2017). Since the 1990s, a large cone of depression has formed in the northeast valley and most artesian wells have dried up (Schmidt, 2003, 2005, 2011, 2015, 2017; DWR, 2003b). Annual groundwater pumping peaked in 1981 at 14,500 AF corresponding to increases in alfalfa, grain and truck-crop production (DWR, 1983). In 1980 and in response to concern about planned water exports, CA Senate Bill 1391 authorized the formation of the first two California groundwater regulating agencies, the Sierra Valley Groundwater Management District (SVGMD), and neighboring Long Valley Groundwater Management District (DWR, 2003a; SB 1391, 1980). Following groundwater pumping reductions and a series of very wet years in the 1990s, groundwater levels recovered to nearly historic conditions near the turn of the century (Schmidt, 2015). Since 2000, groundwater levels have declined below 1980 levels due to increased agricultural pumping (DWR, 1983, 2003b, 2019; Schmidt, 2003, 2017; Bohm, 2016a) and a series of multi-year droughts (Schmidt, 2017). In recent years, annual groundwater pumping has generally exceeded 10,000 acre-feet (AF) and comes primarily from about 50 irrigation wells (out of the total 900 valley wells) (Schmidt, 2017; Bohm, 2016a).

Concurrent with expanding groundwater pumping, Frenchman Dam was constructed in 1961. Frenchman Dam, owned and operated by DWR, created a 55,477 AF reservoir drawing water from Little Last Chance Creek's 52,000-acre drainage (Vestra, 2005). Managed for irrigation, Frenchman Dam shifted surface water from natural spring-time flows, peaking in April, to managed summer-time flow (Vestra, 2005). Now, the natural creek bed is disconnected from groundwater (Bohm, 2016a).

Groundwater overdraft has been common throughout California, especially in the heavily farmed San Joaquin Valley (SJV) where annual groundwater pumping for irrigation from underlying aquifers has chronically exceeded natural recharge rates (DWR 2003a, 2014; Famiglietti, et al., 2011), resulting in land subsidence, decreased aquifer storage, and hydrologic changes to connected surface water systems (DWR, 2014). To address this problem, the California legislature passed the Sustainable Groundwater Management Act (SGMA) in 2014, and the California Department of Water Resources (DWR) categorized the 515 groundwater basins in the state into four priority categories and designated them critically or non-critically overdrafted based upon their scoring criteria (SGMA, 2014; DWR, 2019). Under this legislation, medium- and high-priority basins must form Groundwater Sustainability Agencies (GSAs) to develop and implement Groundwater Sustainability Plans (GSPs) to achieve sustainability of groundwater management over the next two decades (SGMA, 2014).

SGMA identifies six sustainability indicators (DWR 2016b):

(1) Chronic lowering of groundwater levels indicating a significant and unreasonable depletion of supply if continued over the planning and implementation horizon.
(2) Significant and unreasonable reduction of groundwater storage.
(3) Significant and unreasonable seawater intrusion. This result only applies to coastal aquifers.
(4) Significant and unreasonable degraded water quality, including the migration of contaminant plumes that impair water supplies.
(5) Significant and unreasonable land subsidence that substantially interferes with surface land uses.
(6) Depletions of interconnected surface water that have significant and unreasonable adverse impacts on beneficial uses of the surface water. This result is commonly referred to as impacts to "groundwater-dependent ecosystems" (SGMA, 2014; DWR 2019).

"The significant and unreasonable occurrence of any of the six sustainability indicators constitutes an unreasonable result" (DWR 2017). The GSP will define what is significant and unreasonable based on measurements of key data for each sustainability indicator and delineate strategies to respond to the occurrence of undesirable results (SGMA, 2014, DWR, 2016b). January 1, 2015 is the baseline date for beginning assessment of sustainability indicators; undesirable results occurring before this date may optionally be addressed. The conditions underlying each undesirable result can be localized, such as land subsidence affecting critical infrastructure, or basin-wide, such as groundwater declines across a basin or management area. Ultimately, SGMA compliance will require reducing groundwater pumping, increased recharge, or both (DWR, 2016a; Bachand et al., 2016).

The Sierra Valley sub-basin has been designated medium priority, with non-critical overdraft. As a DWR-designated medium priority sub-basin, Sierra Valley will need to submit a GSP to DWR by January 31, 2022. The existing groundwater management agency in Sierra Valley, SVGMD, has adopted GSA status (SVGMD, 2017), as has Plumas County in order to represent a small northwestern portion of the sub-basin outside SVGMD boundaries. These GSAs are responsible for drafting the GSP for the Sierra Valley sub-basin. The Chilcoot sub-basin in Sierra Valley has very low priority status under SGMA and is not required to form a GSA, nor develop a GSP, but is hydrologically connected to the Sierra Valley sub-basin and is covered by the SVGMD management area. Together the Chilcoot and Sierra Valley sub-basins make up the Sierra Valley Groundwater Basin; we will employ this terminology hereafter, using 'basin' independent of a name only when referring to general characteristics of a groundwater basin.

Interest in Sierra Valley and groundwater sustainability extends beyond the region and its farmers. As the headwaters to the Middle Fork Feather River (MFFR), Sierra Valley supplies water to Lake Oroville, part of the State Water Project (USFWS, 2018; DWR, 2018b). The 78-mile stretch of the MFFR downstream of Sierra Valley is designated a Wild and Scenic River (USFWS, 2018). Sierra Valley has an approximately 20,000-acre wetlands complex and approximately 30,000 acres meadow complex, both the largest in the Sierra Nevada (NRCS, 2016). Approximately 280 bird species, 25 special status bird species, and over 1,200 plant species representing 18% of California's flora are found in Sierra Valley (NRCS, 2016). Several efforts and organizations have identified Sierra Valley as a top conservation priority (TNC, 1999; Audubon, 2008; NRCS, 2016). The Washoe and Maidu tribes claim Sierra Valley as part of their ancestral territory (Waechter and Norton 2002; UFRRWMG, 2016; Vestra, 2005).

In this report, we analyze the hydrologic data for the Sierra Valley watershed in the context of SGMA and a changing climate, primarily focusing on the Sierra Valley sub-basin groundwater conditions and the impact of complex hydrology and geology. From this analysis we have estimated sustainable yield and considered the utility of water budgets and numerical models to help manage groundwater. Finally, we consider a broad suite of actions that could be pursued to improve area groundwater sustainability.

4 Methods

4.1 Area Designation

For comparison purposes in this report, areas within the Sierra Valley Groundwater Basin are ascribed to four general regions (see Figure 1):

- the Chilcoot sub-basin;
- the eastern valley – all of the Sierra Valley sub-basin east of the Grizzly Valley Fault;
- the western valley – the area west of the Grizzly Valley Fault, excluding the southwestern valley;
- the southwestern valley – the area south of Calpine

4.2 Data Sources

This manuscript draws upon a broad range of surface water and groundwater data.

4.2.1 Surface Water: reservoir, river, precipitation, evapotranspiration

California Data Exchange Center (CDEC) and United States Geological Society (USGS) websites provided historical and current reservoir level, river flow and river stage data (CDEC, 2018; USGS, 2018). The MFFR station, near Portola, is the only active flow monitoring station in Sierra Valley. Four stations measure rainfall (i.e., Vinton, Portola, Sierraville, Frenchman Dam) within the Sierra Valley watershed and three stations measure snowfall in the surrounding mountains (i.e. Frenchman Cove in the northeast at 5800 ft, Yuba Pass in the southwest at 6700 ft, Independence Creek south of the valley at 6500 ft) (Figure 1, SI Table 1). For precipitation as snow, we report peak snow water equivalent (SWE) – the annual maximum depth of water available if the snowpack melted instantaneously. Peak SWE slightly underestimates total snow water reaching the watershed as periods of melting followed by more snowfall are not accounted for. Only long-term monthly averages were available through the NRCS website for snowfall on the valley floor. With < 1 foot occurring between December and March, these data were considered negligible. Reference evapotranspiration (ETo) data were collected for two stations in the California Irrigation Management and Irrigation System (CIMIS) located in the same ETo region as Sierra Valley (i.e. Buntingville at 4091 ft, 40 miles north , and Camino at 2780 ft, 75 miles southwest) (SI Table 1; DWR 2018c).

4.2.2 Groundwater

We used groundwater data from the California Statewide Groundwater Elevation Monitoring (CASGEM) system (DWR, 2018c) and from SGVMD. Wells in California are given a state well number based on the Township-Range Public Land Survey System (PLSS) (DWR, 2000). Ten township-range rectangles (townships, approximately 36 square miles each) cover the Sierra Valley area, with Township 20-North, Range 14-East (20N14E) in the southwest and 23N16E in the northeast (Figure 1). Townships are typically subdivided into 36 numbered one square-mile PLSS-sections.

DWR currently measures groundwater levels in spring and fall in approximately 70 wells in Sierra Valley. SVGMD owns six of these wells, known as District Monitoring Wells (DMW) and monitors them monthly. Each DMW has two to three nested piezometers at different depths, totaling 16 DMW piezometers. SVGMD also monitors a small number of privately-owned wells (designated W 1, W 2, etc.) outside CASGEM. Some of the 134 Sierra Valley Groundwater Basin wells in the CASGEM system have records that date back to the 1950s, and many to the 1980s. SVGMD wells have been monitored since their installations (1995 and 2004). For this analysis, all wells in the Sierra Valley and Chilcoot sub-basins with more than ten years of water level data were downloaded from the publicly available CASGEM web database (DWR, 2018c), resulting in a database of 75 wells reasonably distributed across depth and townships, with the notable exception of townships 22N14E and 22N15E which lacked shallow wells. CASGEM wells include metadata reports (e.g., total depth, screened interval depth, well type) of different completeness. Screened interval data is available for roughly half the wells used (SI Table 2). Bohm (2016b) provides a detailed overview of the 800+ wells in the valley.

We collected pumping volumes, reported in AF from SVGMD groundwater reports (Schmidt, 2003, 2005, 2011, 2015, 2017). Annual regional pumping data are available since 1989 (Table 1). Finer resolution data reported by PLSS-section, are available from 1998 on. Most pumping occurs during summer of a given year (Schmidt, 2017).

4.3 Data Quality Assurance

We compiled data into a Microsoft Access database, using flags and metadata to query, filter, aggregate and average data for different analyses. For each station, flow and rainfall data were aggregated to monthly and yearly averages, and snow depth to annual peak SWE, removing missing data and agency-flagged questionable measurements.

We filtered well data to create a subset of “analysis wells”. The analysis well dataset includes the 16 SVGMD piezometers, two district-monitored private wells (W1, W5) and 42 other private wells, all registered in the CASGEM system, where the data is publicly available (SI Table 2). Well water level accuracy is +/- 5 ft according to DWR’s method of estimating coordinates and elevations for the reference point and ground surface at a well. Manual depth to water measurements are typically on the order of +/- 0.1ft. Groundwater elevation on a given measurement date was calculated as the reference elevation minus the depth to water. With the exception of the horizontal connectivity analysis of wells pairs across the flow barriers, all data presented comes exclusively from the analysis wells dataset.

We report the metric groundwater elevations (GWE), interchangeable with “groundwater levels”, rather than depth to water to simplify and standardize comparison across the valley’s topography. We also use the term GWE in place of the more accurate technical term "hydraulic head" because it is unknown which wells are drilled into pressurized aquifers and because most SGMA documentation uses "groundwater elevation". Importantly, well water levels in pressurized aquifers may exceed the physical elevation of the water in that aquifer and may even rise above the ground surface elevation, resulting in "artesian" or "flowing" wells (Taylor & Alley, 2001; Harter & Rollins, 2009). In unconfined aquifers not influenced by additional water pressure, GWE represents the physical elevation of the water relative to mean sea level.

4.4 Processing, Statistics and Mapping

For each well, we averaged GWE data over 90-day periods centered on October 1st (representative of conditions after the irrigation season) and April 1st (after winter recharge) (SI Figure 1). These seasonal averages were arranged in a May to April 'pumping year' with winter groundwater recovery following summer groundwater drawdown. Pumping years were categorized into Dry, Normal and Wet 'rain year types' (Table 1). Each pumping year rainfall total at Sierraville were compared to the average rainfall total at Sierraville for all pumping years from 1989 – 2018. Pumping years with rainfall totals outside the 30-year mean +/- half the standard deviation were categorized as wet or dry years, respectively. Normal years thus have 65 – 135% average rainfall, dry years have <65%, and wet years > 135%.

We divided the analysis wells into depth classes based on total well depth; screen interval data were largely unavailable. Two classifications were defined to account for the uncertainty in restrictive layer depths. For averages of groundwater elevations and annual changes, three depths are compared, where the Shallow Zone includes wells down to 150 ft, the Intermediate Zone ranges from 150 – 450 ft below ground surface, and the Deep Zone includes all wells beyond 450 feet, based on stratigraphic cross sections (Figure 2a; Schmidt, 2005). For contour maps and where data limitations occur, primarily a lack of shallow wells in certain townships, we have divided the wells above and below 300 ft into Shallow Layers and Deep Layers (SI Figure 2).

The analysis well data were exported to Excel files as tables to generate plots or for statistical tests using the Statistica program (Tibco, 2019). Analysis included scatterplots for flows, precipitation, and GWE over time; statistical correlations between variables using linear regressions; and column plots, often with error bars.

Sustainable yield for the eastern valley (where overdraft has been occurring) was calculated as the median groundwater pumping rate during years in which GWE were stable – increasing or decreasing by <2 ft. Sustainable yield for the western valley was not estimated because of insufficient data.

Maps were created using ArcMap with inverse-distance weighting interpolation to generate contour and heat maps (Esri, 2019). Groundwater data was often grouped into and averaged over PLSS townships in our analyses, primarily to correspond with pumping data, which was reported by township-sections rather than individual wells in the SVGMD reports (Schmidt, 2011, 2015, 2017).

5 Results

5.1 Surface Water Hydrology

Precipitation data and historical streamflow data show the western valley is wetter with more surface water than the eastern valley (Table 2, SI Table 1). Sierraville in the west averages nearly 2 ft of rain annually compared to slightly more than 1 ft at Vinton and Frenchman Dam in the east. Sierra Valley also becomes drier northward with Sierraville rain totals 20% higher than Portola's. This effect is exaggerated for snow data. The station at the western edge of the watershed, Yuba Pass, has nearly seven times the average annual peak snow water compared to the northeastern station, Frenchman Cove, though elevation differences confound direct comparison. The mountainous terrain likely affects weather in the region by inducing a rain shadow over the eastern valley (Vestra, 2005).

The two main eastern creeks, Smithneck Cr. (averaging 8000 AF annually) and Little Last Chance Cr. (averaging 19,400 AF annually) as regulated discharge from Frenchman Dam (55,477 AF capacity), contribute approximately 27,500 AF annually to the valley as surface water, about 15% of MFFR outflows (Figure 1, Table 2).

As with the precipitation distribution, the western and southwestern valley have greater surface water flows. The Little Truckee Diversion Canal historically imports 7000 AF annually from the Little Truckee River with flows entering Sierra Valley along Highway 89 in the south (Table 2; Erman 1992). MFFR averages 177,800 AF annually with about 25,000 AF annually entering into the MFFR from Big Grizzly Cr downstream and outside of the watershed (Table 2, Figure 1). The combine discharge from Bonta and Berry Creeks totals about 35,000 AF annually into Sierra Valley (Table 2). These three sources (Bonta Cr., Berry Cr., Little Truckee Diversion Canal) together contribute about 42,000 AF annually of surface flows to Sierra Valley about 30% of the MFFR discharge from the watershed (152,700 AF annually). Note the historical Bonta Cr. gauge likely included the flow from Cold Stream, which is the more typical local name for that watershed.

The sum of all historically gauged discharge in the valley comes to 70,600 AF annually, leaving about 48% of total MFFR discharges from Sierra Valley (152,700 AF annually) unaccounted (Table 2). Those surface flows likely originate largely from the southwestern and western valley, based upon the large number of streams (Figure 1) and the greater precipitation in those regions (SI Table 2). The western valley streams also receive contributions from connected groundwater (Bohm, 2016a). Direct surface evaporation and evapotranspiration (ET) also occur within the valley, estimated at 257,700 AF by Dib et al. (2016), suggesting the 82,000 AF of unaccounted for surface water input is an underestimate.

MFFR flow vary seasonally, lowest July through November, and highest typically in March (SI Figure 3). Though median monthly flows are similar to historic values, flows from select recent years differ greatly. For instance, in 2011 and 2017, peak flows were an order of magnitude greater than the historic average, whereas 2015 flows were less than the historic average (SI Figure 3). 2017 also saw two peak flow events, in February (from rain) and April (from snowmelt), different from other years. Historical runoff correlates better with rain than total SWE (SI Figure 4), suggesting a greater proportion of snowmelt runoff infiltrates into the soils and recharges groundwater. DWR (1983) estimate up to 11% of precipitation infiltrates to groundwater in Sierra Valley and other region watersheds.

Frenchman Dam is managed such that summertime releases into Little Last Chance Cr. support valley irrigation (DWR, 1983). Overtopping can occur during spring. Frenchman Dam (55,477 AF capacity) has overtopped eight times between 1989 to 2018, generally during wet years (Table 1, e.g., 1995 – 1999, 2006, 2011, 2017, 2018) with spillway releases of one to four months and typically between March and June. The lowest reservoir storage since 1989 was in Fall 1992 (16% capacity) and more recently fell to 22% in Fall 2015 after a series of dry years.

5.2 Groundwater Hydrology

5.2.1 Response to Groundwater Pumping

Valley groundwater conditions have changed greatly from natural conditions. Into the 1960s, groundwater in most the valley was near surface (Figure 3a) and free-flowing artesian wells were common (DPW, 1937; DWR, 1983). Groundwater elevations (GWE) were highest in the Chilcoot sub-basin and the south valley (Figure 4a), reflecting the near surface groundwater conditions (Figure 3a) and higher topography. Lowest GWE and deepest depth to groundwater were near Beckwourth at the valley's outflow (Figure 3a, Figure 4a). In the 1960s and into the 1970s, shallow wells exhibited an approximate 2-ft seasonal GWE variation, and around 5-ft over longer multi-year periods (SI Figure 5). Recently, GWE variations in eastern valley wells have increased to 5 – 10 ft seasonally and up to 20-ft increase in response to the wet period in the 1990s (SI Figure 5, SI Figure 6, SI Figure 7).

GWEs recorded in wells in the western and southwestern valley and in the Chilcoot sub-basin have been generally stable and more similar to historic conditions, having limited annual groundwater pumping (Figure 3, Figure 5, SI

Figure 8b, SI Figure 7). However, greater seasonal GWE variability is beginning to occur in township 21N14E (SI Figure 8c). Though groundwater pumping volumes in this township are much lower than in the eastern valley (Figure 5), recent pumping increases may be causing this effect (Table 3).

In the eastern valley, deep GWE declines also began around the 1960s (Figure 4b, SI Figure 9). By 1990, deep GWE declines had expanded both eastward and northward (Figure 4d) and GWE declines had accelerated (Figure 6, SI Figure 5), with the greatest deep GWE declines in townships with the longest pumping history (Figure 6a-d, Figure 5). The PLSS townships with higher pumping volumes typically have greater seasonal GWE variations, greater vertical head differences between the deep and shallow aquifer, and more periods of consistent declines (Figure 6, SI Figure 6) as compared to areas with lower pumping volumes (i.e. southwestern valley and Chilcoot sub-basin) (SI Figure 7). Four PLSS townships – 22N15E, 23N15E, 22N16E and 23N16E – appear overdrafted every year with persistent GWE declines (Figure 6 a–d). Three of these four have the highest average annual pumping; all four townships had the greatest increase over the last two decades (Table 3, Figure 5). 90 percent of the total valley pumping in most years occurs in the six eastern townships (Table 3). Two southeastern townships, 21N15E and 21N16E, have similar total groundwater pumping volumes, but GWE declines are not as steep (Figure 6 e–f, SI Figure 7) and the regional cone of depression has progressed more slowly (Figure 4, Figure 5). A poor linear fit between pumping and annual GWE change suggests confounding factors and/or data uncertainty.

Overall, valley-wide groundwater pumping trend has been increasing over the past two decades, exceeding 10,000 AF during the drought years and in the summer of 2016 (Table 1). Pumping during the 2017 and 2018 irrigation seasons has decreased to pre-drought levels (SVGMD, 2019), and wet winters have eased stress on the groundwater system (Figure 6, DWR, 2018c).

5.2.2 Response to Precipitation

Precipitation has affected both GWE and agricultural pumping. The 1990s encompass a wet period with six of 10 years above normal rainfall in Sierra Valley (Table 1) and correspond with the greatest GWE recovery (Figure 4, Figure 7). Average pumping rates also decline with increasing precipitation – wet years have roughly 2000 AF less pumping than normal and dry years (Table 3). Wet years have sometime but not always stabilized or increased deep GWE in subsequent years. For the wet years 1993, 1995, 1999, 2006, 2011 and 2017 (Table 1) which stabilized or increased GWEs at all depths for the given years, over half of the following pumping years continued to experience GWE recoveries (i.e., 1994, 1996, 2012, 2018) (Figure 7). For all wet years, GWE recovery did not continue into the second subsequent year (Figure 6, Figure 7). For several wet years (i.e., 1997, 1999, 2006), GWE stabilization the following year did not occur. 1997 had the greatest rainfall over the last 30 years, at 314% of normal (Table 1), yet groundwater levels did not increase significantly that year or the next (Figure 7).

Together, these data show years of high precipitation can extend recharge into the following year, but the relationship is apparently confounded by other factors (e.g. groundwater flow lag times, effects of precipitation phase and timing). The potential to improve GWE from the wet year generally disappear beyond the following year.

5.2.3 Vertical Connectivity

In an unconfined aquifer system with homogenous hydraulic properties, shallow GWE changes would be similar to deep GWE changes (Taylor & Alley, 2001; Harter & Rollins, 2009). In most Sierra Valley townships, deep wells have much deeper GWE and greater seasonal changes than shallow wells (Figure 6, Figure 7). Deep and shallow GWE changes in wells are not proportional, except in the valley periphery (SI Figure 10), indicating limited water exchange between the two zones. However, the zones do not appear to have distinct, contiguous boundaries. Intermediate wells rarely behave as an independent set of wells, often exhibiting GWE behavior similar to either deep or shallow groundwater, notably in townships 23N16E and 21N15E (Figure 6, SI Figure 6, SI Figure 7). Sierra Valley stratigraphy shows non-contiguous fine-grained layering (Figure 2a; Schmidt, 2003), resulting in confined or semi-confined areas (Figure 2b) and, in places, perched aquifers isolated from pumping effects (SI Figure 8d).

Confined and semi-confined aquifer systems may respond more dramatically to pumping and precipitation than unconfined aquifers (Taylor & Alley, 2001; Harter & Rollins, 2009). The flowing artesian conditions historically present in many wells provide evidence that there were pressurized aquifers in the basin before pumping began (DWR, 1983; Bohm, 2016a), and the greater range of seasonal variability of the deeper wells (Figure 5, Figure 7) suggests these aquifers may still be pressurized. Wells nearer the valley periphery (i.e., 20N14E, 21N14E, Chilcoot sub-basin), have less vertical head differences between shallow and deep well GWE (SI Figure 10). The low-permeability fine-grained layers separating aquifers may be thinner or non-existent near the valley periphery because of higher-energy hydrology at the valley-mountain interface preventing fine particle settling (Figure 2b; Bohm, 2016a).

5.2.4 Horizontal Connectivity and Lateral Flow

GWE data shows groundwater enters the valley in three main areas. Two areas of upward head gradient clearly identify groundwater supply areas, the Chilcoot sub-basin and the south valley (Bohm, 2016b). GWEs have not declined in these areas, remaining similar to historic conditions (Figure 4, SI Figure 9). The Smithneck Creek drainage also appears to be a groundwater supply area with slower GWE declines despite pumping near Loyalton (Figure 6e & f, Figure 5). This is consistent with the 1983 DWR report that indicated groundwater mounding in the area near Loyalton (DWR, 1983). These three areas appear to have consistent groundwater flow entering the valley, distinct from periodic net recharge in the eastern wells following above-average precipitation years.

Groundwater data suggest faults are affecting horizontal connectivity in the valley; faults and locations of wells in used in this assessment are identified in Figure 8, and the wells compared are listed in SI Table 3. On the west side of the Grizzly Valley East Fault (GVE), well GWEs lack the steep annual declines and recovery characteristic of pumped groundwater that is apparent in wells on the east side of the fault (Figure 9a, well pairs 2 & 3). Groundwater on both sides of the north end of the GVE fault have similar ranges of seasonal change but a sizeable gradient between the water levels indicates some isolation (well pair 1). A local pumping test corroborates this interpretation – neither piezometer in DMW 6 showed any response to nearby pumping on the eastern side of the fault line (Schmidt, 2006). However, the isolating effects appear to be discontinuous across the length of the faults (Figure 8). Across GVE near Loyalton, there is no gradient between wells on either side of the fault, though the deeper eastern well has smaller seasonal variability (well pair 4, Figure 9b), potentially related to different proximity to other pumping wells. Similarly, the GVW fault near the center of the valley shows synchronous trends on either side, though increasing pumping appears to affect the eastern well (pair 5, Figure 9c). Pairs 6 & 7 across GVW (not shown) in the southern periphery had some isolation between the wells, though this may be an artifact of higher groundwater levels closer to the uplands.

Overall, well data suggests the GVE and GVW impede horizontal flow along the eastward gradient, though the impediment to flow may not be contiguous along the faults. This conclusion is supported by Bohm (2016a), who suggested fault lineaments in the northwest direct can inhibit groundwater flow. The identification of lineaments conducted by Bohm, however, are discrepant with the California Geological Survey map we used to identify fault lineaments. The exact lineaments for the faults thus remain in question, potentially contributing to the non-contiguous fault effects identified by our assessment. Including fault effects on horizonal connectivity greatly affects modeled GWEs throughout Sierra Valley. Including the GVE fault as a barrier to the interpolation of GWE contours produces a map that clearly divides the overdrafted and non-overdrafted areas, with nearly 60 feet of difference between two deep wells less than a mile apart on either side of GVE (Figure 10).

Wells on either side of the Chilcoot sub-basin divide have distinct groundwater regimes (Figure 9d). However, groundwater flow gradients based on contours indicate that the Chilcoot divide may not impair flow very severely, or to a greater degree in the shallow zone (Figure 5).

5.2.5 Sustainable Yield

Average annual pumping for the entire valley is about 8500 AF from 1999 to 2017, with 97% coming from the 6 eastern township and 73% from the four overdrafted northeastern townships (Table 3). We estimated sustainable yield for the eastern valley by determining groundwater pumping levels for periods of stable, declining and increasing GWEs. For the four overdrafted PLSS townships, median annual groundwater pumping was 3900 AF for years with rising GWE (> 2-ft GWE increase), 6000 AF for years with stable GWE (+/- 2-ft), and 6450 AF for years with declining GWE (> 2-ft decrease) (Figure 11). Median pumping rates differ significantly for periods of declining and rising GWE. From this analysis, we estimate sustainable yield for these four overdrafted townships at 6000 AF annually, the same as the safe yield estimate of Schmidt (2017).

6 Discussion

Several relevant issues are discussed here:

1. Defining Sierra Valley Groundwater Sustainability through SGMA Sustainability Indicators;
2. Climate Change Exacerbating Groundwater Recharge and Management;
3. SGMA Nuts and Bolts: Sustainable Yield, Adaptive Management, Management Areas and Data; and
4. Valley Adaption Strategies: Irrigation Efficiencies and Recharge.

6.1 Defining Sierra Valley Groundwater Sustainability through SGMA Sustainability Indicators

The groundwater history in Sierra Valley can be broken roughly into four periods of sustainable and non-sustainable conditions, with increased irrigation pumping identified as the major reason for the transition to non-sustainable conditions (DWR, 1983, 2003b, 2019; Schmidt, 2003, 2017; Bohm, 2016a):

- Prior to the 1960s representing sustainable groundwater levels and pre-development conditions;
- The 1960s to 1990 representing steady GWE declines;
- The 1990s representing GWE recovery; and
- Post 2000 with accelerated groundwater pumping and GWE declines.

Changes in Sierra Valley's groundwater conditions and threats to sustainable management can be ascribed to five of six SGMA sustainability indicators:

(1) <u>Chronic lowering of groundwater levels indicating a significant and unreasonable depletion of supply if continued over the planning and implementation horizon.</u> GWE declines began occurring in the 1960s through the 1990s, and resumed after 2000 (Figure 4, Figure 7, SI Figure 9). Deep GWE wells in the eastern valley have declined more than 30-ft in the last 20 years (Figure 4, Figure 5). Until around 1960, shallow groundwater in most the valley was near surface (Figure 3a) and free-flowing artesian wells from pressurized deeper aquifers were common (DPW, 1937; DWR, 1983).

(2) <u>Significant and unreasonable reduction of groundwater storage.</u> Approximately 237,000 AF has been withdrawn from the Sierra Valley sub-basin over the last 30 years, 90% of which was pumped from the eastern valley, primarily through deep irrigation wells. DWR (1983) estimated a basin storage loss of 11,000 AF in response to the 14,500 AF pumped in 1981. The average depth of agricultural wells in Sierra Valley is 580 ft, while in some places the total basin depth is 1500 ft below ground surface (DWR, 2003b). DWR (2003a) estimates total Sierra Valley aquifer storage at 7.5 MAF and a 1% reduction in total groundwater capacity.

(3) <u>Significant and unreasonable seawater intrusion.</u> This result only applies to coastal aquifers.

(4) <u>Significant and unreasonable degraded water quality, including the migration of contaminant plumes that impair water supplies.</u> Groundwater quality has not been assessed for this hydrologic groundwater

assessment. Water quality data analyses are available in other reports (Schmidt, 2003; Vestra, 2005; DWR, 2003b; Bohm, 2016b).

(5) <u>Significant and unreasonable land subsidence that substantially interferes with surface land uses.</u> GWE declines can cause subsidence (Freeze and Cherry, 1979; Farr et al., 2016; DWR, 1983; Famiglietti et. al, 2011; Murray & Lohman, 2018) and subsidence in Sierra Valley has been attributed to GWE declines (DWR 1983; Farr et al., 2016). Sierra Valley subsidence rates have been up to several feet per decade (DWR 1983) and up to several inches annually (Farr et al., 2016), corresponding with areas of overdraft, (DWR, 1983). The withdrawals from the Sierra Valley sub-basin have surely dewatered unconfined aquifers and depressurized confined aquifers, which has likely caused compression of sediment pore space, particularly in fine-grained silts and clays. This compaction of sediments is often inelastic, resulting in permanent loss of storage or land subsidence.

(6) <u>Depletions of interconnected surface water that have significant and unreasonable adverse impacts on beneficial uses of the surface water.</u> Among the beneficial uses, and particularly relevant to Sierra Valley and connected to groundwater hydrology, is impacts to “groundwater-dependent ecosystems” (SGMA, 2014; DWR 2019). The western valley has greater precipitation (SI Table 1), greater recorded stream contributions (Table 2), more named and unnamed streams than elsewhere in the valley (Figure 1) and connected groundwater contributions (Bohm 2016a). Because of this greater water supply, the western valley supports approximately 20,000 acres of wetlands complex and 30,000 acres of montane meadow complex rich in flora and fauna and both the largest in the Sierra Nevada (NRCS, 2016), making Sierra Valley a top conservation priority (TNC 1999; Audubon 2008; NRCS 2016). Increasing shallow GWE variation in the southwestern valley (i.e. DMW 3 and 4, Figure 12a, SI Figure 8c) suggests greater pressure on shallow GWE supplies in that region, potentially in response to increased agricultural pumping in that area (Table 3). The eastern valley is not as affected by shallow GWE because overdraft has disconnected surface water from groundwater (Bohm 2016a). Impacts to deep groundwater may also potentially affect “groundwater-dependent ecosystems” if existing stream contributions from artesian wells and springs decrease.

Though chronic overdraft that could be defined as significant and unreasonable has occurred in Sierra Valley since the 1960’s, the GSP will only be required to address those effects occurring after January 1, 2015 (DWR, 2019).

6.2 Climate Change Exacerbating Groundwater Recharge and Management

A climate model by Pierce & Cayan (2013) predicts Sierra Nevada snowpack will have decreased 48 – 65% by the end of this century from climatic warming caused by human-generated greenhouse gas and aerosols emissions. Expected continued climatic trends include increased rain and less snow in annual precipitation (Godsey 2014; Dib et al., 2016; Mao et al., 2015), greater magnitude of peak runoff and longer summer dry periods in rivers (Stewart, 2004), and greater water loss from the watersheds with less water able to move to groundwater as subsurface flows (Godsey 2014). Dib et al. (2016) predict the MFFR watershed will lose much of the deep snowpack by 2100.

Climate change effects have begun in the Sierra Nevada, and more extreme events have been observed. Freeman (2012) report a shift to earlier runoff in Sierra Nevada with typical April through June runoff shifting into March. Increased dry periods consisting of successive, low precipitation years have been occurring over the last 20 years, as expected by Huang et al. (2018). Sierra Valley experienced the lowest precipitation on record in 2015 following several dry years 2012 – 2014 (Table 1). 2017 may foreshadow greater watershed runoff variance with extreme events (Huang et al., 2018), as the timing and shape of the 2017 MFFR flows differ from any other year on record (SI Figure 3).

Challenge associated with groundwater management will grow as the climate in Sierra Valley changes. Stewart (2004) suggests earlier snowmelt will challenge California storage efficiency of reservoirs, leading to less available surface water at the end of the growing season, consistent with DWR (2014) expectations. Lessened snowmelt is expected to decrease reservoir storage in Lake Davis (Dib, et al., 2016), and Frenchman Lake could see similar challenges with earlier peak storage and less late-summer water availability (Stewart, 2004). Decrease in snow will also likely decrease groundwater flows from the upland watershed due to less high-elevation infiltration (SI Figure 11; Huntington and Niswonger 2012). Historical streamflow data for MFFR also indicates earlier peak flows than current data, potential evidence for changes in hydrology over the last 50 years (SI Figure 3). 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, 2004; Dib et al., 2016). Dib et al. (2016) forecasts groundwater pumping will increase up to 25% by 2100 assuming a similar population and level of agricultural production. These forecasted changes in hydrology will ultimately affect irrigators; less available surface water leads to greater dependence on groundwater pumping, raising costs to irrigators and jeopardizing future supply.

6.3 SGMA Nuts and Bolts: Sustainable Yield, Adaptive Management, Management Areas and Data

Our analysis estimates sustainable yield for the eastern valley at 6000 AF annually, the same as safe yield estimates by Schmidt (2017). Sustainable yield estimates have not been defined for the western and southwestern valley because current well coverage is not sufficient to provide defensible estimates of withdrawal limits, though groundwater pumping limitations might be necessary to prevent undesirable results in these areas as well. Potential signs of groundwater stress in those regions include greater seasonal water level variations inconsistent with past data in the western and southwestern valley (SI Figure 8c).

Ideally, sustainable yield would be determined for an entire groundwater basin and its subregions to help guide groundwater planning under SGMA (DWR, 2019). However, for Sierra Valley, uncertainties confound this goal. Complexity in Sierra Valley and its watershed as identified from our analyses and supported by the literature include: faulting affecting lateral flows (Figure 9, Schmidt 2005, Bohm 2016a) and interpretation of the well data (Figure 10); low-permeability layers that effectively limit vertical infiltration to deeper aquifers; precipitation gradients (Table 2, SI Table 1; Vestra 2005) precluding accurate quantification of total basin and valley precipitation; proximity to snowline increasing the importance of rain and snow as the precipitation source (Pardo-Igúzquiza et al., 2018; Wrzesien et al., 2017; Hatchett et al., 2017); and a large number of streams and creeks providing surface water into the valley (Figure 1, Table 2). These complexities introduce uncertainty associated with distribution and total precipitation, runoff periods, subsurface flow paths and groundwater budgets, and these factors are often very difficult to measure. Uncertainty associated with this complexity could be narrowed, though it would require substantial research efforts, such as: geophysical methods calibrated to well logs to better describe the vadose zone and the underlying aquifer lithology (LBL, 2019); well tests to assess fault effects on groundwater flow; extensive stream monitoring to better develop a surface water budget; more spatially distributed rain and snow monitoring stations to quantify precipitation and its type; evapotranspiration and weather stations. Though these methods are all currently available, it is unlikely that one can 1) collect enough data to narrow hydrologic uncertainty in modeled groundwater flow and 2) use the results to guide adaptive management strategies. Vestra (2005) estimated the total watershed water budget at over 600,000 AF y^{-1}; Dib et al. (2016) estimated the total valley water budget at 200,000 AF y^{-1}. Our estimated sustainable yield for the eastern valley of 6000 AF y^{-1} is about 3% of the valley water budget by Dib et al. (2016) and about 1% of the total water budget by Vestra (2005). Given that the sustainable yield makes up such a small percent of these water budgets, uncertainty cannot be narrowed sufficiently to provide reasonable predictions of climate change or management effects to the level needed to inform on sustainable yield decisions and strategies.

Thus, an adaptive management approach will be needed that relies upon measured data trends and relationships. Sufficient data and defensible standard methods will be required to limit uncertainty in the results and can be guided by California's best management practice recommendations under SGMA (DWR, 2016a). Incorporated into this effort should be –

- Quality assurance and quality control (QAQC) to identify poor or inadequate data;
- Standard installations and calibration (e.g., well transducers, pump flow meters) to minimize recording errors;
- Standard data collection schedules to synchronize data collection across monitoring platforms; and
- Complete meta data (e.g., top of casing elevation, screen intervals) to minimize errors in data interpretation or calculations.

An important need to support an adaptive management strategy will be sufficient data density, appropriate assumptions, and appropriate data management and analyses. If developing groundwater contour models, insufficient spatial density can lead to inaccurate contour models (Figure 12). Using data only from the SVGMD wells, a groundwater contour model inaccurately describes GWE trends and introduces greater uncertainty. These errors and uncertainty affect interpretation of groundwater conditions: e.g.,

- Calculated boundaries and shape of overdraft zone;
- Potential correlation errors between GWE and other sustainability indicators (e.g. subsidence); and
- Horizontal influence of specific groundwater pumps.

These errors are similar in effect to other mistaken assumptions, such as not considering the effects of faults on horizontal or lateral groundwater transport (Figure 10). An important focus under the SGMA process will be to determine an appropriate data network that account for geologic and hydrologic considerations, and best leverages available data opportunities (e.g., CASGEM network, INSAR data). Temporal data density will also need to be considered. CASGEM data is collected semi-annually and District data is collected monthly. Ideally, groundwater level and groundwater pumping data should be collected on synchronous schedule to better link groundwater management with groundwater responses. All data should be integrated into a database and appropriate queries developed to allow data analyses across different monitoring platforms (e.g. groundwater elevation, groundwater pumping, subsidence) while considering such factors such as groundwater depth, seasonality and faulting.

SGMA discusses implementing management zones to focus appropriate sustainability strategies and resources (DWR, 2016a). Significant and unreasonable effects that lead sustainability indicators to become undesirable effects will not be consistent through Sierra Valley, given the aforementioned complexity. For instance, groundwater overdraft in Sierra Valley occurs primarily in the area east of GVE (Figure 8) which is largely isolated from the high groundwater levels in the western valley because of limited groundwater flow across GVE (Figure 8, Bohm 2016a, Schmidt 2005). Groundwater recharge sources also vary throughout the valley. Smithneck Cr. appears to recharge the area near Loyalton, potentially helping to limit overdraft despite heavy pumping (Table 3, Figure 5), whereas groundwater flow into the overdraft zone from the Chilcoot sub-basin appears to be restricted by a high bedrock feature (Figure 9d; Vestra, 2005). As discussed earlier, groundwater dependent ecosystems and shallow groundwater interactions will be a greater priority in the west than in the eastern valley. For Sierra Valley, a management zone encompassing the overdraft zone would focus on corrective actions and adaptive management related to declining deep GWEs, deep groundwater storage loss, and land subsidence. A management zone encompassing the western and southwestern valley could focus on preventative actions to protect groundwater-dependent ecosystems. Monitoring programs and accompanying analyses could be designed specific to the management area goals and needs to maximize resources investment and their value.

6.4 Hydrologic Data Gaps

A number of data gaps have become evident from this analysis:

<u>Stream network monitoring.</u> Limited steam monitoring currently exists in Sierra Valley with only the MFFR monitored (CDEC, 2018). A stream monitoring effort for a comprehensive water budget is impossible given the resources available in Sierra Valley and the high degree of uncertainty and complexity. Long-term selected stream

monitoring could help document climate change effects and be incorporated into other research efforts (e.g., model validation/calibration, groundtruthing).

Groundwater well network. The current District well network provides insufficient deep groundwater data density and accuracy. The CASGEM online system provides a cost-effective opportunity to expand the well network, and well construction reports are available that provide well metadata. Metadata includes well depth, screened interval, location and elevation (DWR, 2018c). Enrolled private wells currently have groundwater elevation accuracy of +/- 5 ft, greater than the 0.5 ft error deemed acceptable for a GSP monitoring network (DWR, 2016b), meaning the metadata of wells will need to be improved. Review and screening of available CASGEM wells to provide good spatial distribution and density likely offers a cost-effective approach to expand the GWE monitoring network.

Subsidence and its relationship to GWE management. Selected and limited subsidence monitoring can be used to groundtruth INSAR data (Farr et al., 2016) and to provide data for better linking GWE management to subsidence in Sierra Valley.

Groundwater Dependent Ecosystems. Shallow groundwater data in the western and southwestern valley will be needed to address the surface water to groundwater interaction sustainability indicator. Shallow GWE monitoring will be needed to ensure stress on these systems is not occurring from agricultural pumping. Piezometers selectively installed with paired surface water elevation monitoring can be used to understand valley groundwater and surface water interactions. Comparing groundwater and surface water temperatures in such paired stations can also provide information on groundwater-surface water interactions (USGS, 2003; Constanz, 1998).

6.5 Valley Adaption Strategies: Irrigation Efficiencies and Recharge

Two fundamental adaptation strategies are available in Sierra Valley: decreasing groundwater pumping or increasing groundwater supplies. These strategies can be focused on deep or shallow groundwater and within or outside the valley itself. A number of actions can be taken to implement these strategies:

6.5.1 Reducing Irrigation Use through Increasing Efficiencies

Three lines of action could improve water use efficiencies without decreasing irrigated acreage. These actions all focus on improving irrigation efficiencies:

- Organic soil amendments. Organic soil amendments (e.g., biochar, woodchips) can reduce water loss to soil evaporation and increase soil water availability to crops (Basso et al., 2012; Yu et al., 2017; Li et al., 2017). Soil amendments, when properly selected, can also increase nutrient availability, increase carbon storage, alter pH in soils and increase yields, (Abujabah et al., 2015; Gul et al., 2014; Brantley et al., 2015), incentivizing a switch in management practices that reduce frequency of irrigations. Effectiveness and economics of organic amendments and biochar depends upon the interactions with the background soils (Gul et al., 2014; Brantley et al., 2015; Basso et al., 2012; Yu et al., 2017) and duration of its effects and agronomic benefits (Spokas et al., 2012). To implement these methods broadly in Sierra Valley, feasibility and economic analyses are needed.
- CIMIS Stations. Insufficient CIMIS stations in Sierra Valley prevent adequate modeling of ET and precipitation and hinder irrigation planning use efficiencies by crop.
- Improving irrigation system efficiencies. Several studies conducted across the western U.S. conclude changes to center-pivot irrigation systems can reduce evaporative and wind losses (Kisekka et al., 2017; Zhu, 2016; Rajan, et al., 2015). Converting to drip or Low Elevation Spray Application (LESA) systems have been shown to increase irrigation efficiency by 10 – 20% (Kisekka et al., 2017; Rajan et al., 2015). A current study is underway by Bachand et al. (2020b) in collaboration with UCCE to assess the potential of LESA systems to improve irrigation efficiencies in Sierra Valley. Improving irrigation through improved system technology or through modifying current system operations could help stretch irrigation water in

Sierra Valley. More studies are needed before large-scale investment are made in Sierra Valley to upgrade current systems.

6.5.2 Within Valley Challenges to Recharging the Deep Aquifer

Three methods of recharge are commonly practiced in California: groundwater injection wells (SWRCB), infiltration basins (SWRCB; DWR, 2018a), and flooding agricultural land and other working landscapes, commonly termed On-Farm Recharge (OFR) or FloodMAR (DWR, 2018a; Bachand et al., 2016). Injection wells are a cost- and resource-intensive strategy but can target deep aquifers (Sheng, 2005; Baveye, et al., 1998). Injected water requires treatment to federal drinking water standards, and even after treatment may still contain water quality constituents of concern that degrade the groundwater quality or clog wells (SWRCB; Baveye, et al., 1998). Infiltration basins, a less expensive alternative, are another method of direct recharge but are limited by the hydrogeologic properties of the aquifer's sediments (Sheng, 2005; Baveye, et al., 1998; Bouwer, 2002). Ross and Hasnain (2018) estimated groundwater injection wells, including capital costs and annual operating costs, cost about \$550 AF^{-1} compared to \$230 AF^{-1} for recharge basins. OFR and FloodMAR can be an effective and inexpensive recharge strategy because of for dual use of lands for farming and flooding and because of flexibility to scale up or down as needed to accommodate source water flow variance (Bachand et al., 2016; Dahlke et al., 2018; DWR, 2018a). Implementing OFR or FloodMAR requires site suitability considerations – e.g. soils, access to water, suitable crops, on-farm and regional infrastructure – and other considerations such as water quality, finances, development of appropriate management practices, and tracking and accounting of recharge volumes. FloodMAR and its derivatives are the main recharge technology being targeted by DWR to affordably provide sufficient recharge at sufficient scale as a California-wide SGMA solution (DWR, 2018a).

Recharge strategies for Sierra Valley face challenges. Injection wells can directly recharge to specific depths and aquifer layers but this option is likely too expensive given the resources and land uses in Sierra Valley. Infiltration basins would be a lower cost option, having lower maintenance costs, and requiring less or no water treatment (Maliva, 2014). However, the generally impermeable soils and limited available source water in the eastern valley present challenges for effective recharge through infiltration basins, OFR and FloodMAR in Sierra Valley.

6.5.3 Valley or Near Valley Recharge for Surface Water Beneficial Uses and Groundwater Dependent Ecosystems

OFR projects are being pursued in Sonoma Co, California to recharge shallow groundwater and promote subsurface flow from upper, perched aquifers to local streams to benefit groundwater dependent ecosystems (Bachand et al., 2020a). Restoration in meadows and forests can change groundwater flows and timing by storing water in local aquifers for release during dry periods, regulating surface water outflows that provide recharge, and/or draining water along subsurface flow paths to regional aquifers (Wagner, 2015; Hunsaker et al., 2015). Meadow restorations through modifying incised or oversized steams and channels to redirect stream flows onto floodplains can slow surface water and reduce losses from a watershed and promote local groundwater recharge (IWJV, 2019; Hill et al., 2011; Hunt et al., 2018; Hoffman et al., 2013). Implementing valley OFR projects or near valley wetland and stream restoration projects would be expected to slow surface water flows into and through the valley (UFRRWMG, 2016) reducing losses as outflow into the MFFR. These recharge and restoration projects can extend stream baseflows through the year by increasing local groundwater storage and then subsequently have local groundwater seep back into streams (Bachand et al., 2020; Hill et al., 2011; Hoffman et al., 2013; Hunt et al., 2018). Thus, though OFR projects within the valley will likely not significantly improve deep groundwater (Figure 2, SI Figure 10), potential exists to help address groundwater dependent ecosystems.

6.5.4 Upland Recharge Opportunities and Frenchman Dam Re-Operation

Low investment costs and multi-use lands potentially provides some incentive for OFR for deep groundwater recharge during spring when Frenchman Dam overtops, particularly in more alluvial areas upstream of the valley where soil infiltration rates are higher. Having overtopped eight times between 1989 to 2018 with spillway releases of 1 – 4 months, Frenchman Dam offers flood flows for potential recharge and restoration purposes. Climate change will likely increase the frequency of these events (Freeman, 2012; Stewart et al., 2004; Benganskas & Fisher, 2017; Huang et al., 2018). DWR has begun investigating changes in reservoir operation throughout California to better leverage groundwater storage in California's water resources portfolio (DWR, 2017). Potentially, changes in Frenchman's Dam operation could improve opportunities to capture and recharge available flows through reconnecting Last Chance Creek to its floodplain upstream of the valley for deep groundwater recharge or downstream in the valley to support groundwater dependent ecosystems.

The Upper Feather River Integrated Regional Water Management Plan (UFRRWMG, 2016) proposes various projects to improve forest management (e.g., 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). These projects could potentially improve groundwater conditions. Forest thinning in forests with overgrown canopy can reduce forest fire fuels (North et al., 2009) and reduce evapotranspiration losses (Bohm, 2015; Smerdon et al., 2009; Wyatt et al., 2011), potentially increasing subsurface flow to groundwater. Conklin et al. (2015) report vegetation density is more tightly linked to evapotranspiration in forests more limited by precipitation. Forest thinning practices should be designed based upon the stand structure and density, topography, aspect and local climate (North et al., 2009). Nearly 15% of the land within the Sierra Valley Groundwater Basin is state- or federal- owned land (SI Table 4). Several potential subsurface flow pathways exist to recharge valley groundwater (SI Figure 11, Bohm 2016a). Once stream water, rain, or snowmelt has infiltrated into the mountain subsurface, groundwater flows follow hydraulic gradients to recharge meadows and basins, with infiltration on ridges and mountain tops reaching deeper into the subsurface, potentially recharging deeper aquifers (Harter & Rollins, 2009; Bohm, 2016). Groundwater flows from precipitation in mountainous uplands may take decades or centuries to recharge a basin (Freeze & Cherry, 1979; Harter & Rollins, 2009; Bohm, 2016). Thus, such efforts should be approached as multi-purpose projects with long time frames.

7 Conclusion

Agricultural groundwater pumping in the eastern half of Sierra Valley since the 1970s has resulted in groundwater overdraft, averaging around 8600 AF annually over the last 20 years and exceeding 10,000 AF y^{-1} from 2013 – 2016. Under California's new groundwater legislation, SGMA, the Sierra Valley sub-basin has been designated a medium-priority basin, due to chronic groundwater declines and the valley's high ecological value as the largest freshwater marsh and meadow system in the Sierra Nevada. As the GSA for the sub-basin, SVGMD is tasked with achieving sustainable groundwater management over an approximate 20-y timeframe. The first step is the development of a Groundwater Sustainability Plan (completed by January 2022) that uses available hydrologic information to 1) define methods and protocols for tracking groundwater trends and 2) develop a suite of actions to move the basin towards groundwater sustainability.

We estimate sustainable yield for the overdrafted region east of the Grizzly Valley Fault at about 6000 AF y^{-1}. Groundwater pumping during the last 20 years in that area exceeds sustainable yield estimates by nearly double, depending upon the year. This overdraft has directly resulted in shallow and deep groundwater declines, the loss of artesian wells and springs, and subsidence in this area. Shallow groundwater west of the fault is showing some signs of increasing response to pumping, potentially putting stress on the valley's large marsh and meadow system. Defining management areas will be critical to prioritizing different sustainability indicators and avoiding undesirable results.

Hydrologic budgets and numerical models are being used throughout California to help develop groundwater sustainability strategies. With an estimated annual watershed water budget over 600,000 AF y^{-1} and valley water budget near 200,000 AF y^{-1}, Sierra Valley is a poor choice for those tools to develop a sustainable groundwater management strategy forward. With sustainable yield about 1% of the total watershed water budget and 3% of the total valley water budget, uncertainty resulting from the hydrologic, geologic, management and monitoring complexity will render those tools inadequate in providing robust, cost effective and defensible information. Thus, we recommend an adaptive management approach moving forward, developing in tandem a robust and defensible data set. Aside from utilizing strong QAQC and standard practices, this dataset will require sufficient accuracy and appropriate assumptions to provide groundwater contour models and other actionable deliverables. In addition to standardizing data collection protocols, the GSP monitoring network will require sufficient temporal and spatial data density, and appropriate data management and analyses tools to analyze different metrics for sustainability (e.g. groundwater elevation, groundwater pumping, subsidence) while considering uncertainties presented by hydrologic and geologic complexities. Hydrologic data gaps we have identified that need to be addressed under the SGMA program include: stream network monitoring, to inform on local climate change effects; an improved groundwater network with sufficient temporal and spatial data density; land surface surveying to groundtruth subsidence data and define relationships with GWE changes; and groundwater dependent ecosystems.

For sustainable groundwater management, a number of actions are potentially available to increase water supply and to reduce water demand. These actions include: improving efficiencies of irrigation systems; using organic amendments to improve water holding capacity; increasing multipurpose forest restoration programs to increase forest health, reduce fuels, reduce runoff and increase groundwater recharge; and operational changes to Frenchman Dam to increase recharge opportunities. SVGMD is composed of private landowners and will need to consider watershed factors and management outside their immediate control, including the 57% of the watershed under public ownership. Thus, the development and adoption of a collective vision with a broad stakeholder community beyond SGMA requirements could facilitate groundwater sustainability efforts and address the long-term water management needs in Sierra Valley.

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9.2 Tables

Table 1. Annual valley-wide pumping totals, rainfall totals and rain year type for last three decades. Wet years are shaded blue and dry years are shaded orange. Normal years are not shaded.

Pumping Year	Pumping Totals (AF)	Total Rainfall at Sierraville (in)	Percent of 30 Year Avg Rain	Rain Year Type
1988 - 1989		14.08	52%	Dry
1989 - 1990	7656	16.84	62%	Dry
1990 - 1991	10131	11.72	43%	Dry
1991 - 1992	8317	16.76	62%	Dry
1992 - 1993	9113	50.64	187%	Wet
1993 - 1994	4094	11.32	42%	Dry
1994 - 1995	7329	38.59	143%	Wet
1995 - 1996	4100	33.88	125%	Normal
1996 - 1997	5819	84.92	314%	Wet
1997 - 1998	5316	21.64	80%	Normal
1998 - 1999	3461	55.39	205%	Wet
1999 - 2000	4865	39.11	144%	Wet
2000 - 2001	5979	15.08	56%	Dry
2001 - 2002	7491	19.00	70%	Normal
2002 - 2003	8277	23.85	88%	Normal
2003 - 2004	7828	23.19	86%	Normal
2004 - 2005	9628	23.60	87%	Normal
2005 - 2006	7166	43.55	161%	Wet
2006 - 2007	7197	11.99	44%	Dry
2007 - 2008	9024	14.94	55%	Dry
2008 - 2009	8557	16.20	60%	Dry
2009 - 2010	5626	24.73	91%	Normal
2010 - 2011	9576	34.05	126%	Normal
2011 - 2012	6157	18.40	68%	Dry
2012 - 2013	9488	17.59	65%	Dry
2013 - 2014	12354	13.56	50%	Dry
2014 - 2015	12325	12.74	47%	Dry
2015 - 2016	14292	27.65	102%	Normal
2016 - 2017	10983	55.13	204%	Wet
2017 - 2018	6600	21.84	81%	Normal

Table 2. Historical streamflow summary for tributaries to MFFR.

Only 45% of the historical flows through the MFFR gauge was accounted for in the measured streams. The other 55% likely comes from the many ungauged streams that ring the valley, and contributions from groundwater in the western valley. MFFR is the only active stream gauging station.

Stream Name	Average Flow (CFS)	Average Discharge (AF / Year)	Period of Record	Monitoring Agency	Percent of Feather R.
Smithneck Creek	11.1	8,076	1937 – 1966	DWR	4.5%
Bonta Creek[1]	39.0	28,224	1940 – 1959	DWR	16%
Berry Creek	11.3	7,838	1940 – 1967 1971 – 1983	DWR USGS	4.4%
Little Truckee Diversion[2]	19.4	7,039	1937 – 1966	DWR	4.0%
Little Last Chance Creek	26.8	19,400	1959 – 1979	USGS	11%
Big Grizzly Creek	34.7	25,100	1926 – 1931 1951 – 1952 1955 - 1979	USGS	14%
Middle Fork Feather River	246	177,800	1969 – 1979 2007 – Present[3]	USGS	100%

Notes:
1 – Gauge location unclear, may include Cold Stream
2 – Diversion is open no longer than 6-month irrigation season, often less, and feeds into Cold Stream
3 – Recent data not included in calculation of mean

Table 3. Average pumping (AF/year) by township for last two decades and by rain year type.

The eastern valley has consistently pumped more groundwater than western valley. Dry and normal years typically have greater pumping than wet years. Adapted from Schmidt (2017).

Decade / Rain Year Type	20N 14E	21N 14E	21N 15E	21N 16E	22N 14E	22N 15E	22N 16E	23N 15E	23N 16E	Valley Total
1999 – 2007	78	100	876	845	104	2566	146	1026	1261	7003
2008 – 2017	128	252	1271	803	70	2975	803	1334	2457	10092
Dry Years	133	282	1096	879	35	3216	527	1244	1925	9337
Normal Years	93	139	1214	765	32	2853	350	1298	1995	8739
Wet Years	135	231	774	869	212	1967	263	855	1604	6910

9.3 Figures

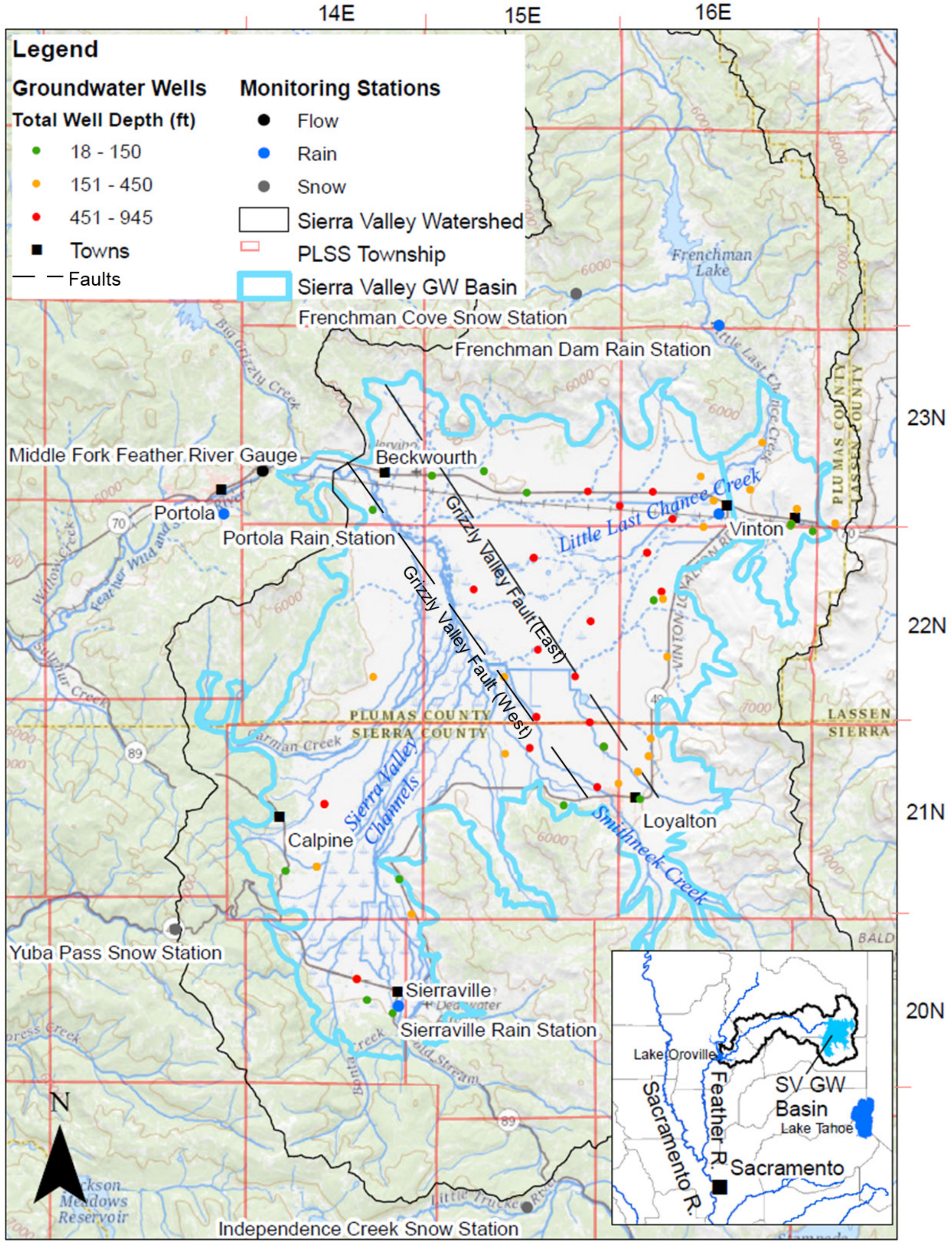


Figure 1. Map of Sierra Valley GW basin, streams and watershed boundaries, monitoring stations, and groundwater wells. Public Land Survey System Township-Range divisions are outlined in red, consisting of at most 36 one-square-mile PLSS-sections, with township and range labels on the right and top of the figure, respectively. Wells are divided into three depth zones. We refer to the 'eastern valley' as the area east of both Grizzly Valley Fault lines. The collection of perennial and ephemeral surface water channels are generally ascribed to three tributaries – the Sierra Valley Channels, Smithneck Cr. and Little Last Chance Cr.

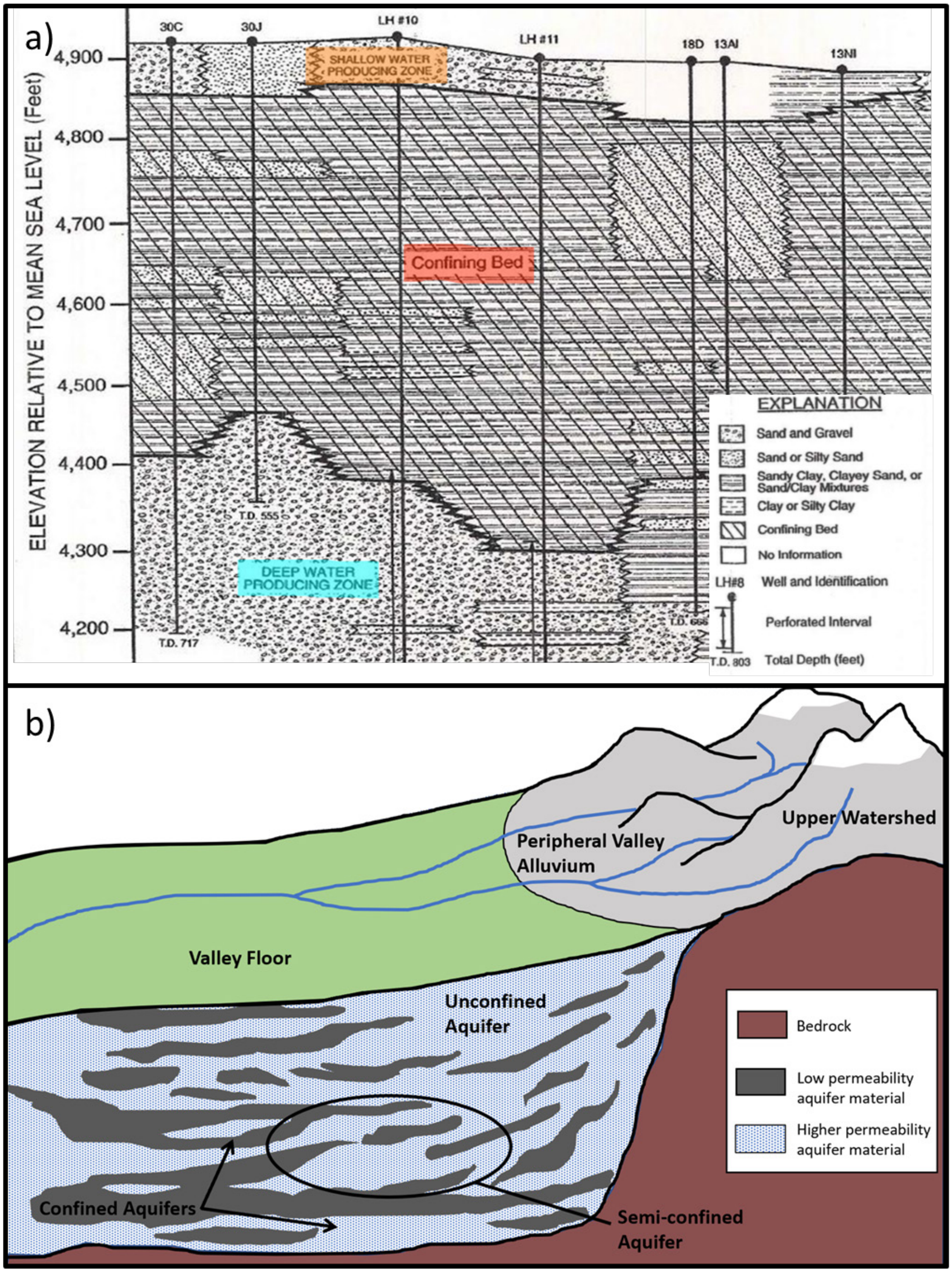


Figure 2. Examples of alluvial aquifer stratigraphy and structure

- *a) Stratigraphic cross section of Sierra Valley. Generalized depth zones include Shallow Zone, 0 – 150 ft, Intermediate Zone, 150 – 450 ft, Deep Zone 450 – 1000 ft. Developed from well drillers' logs; adapted from Schmidt, 2005.*
- *b) Conceptual aquifer schematic showing different aquifer types. Historical depositions of coarse, water-bearing sedimentary layers interlayered with low-permeability silts and clays create complex structure of semi-confined and confined aquifers in a groundwater basin.*

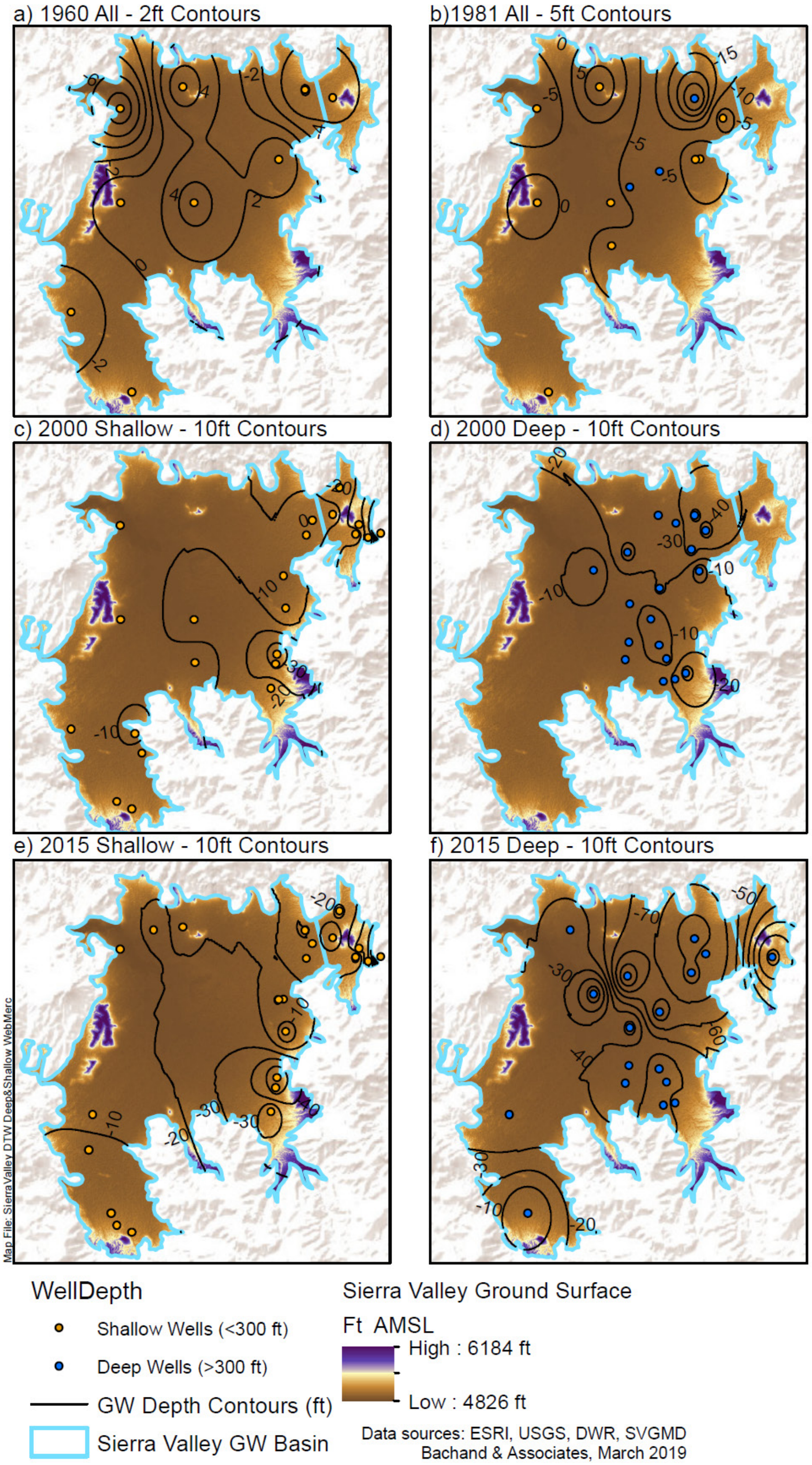
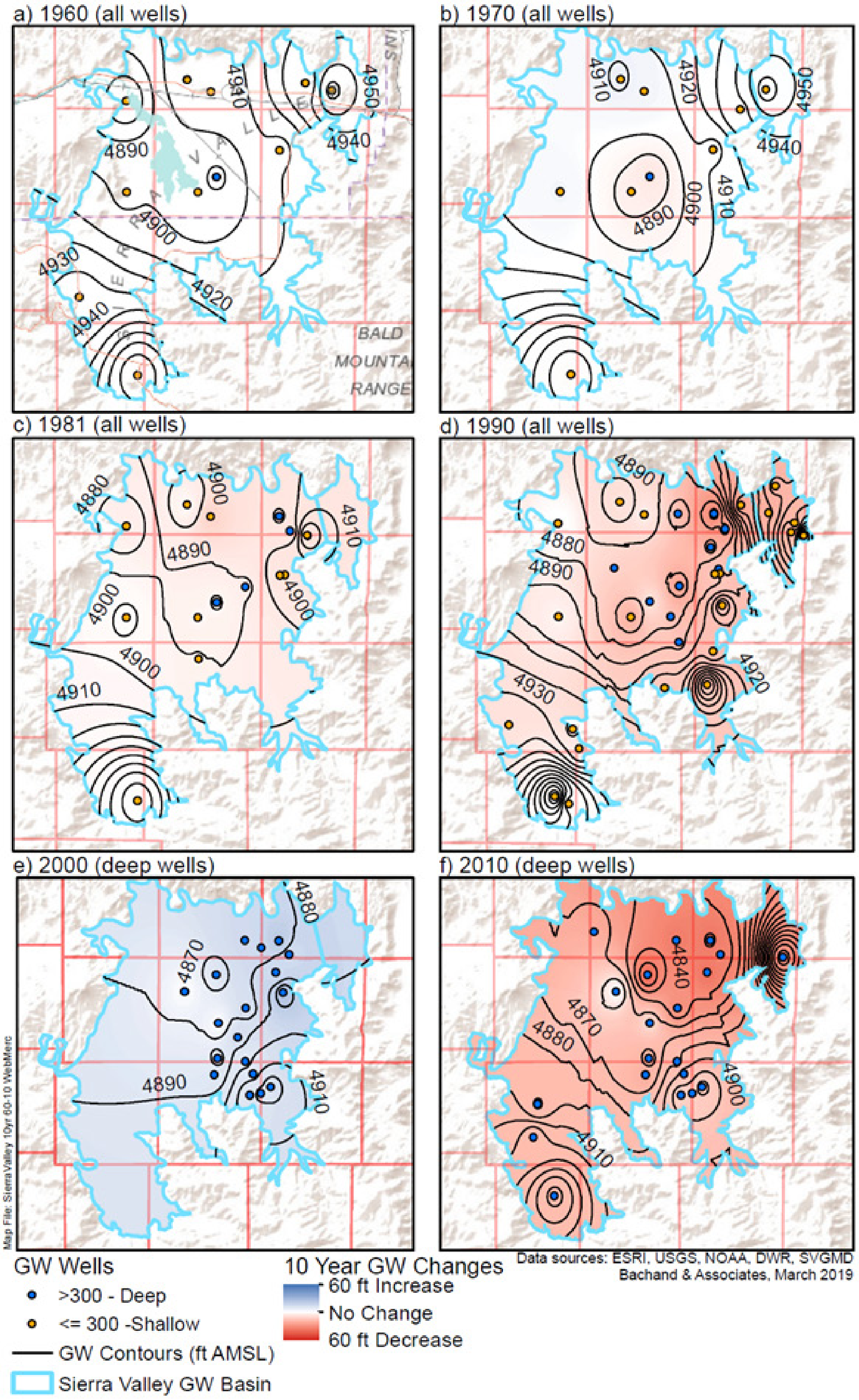


Figure 3. GW level contours relative to ground surface for shallow wells.

Negative numbers indicate depth of groundwater below ground surface; positive numbers indicate groundwater levels above ground surface (only occurs in panel a – 1960). A digital ground surface elevation model is displayed for the Sierra Valley GW basin, with purple colors indicating higher elevations and brown lower.



a) 1960 (all wells)

b) 1970 (all wells)

c) 1981 (all wells)

d) 1990 (all wells)

e) 2000 (deep wells)

f) 2010 (deep wells)

Data sources: ESRI, USGS, NOAA, DWR, SVGMD
Bachand & Associates, March 2019

Figure 4. GWE contours and 10-year changes from 1960 to 2010.

Deep wells are the primary concern for groundwater level declines, but most deep wells were not drilled until the 1980s; all wells are used to generate contours until 1990.

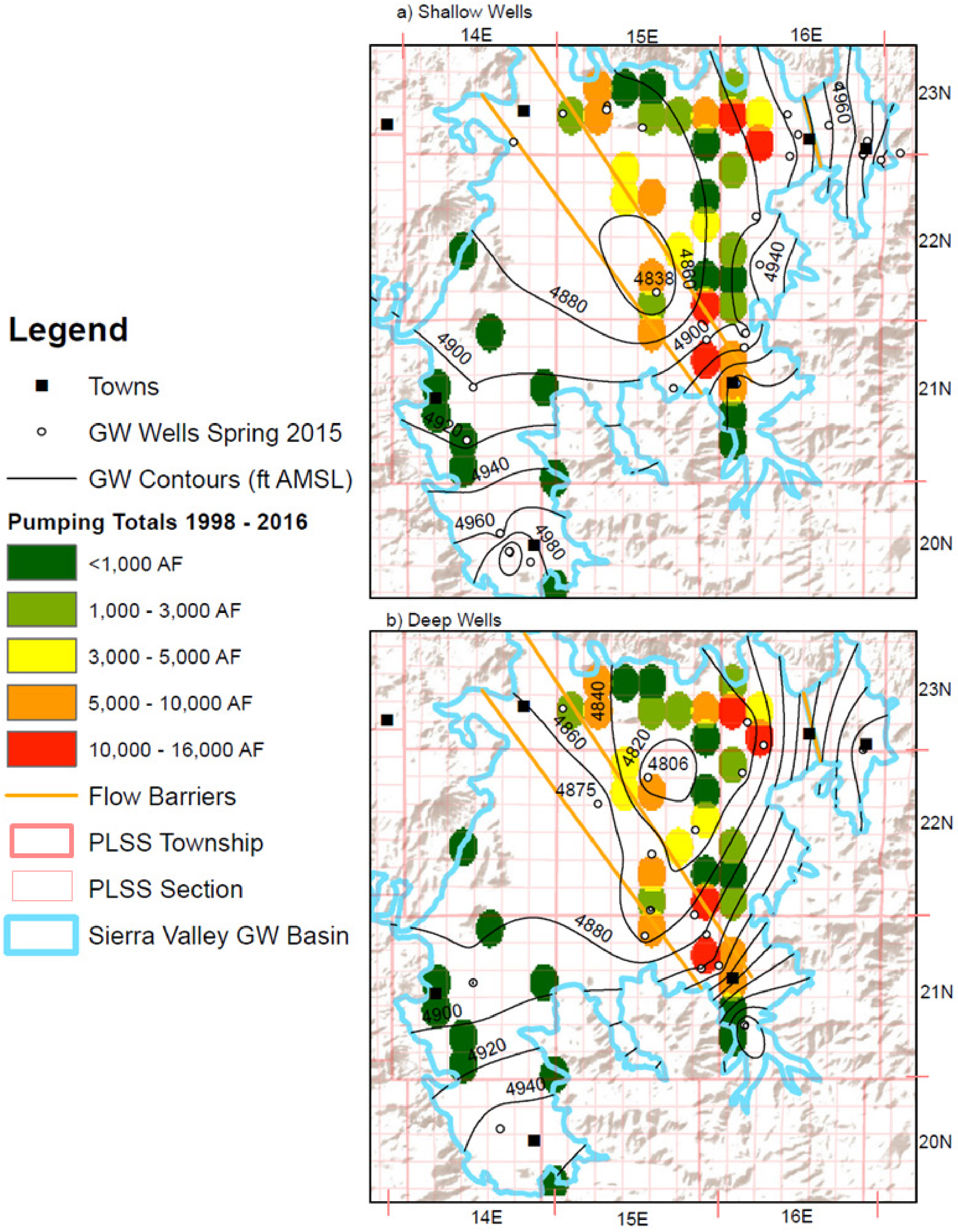


Figure 5. Spring 2015 GWE contours at 20 ft intervals for deep and shallow wells and cumulative 20-y pumping totals. Shallow elevation contours (wells <= 300 ft) indicate different areas of concern from deep wells (>300 ft). Sources of groundwater in the Smithneck drainage and the Chilcoot sub-basin likely buffer some of the effects of pumping near Loyalton and Vinton, respectively.

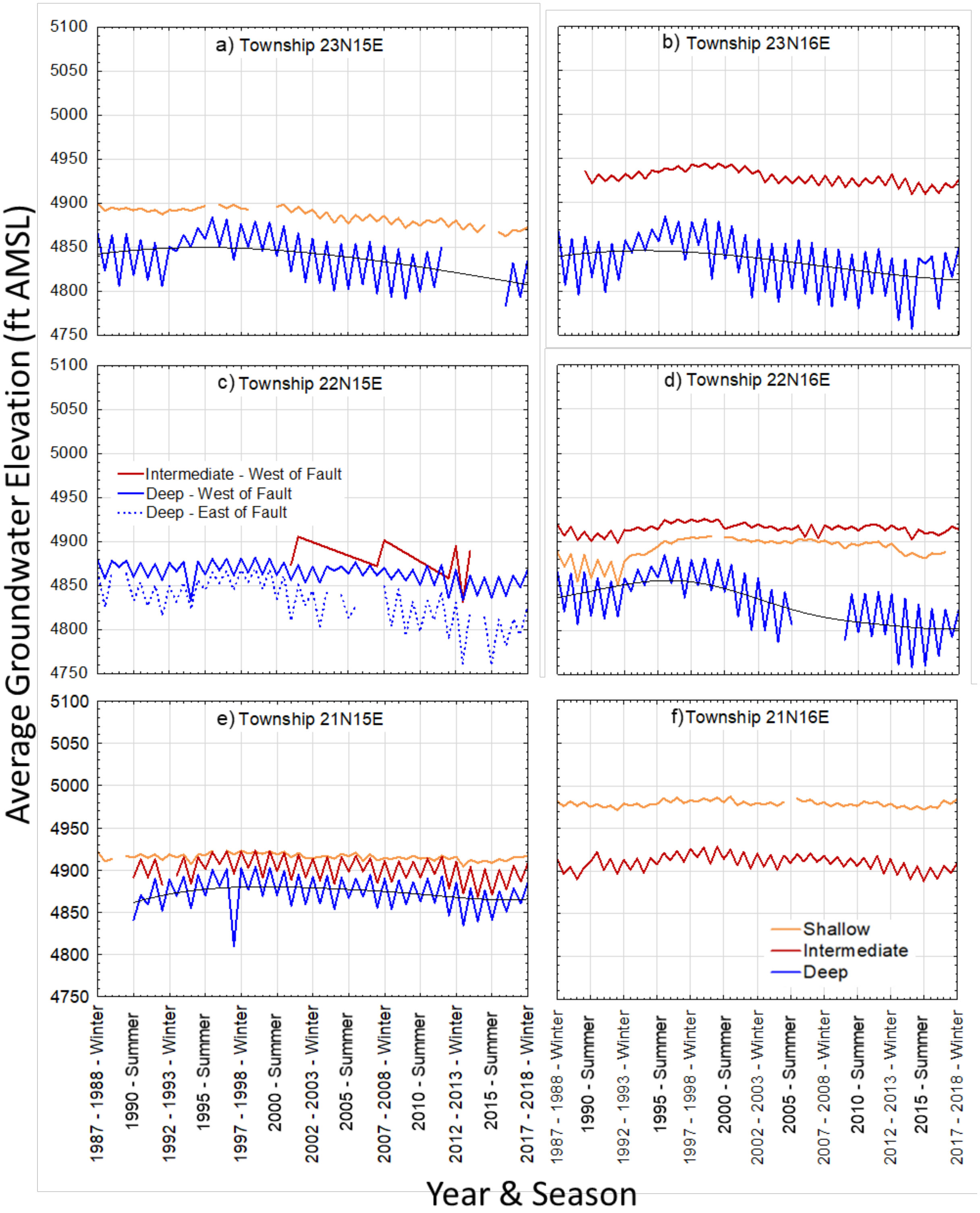


Figure 6. Average GWE by township and depth for the eastern valley.

Black lines show distance weighted least-squares fits, applied only to deep wells, showing the increasing trend through the nineties and the decreasing trend since 2000. Note the greater seasonal changes and steeper declines in the deep wells and the differences east and west of the fault in panel c. See Figure 1 for location of townships.

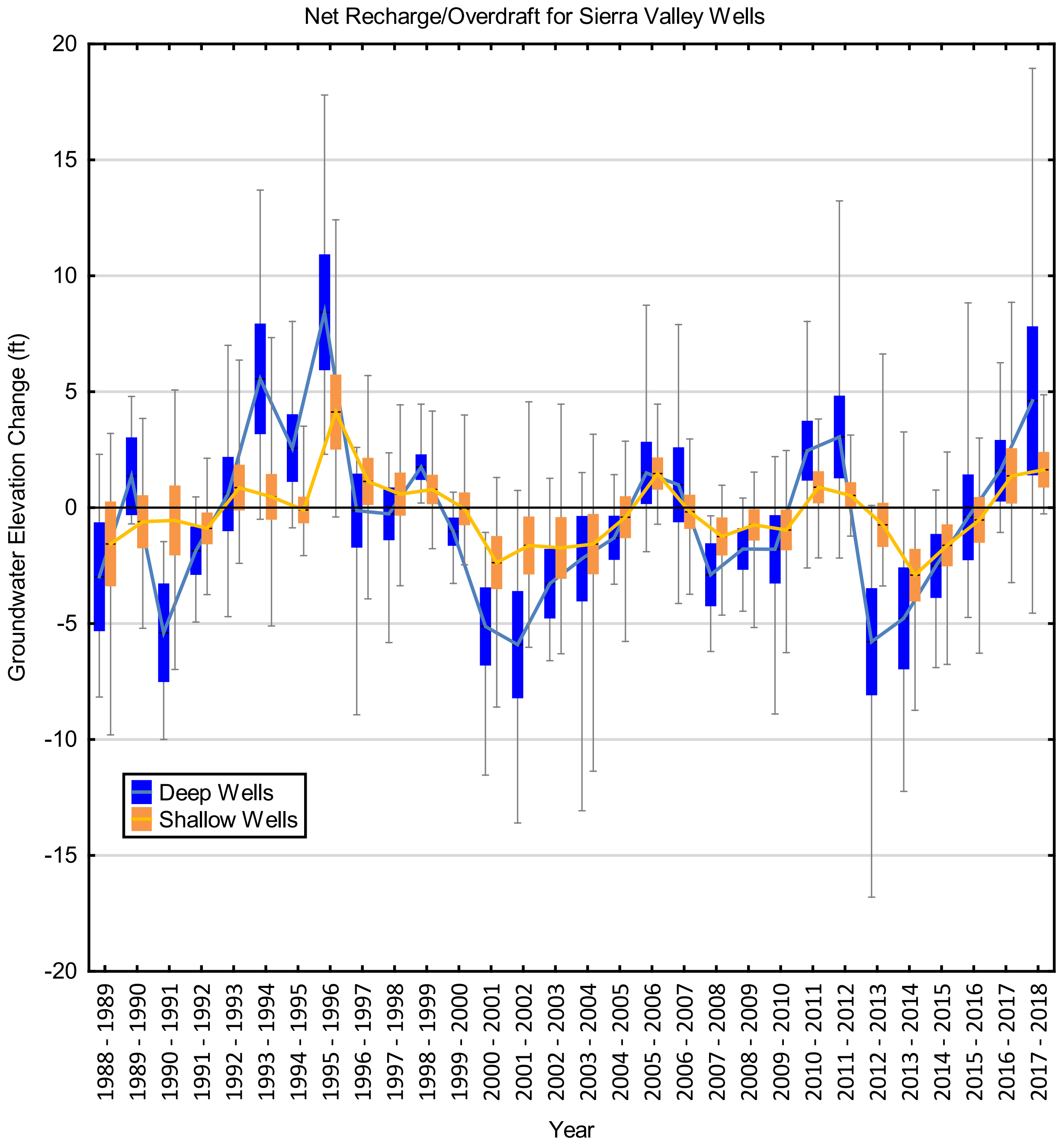


Figure 7. Graphical summary of annual GWE changes in deep and shallow wells over last 30 years.

Orange and blue lines represent mean well water level changes from the prior spring for shallow and deep, respectively, with boxes and whiskers showing 95% CI and minimum/maximum GWE change values for a given year. Annual net increases correspond with periods of greater precipitation, while in most years groundwater levels decline. Deep wells typically have greater annual changes than shallow wells, though minimum and maximum values indicate considerable variation, with spring well levels changing by more than 10 ft over a year in response to dry and wet conditions.

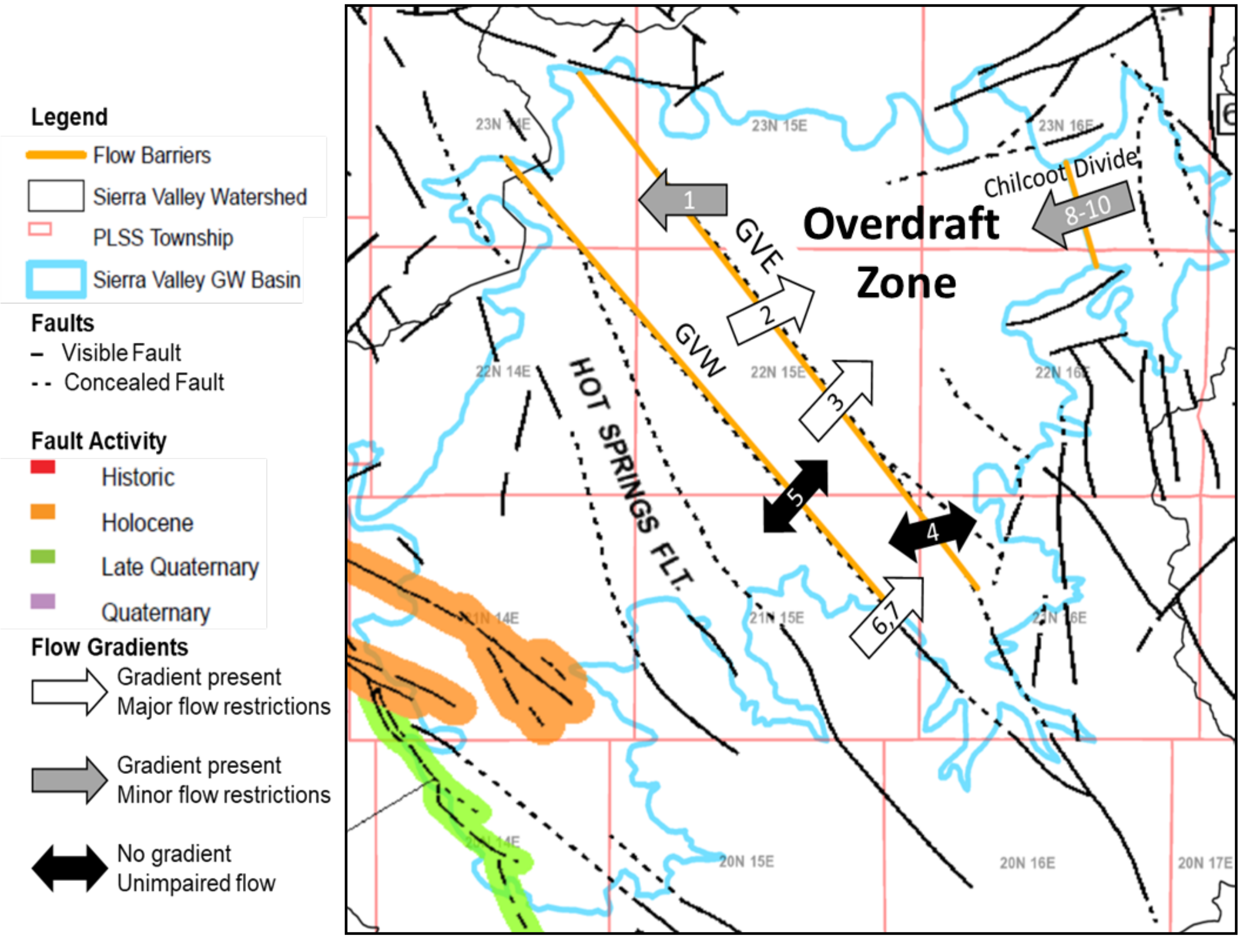


Figure 8. Faults and flow barriers in Sierra Valley.
Barriers to flow assessed in our analyses (thin orange lines) are the Grizzly Valley west and east fault lineaments, GVW and GVE, and the Chilcoot Sub-basin Divide. Arrows show the results of the well comparisons: numbers indicate well pairs, shading indicates extent of flow impairment, and arrow orientation approximates the direction of downward gradient between the two wells (see Figure 9 for example data and SI Table 3 for well numbers). The overdraft zone is bounded by the GVE and the Chilcoot Divide, and the northeastern Sierra Valley sub-basin boundaries. Other faults shown, mapped by the California Geological Society, were not evaluated due to lack of well data.

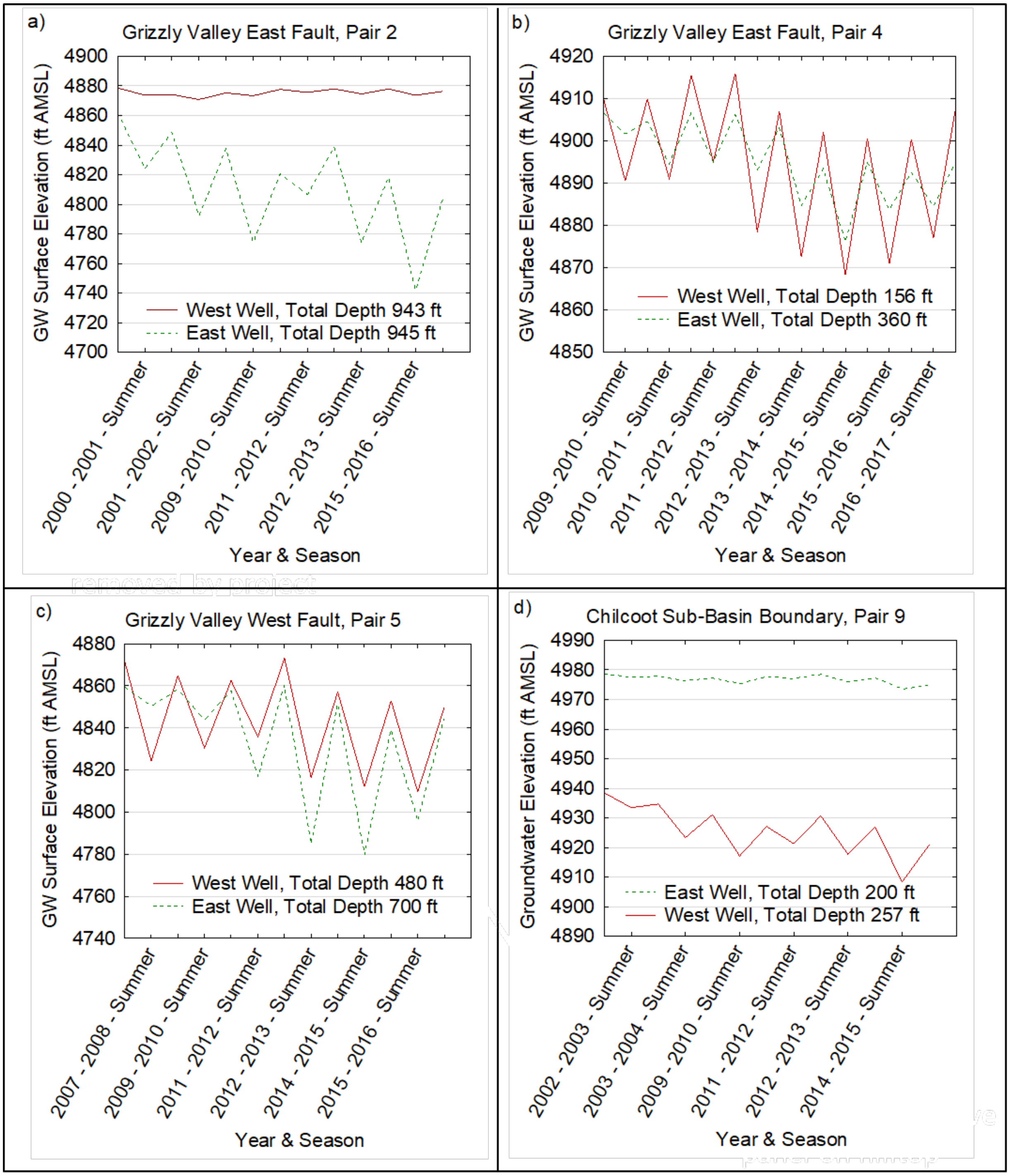


Figure 9. Well comparison across geologic barriers in Sierra Valley.
Panels a) and b) show the difference between wells on either of the Grizzly Valley East Fault, indicating isolation in the center of the valley (pair 2), but less separation closer to Loyalton (pair 4). Panel c) indicates the lack of isolation of wells across the Grizzly Valley West Fault. d) shows the large gradient between wells on either side of the Chilcoot sub-basin boundary. Not all well pairs used in this analysis are shown. Not all seasons/years have data for both wells in a pair, and thus graphs are not continuous time-series. Well pair locations are shown on Figure 8.

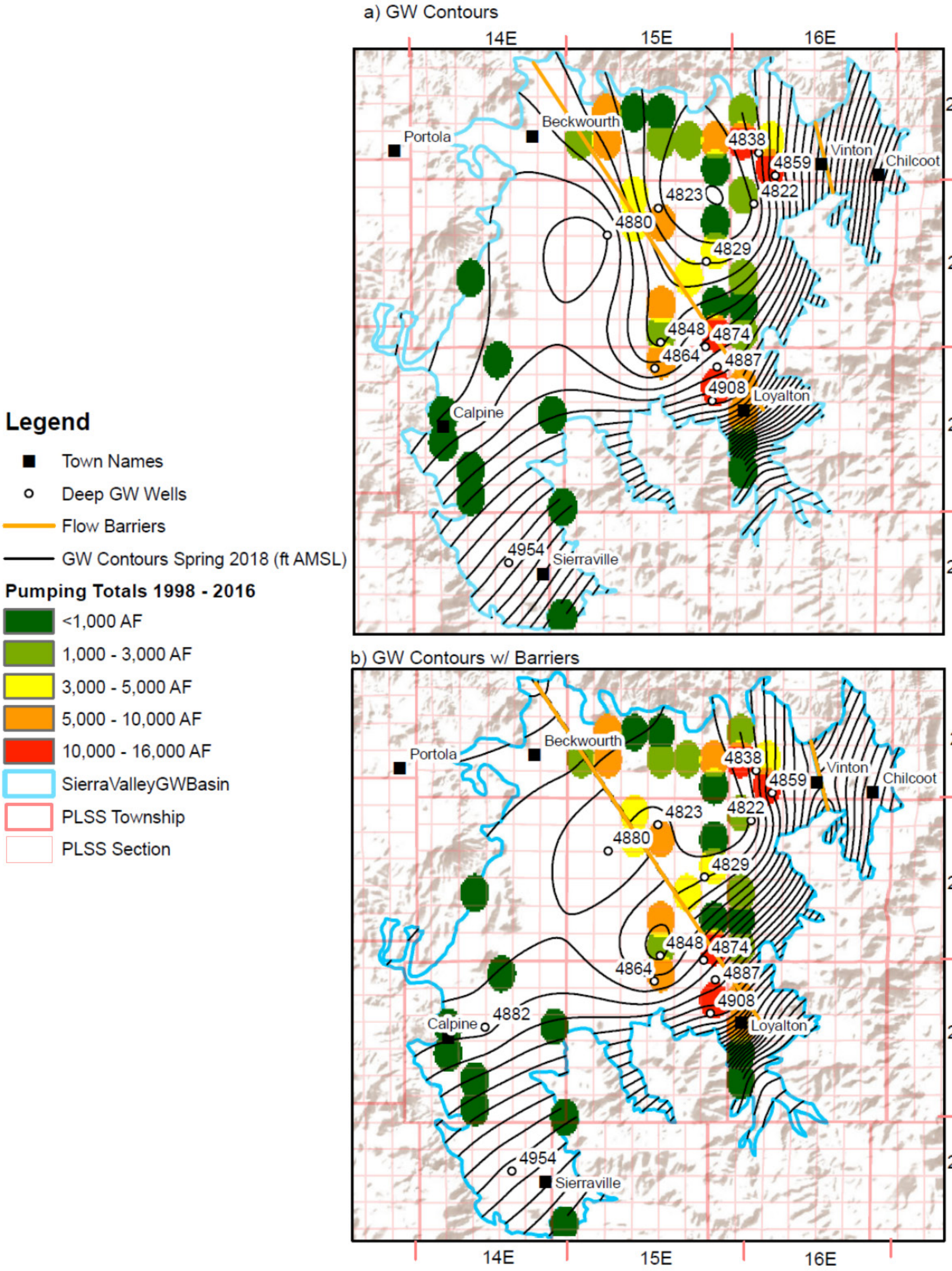


Figure 10. Sierra Valley GWE contours for deep wells (>300 ft) with and without consideration of flow barriers.
a) 10 ft contours generated without consideration of the flow barriers. b) 10 ft contours showing discontinuity of groundwater bodies on either side of fault. GWE values are shown to the right of the well points, indicating the 60 ft difference in water levels for two wells roughly two miles apart. Because flow impairments are not homogenous across the fault, the isolation shown between groundwater bodies is likely exaggerated. There is no deep well data for Chilcoot for 2018.

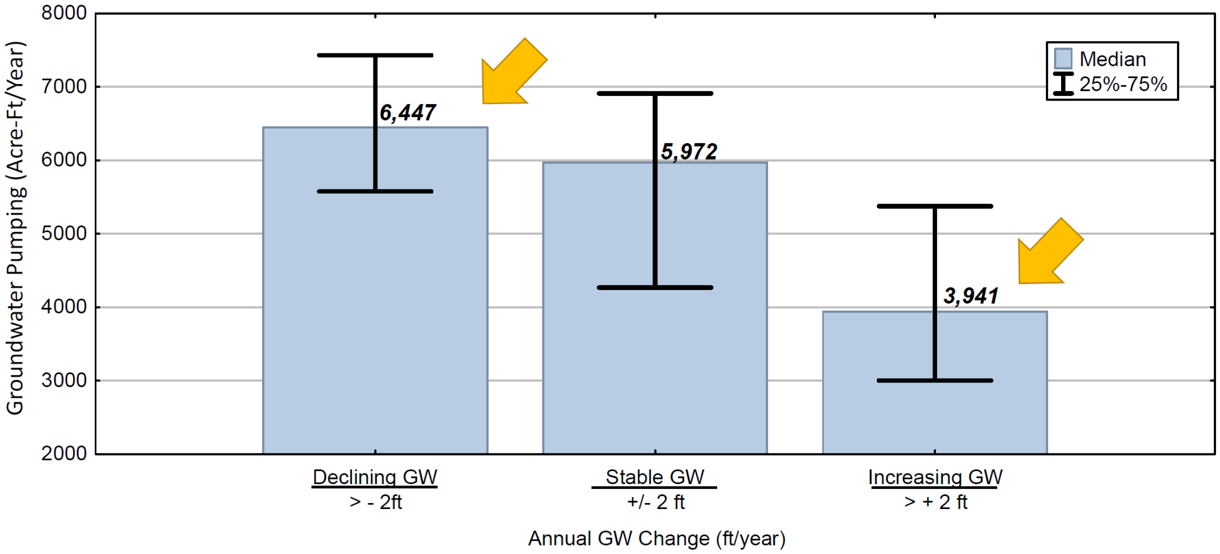
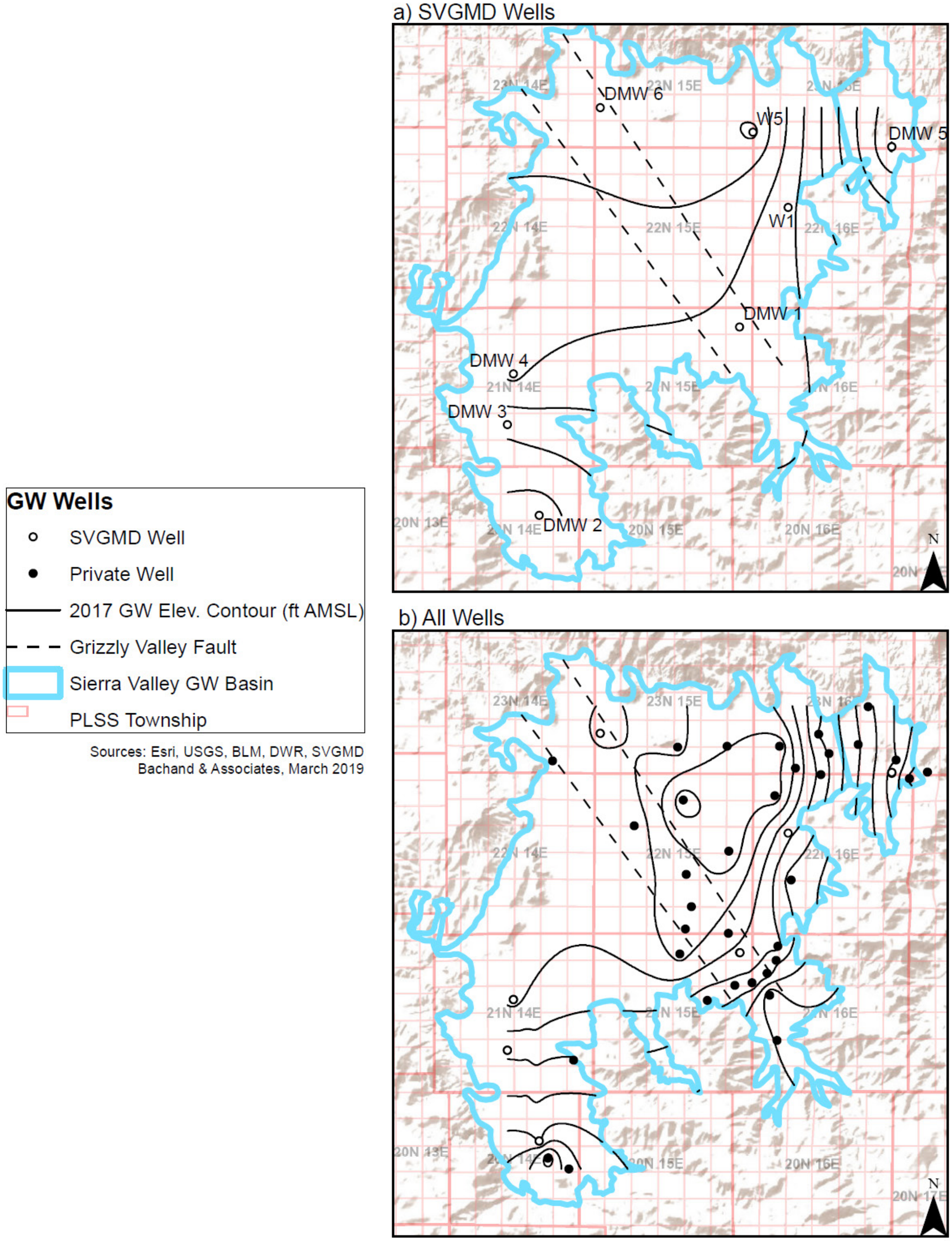


Figure 11. Median pumping volumes categorized by extent of annual GWE changes.
Years with groundwater elevation declines in the eastern Sierra Valley sub-basin greater than 2 ft have greater GW pumping than years with GWE increases. Pumping values that have resulted in stable GW for a given year have a median of just under 6000 AF, but range from 4000 AF to 7000 AF – this variability is likely associated with the amount of GW recharge the following winter.



Sources: Esri, USGS, BLM, DWR, SVGMD
Bachand & Associates, March 2019

Figure 12. Groundwater contours for spring 2017, generated with and without CASGEM wells.

Well selections are: a) nested piezometers monitored by SVGMD (used deepest piezometer); b) CASGEM wells monitored by DWR. Without the CASGEM wells, contour models of the groundwater basin do not adequately characterize areas of groundwater declines.

10 Supplemental Information

10.1 Appendix A – Supplemental Tables

SI Table 1. Summary of surface water stations, showing average values over last decade for each station. Differences in average rainfall and peak SWE around the valley exemplify spatial inequity of precipitation west to east.

Hydrologic Component	Annual Average 2007 - 2017	Standard Deviation	Site	Elevation (ft)
Peak SWE (in)	3.8	3.50	Frenchman Cove	5800
	25.5	7.8	Yuba Pass	6700
	12.7	8.1	Independence Creek	6500
Rainfall (in)	14.6	6.4	Vinton	4944
	22.9	11.8	Sierraville	4973
	18.7	9.7	Portola	4850
	13.2	7.3	Frenchman Dam	5517
Total River Discharge (AF)	112300	160000	Middle Fork Feather River at Portola	4849
Peak Flow (CFS)	650	961		
Evapotranspiration (in)	55.8	1.8	Buntingville	4091
	57.8	3.2	Camino	2780

SI Table 2. CASGEM wells included in the final "analysis wells" dataset.

Our analysis dataset includes 60 wells of the 134 in the CASGEM system and the 900 or so wells drilled in the valley. Well metadata is important to the accuracy of water level measurements – wells with more than one screen measure and draw groundwater from several depths; irrigation wells are more likely to have lower groundwater levels if the well has been pumped recently; older wells may have cracks in the casing, drawing in additional water. Groundwater sub-basin names are abbreviations - Sierra Valley is labeled SV, Chilcoot is labeled Ch.

State Well Number	Local Well Name	Earliest Measurement	Last Measurement	Ground Surface Elevation at Well (ft AMSL)	Total Well Depth (ft)	Number of Screens	SVGMD Well	Well Use	GW Basin Name	Latitude (NAD83)	Longitude (NAD83)
20N14E11P001M	DWM 2s	9/3/2002	4/2/2018	4953.3	110	1	Y	Observation	SV	39.5951	-120.391
20N14E11P002M	DMW 2i	9/3/2002	4/2/2018	4953.4	260	1	Y	Observation	SV	39.5951	-120.391
20N14E11P003M	DMW 2d	9/3/2002	4/2/2018	4953.4	670	1	Y	Observation	SV	39.5951	-120.391
20N14E13Q002M		9/5/1957	4/2/2018	4989.3	30	NA	N	Residential	SV	39.5799	-120.37
20N14E14R001M		4/28/1981	4/2/2018	5038.6	40	NA	N	Residential	SV	39.5856	-120.385
21N14E16H001M	DMW 4s	9/3/2002	4/2/2018	4919.4	250	1	Y	Observation	SV	39.6722	-120.409
21N14E16H002M	DMW 4i	9/3/2002	4/2/2018	4920.1	560	1	Y	Observation	SV	39.6722	-120.409
21N14E16H003M	DMW 4d	9/3/2002	4/2/2018	4919.8	720	1	Y	Observation	SV	39.6722	-120.409
21N14E25P003M		4/27/1981	4/2/2018	4938.6	60	NA	N	Residential	SV	39.6391	-120.367
21N14E28G001M	DMW 3s	9/3/2002	4/2/2018	4915.2	200	1	Y	Observation	SV	39.6444	-120.414
21N14E28G002M	DMW 3i	10/3/2002	4/2/2018	4915.2	295	1	Y	Observation	SV	39.6444	-120.414
21N14E28G003M	DMW 3d	10/3/2002	4/2/2018	4915.2	440	1	Y	Observation	SV	39.6444	-120.414
21N14E29J001M		4/21/1959	3/26/2002	4936.13	30	NA	N	Residential	SV	39.6426	-120.432
21N14E36Q002M		4/21/1981	10/18/2006	4923.61	242	NA	N	Irrigation	SV	39.6236	-120.36
21N15E01K001M	DMW 1d	10/26/1995	4/2/2018	4916.6	600	1	Y	Observation	SV	39.6976	-120.249
21N15E01K002M	DMW 1s	10/26/1995	4/2/2018	4916.6	100	NA	Y	Observation	SV	39.6976	-120.249
21N15E03M003M		10/25/1990	4/2/2018	4895.6	700	NA	N	Irrigation	SV	39.697	-120.292
21N15E04Q001M		10/23/1980	4/7/2004	4896.59	160	NA	N	Irrigation	SV	39.6944	-120.306
21N15E12J001M		4/22/1981	4/2/2018	4945.7	360	3	N	Irrigation	SV	39.6813	-120.241
21N15E12P003M		9/30/1981	4/2/2018	4930.7	514	NA	N	Irrigation	SV	39.6798	-120.253
21N15E14L001M		4/24/1981	4/2/2018	5003.7	127	NA	N	Residential	SV	39.6717	-120.272
21N16E06H003M		4/16/1980	4/2/2018	4953.7	156	NA	N	Residential	SV	39.7011	-120.222
21N16E07A001M		4/16/1981	4/2/2018	4969.7	200	NA	N	Irrigation	SV	39.6935	-120.223
21N16E07G001M		10/25/1990	4/2/2018	4963.7	400	NA	N	Irrigation	SV	39.6864	-120.23
21N16E18G002M		10/1/1986	4/2/2018	4998.7	135	NA	N	Residential	SV	39.6744	-120.228
22N14E26L001M		10/4/1958	4/15/1999	4898.03	198	NA	N	Stockwatering	SV	39.7283	-120.381
22N15E08Q001M		4/28/1982	4/2/2018	4880.52	943	NA	N	Stockwatering	SV	39.7667	-120.324
22N15E10B001M	Roberti Well	2/27/1991	4/2/2018	4894.54	945	2	N	Irrigation	SV	39.7808	-120.289
22N15E13N001M		4/9/1980	4/2/2018	4896.57	740	3	N	Irrigation	SV	39.7528	-120.257
22N15E22Q001M		10/16/1958	4/2/2018	4884.47	600	NA	N	Stockwatering	SV	39.7403	-120.287
22N15E26K003M		10/4/1985	10/29/2003	4889.57	735	NA	N	Residential	SV	39.7284	-120.266
22N15E28L001M		4/16/1958	4/14/1999	4885.07	296	NA	N	Stockwatering	SV	39.7282	-120.307
22N15E34L006M		6/2/1995	4/2/2018	4888.58	480	NA	N	Stockwatering	SV	39.7106	-120.288
22N15E36N001M		10/10/1980	4/2/2018	4900.57	803	1	N	Irrigation	SV	39.7082	-120.257
22N16E01A002M		3/26/1985	4/2/2018	5093.6	130	NA	N	Residential	Ch	39.7925	-120.129
22N16E04A001M		4/26/1966	4/3/2018	4935.6	251	NA	N	Stockwatering	SV	39.7945	-120.192
22N16E06R002M		4/11/1981	4/2/2018	4911.58	816	1	N	Irrigation	SV	39.7831	-120.225
22N16E08P001M		4/21/1981	4/14/1999	4913.59	615	NA	N	Irrigation	SV	39.7659	-120.216
22N16E17C001M	W 1	4/9/1980	4/2/2018	4910.59	184	1	Y	Observation	SV	39.7627	-120.215
22N16E17E002M		3/13/1959	4/2/2018	4904.89	125	NA	N	Stockwatering	SV	39.7622	-120.221
22N16E20P002M		4/17/1981	4/2/2018	4938.22	205	2	N	Residential	SV	39.7372	-120.213
23N14E35L001M		9/3/1957	4/3/2018	4880.96	18	NA	N	Stockwatering	SV	39.802	-120.382
23N15E26R001M		4/10/1981	4/17/2012	4900.56	763	1	N	Irrigation	SV	39.81	-120.258
23N15E29H001M		10/1/1958	10/20/2014	4899.93	145	NA	N	Stockwatering	SV	39.819	-120.318
23N15E30M001M	DMW 6d	10/27/2004	4/3/2018	4890.48	350	1	Y	Observation	SV	39.817	-120.348
23N15E30M002M	DMW 6s	10/27/2004	4/3/2018	4890.48	140	1	Y	Observation	SV	39.817	-120.348
23N15E34D001M		10/2/1958	4/3/2018	4891.83	137	NA	N	Stockwatering	SV	39.8094	-120.293
23N15E36H002M	W 5	1/2/1996	5/4/2018	4905	688	1	Y	Observation	SV	39.8036	-120.24
23N16E23F001M		6/27/1958	4/3/2018	4993.59	200	NA	N	Stockwatering	Ch	39.8315	-120.158
23N16E27R001M		9/5/1957	4/3/2018	4966.79	300	NA	N	NA	Ch	39.8107	-120.165
23N16E28L001M		10/2/1958	4/3/2018	4942.09	257	NA	N	Stockwatering	SV	39.8165	-120.193
23N16E30R001M		10/4/1980	4/3/2018	4918.58	820	1	N	Irrigation	SV	39.8098	-120.221
23N16E32Q001M		10/4/1980	4/3/2018	4923.59	820	1	N	Irrigation	SV	39.7979	-120.21
23N16E33A002M		2/25/1991	4/3/2018	4943.59	297	1	N	Residential	SV	39.8059	-120.186
23N16E36L004M		10/3/1986	4/3/2018	5033.6	250	NA	N	Residential	Ch	39.8024	-120.139
23N16E36N002M		4/30/1981	4/3/2018	5013.6	50	NA	N	Irrigation	Ch	39.7951	-120.142
23N16E36N003M	DMW 5d	10/27/2004	4/3/2018	5010.6	330	1	Y	Observation	Ch	39.7956	-120.142
23N16E36N004M	DMW 5i	10/27/2004	4/3/2018	5010.6	205	1	Y	Observation	Ch	39.7956	-120.142
23N16E36N005M	DMW 5s	10/27/2004	4/3/2018	5010.6	100	1	Y	Observation	Ch	39.7956	-120.142
23N17E31Q002M		10/23/1991	4/3/2018	5213.6	270	NA	N	Residential	Ch	39.796	-120.116

SI Table 3. Well pairs used in flow barrier analysis.

Well data for select comparisons are shown in Figure 9.

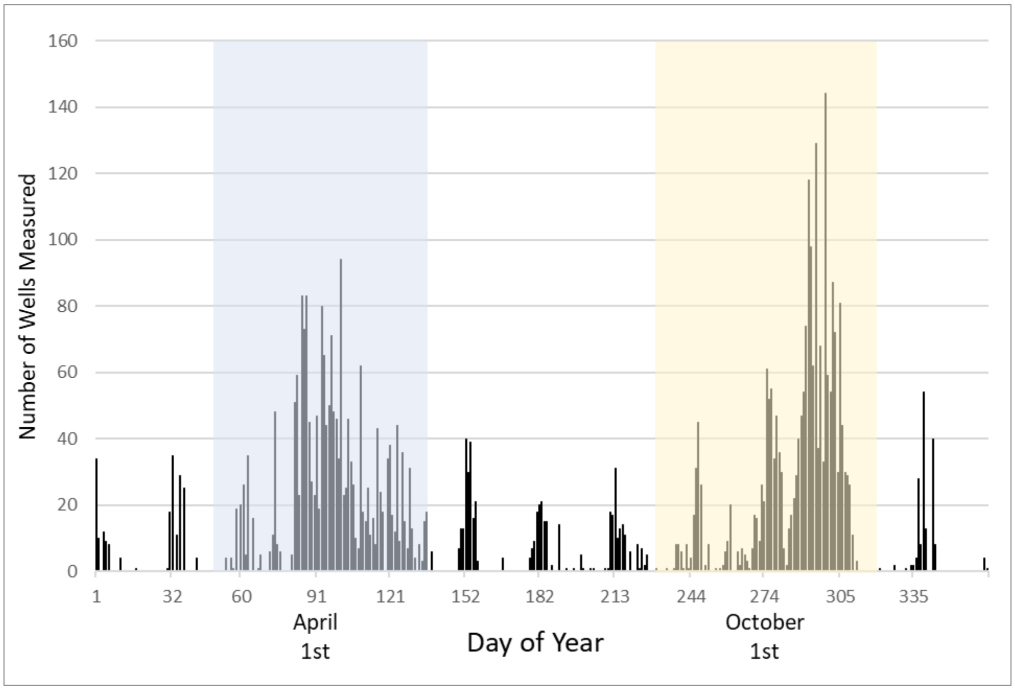
Well Pair	Geologic Feature	Well West	Well East
1	Grizzly Valley Fault East	23N15E30M002	23N15E29H001
2	Grizzly Valley Fault East	22N15E22Q001	22N15E13N001
3	Grizzly Valley Fault East	22N15E08Q001	22N15E10B001
4	Grizzly Valley Fault East	21N15E12J001	21N16E06H003
5	Grizzly Valley Fault West	21N15E03M003	22N15E34L006
6	Grizzly Valley Fault West	21N15E14L001	21N15E12P003
7	Grizzly Valley Fault West	21N15E14L001	21N15E12J001
8	Chilcoot Sub-basin Divide	23N16E28L001	23N16E23F001
9	Chilcoot Sub-basin Divide	23N16E33A002	23N16E27R001
10	Chilcoot Sub-basin Divide	22N16E04A001	23N16E36N003

SI Table 4. State and Federal Lands within the entire Sierra Valley GW Basin.

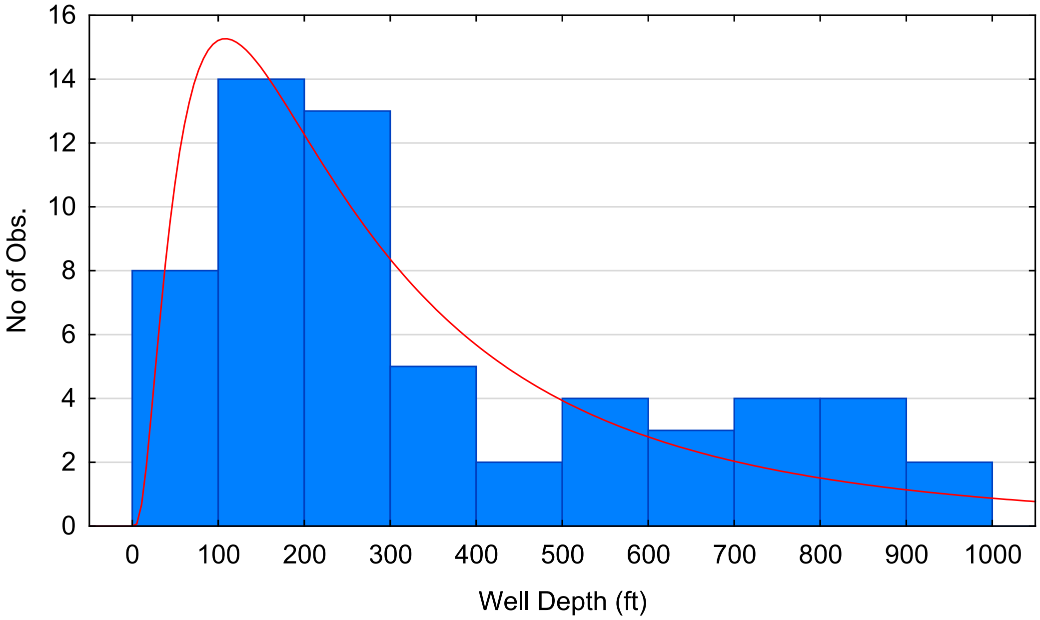
A total of 15% of the land within the basin is government-owned land, primarily situated at the valley periphery. The other 85% is under private ownership.

Land Owner		Area (acres)	% of Basin Area
Sierra Valley GW Basin		117,351	100.0%
Federal Lands	Bureau of Land Management	1,615	1.4%
	United States Forest Service	10,962	9.3%
	Plumas National Forest	2,468	2.1%
	Tahoe National Forest	8,494	7.2%
State Lands	California Department of Fish & Wildlife	3,697	3.2%
	Crocker Meadows Wildlife Area	1,636	1.4%
	Antelope Valley Wildlife Area	1,016	0.9%
	Smithneck Creek Wildlife Area	1,045	0.9%

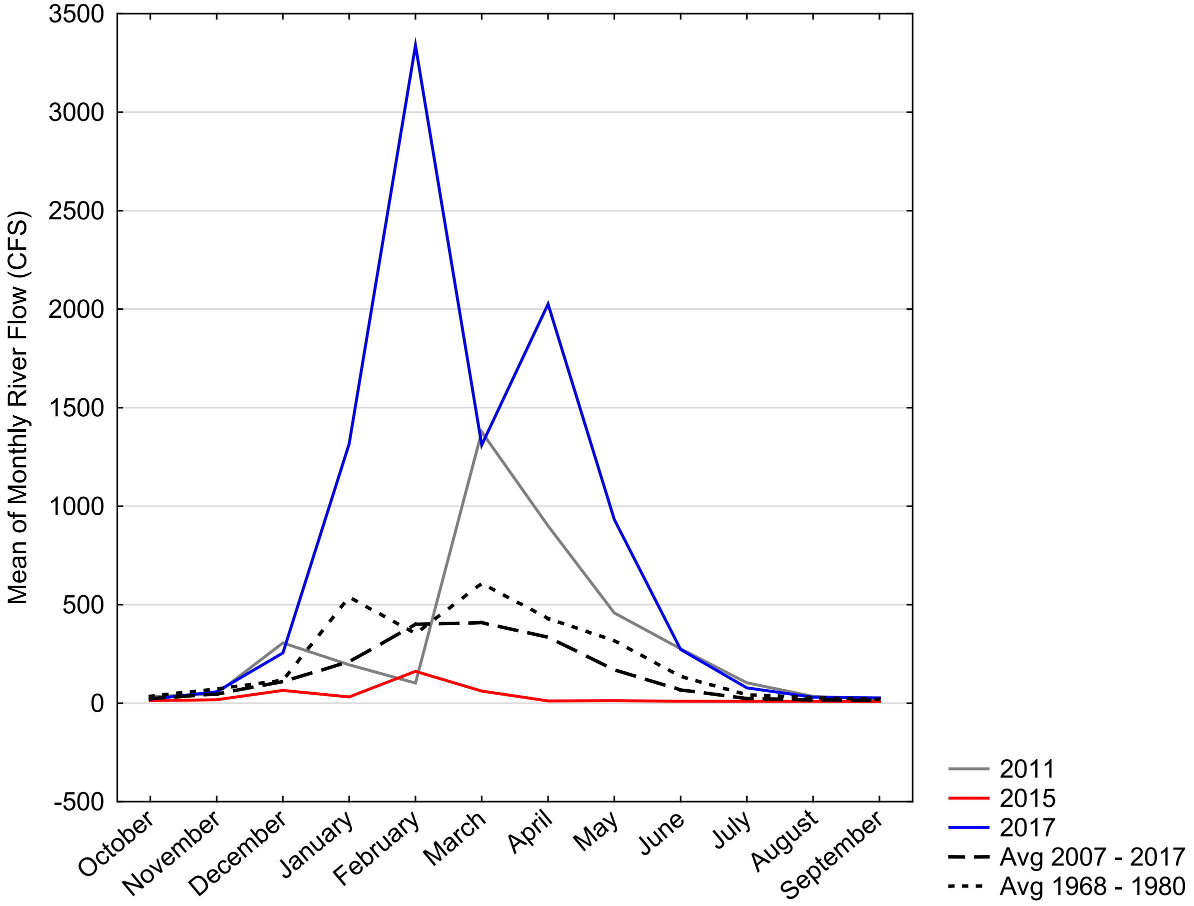
10.2 Appendix B – Supplemental Figures



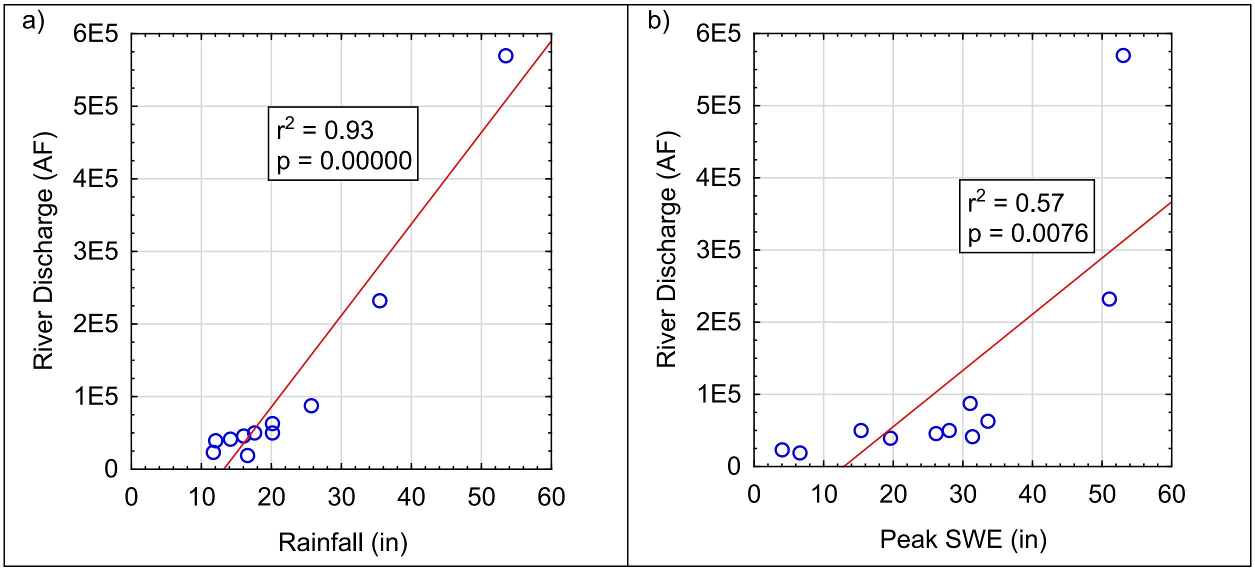
SI Figure 1. Date distribution of all CASGEM well measurements from 2009 to 2018.
DWR's collection of well data in Sierra Valley varies widely, but occurs most frequently in April and October. Colored boxes show the 90-day spring and fall periods over which groundwater well measurements were averaged to assess conditions following winter recharge and summer irrigation.



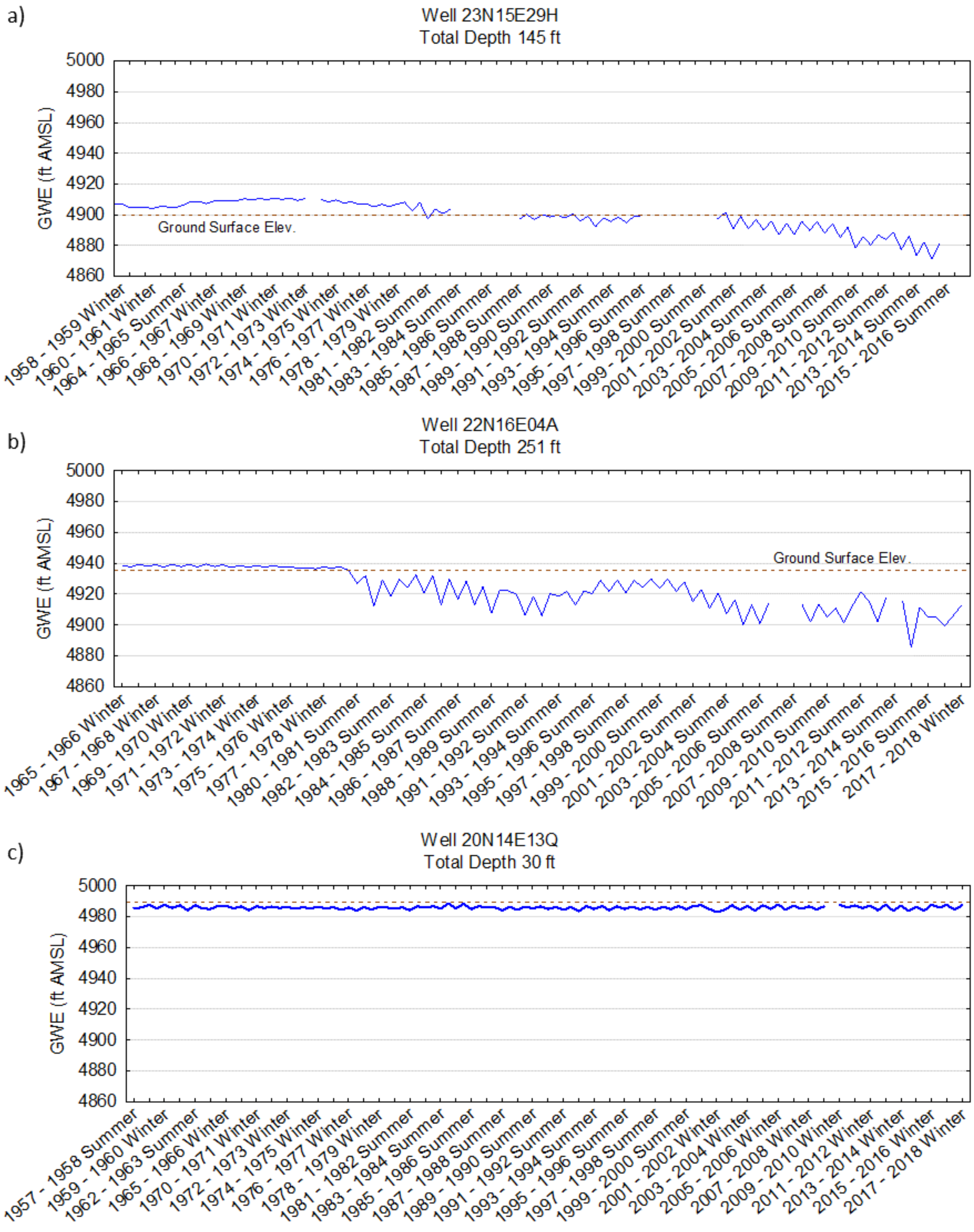
SI Figure 2. Histogram of well depths throughout Sierra Valley for wells in the analysis dataset.
Despite the larger number of shallow wells, they are not distributed evenly across the valley, notably lacking in the eastern valley.



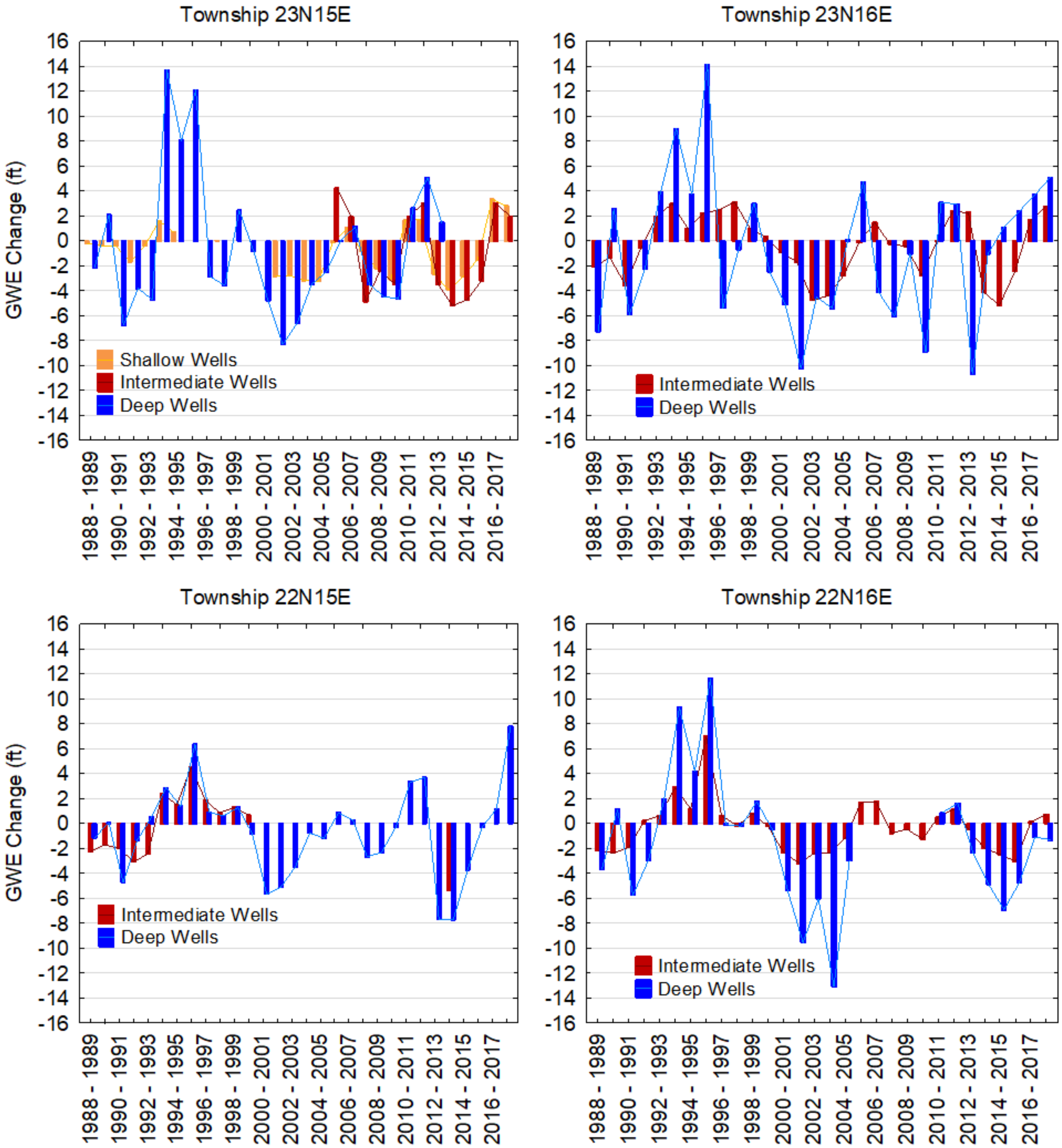
SI Figure 3. Average monthly flow of Middle Fork Feather River at Portola for several key years.
The magnitude and timing of the unique flow regime of 2017 is apparent compared to other years, in which peak flow usually comes in March. The recent and historical decadal averages are similar, with recent years having slightly lower monthly flows and later peak flows.



SI Figure 4. Scatterplots of annual totals of river discharge against a) rain and b) snow phases of precipitation.
Rainfall appears to have better linear fit relationship, indicating discharge is more dependent on rainfall than snowpack.

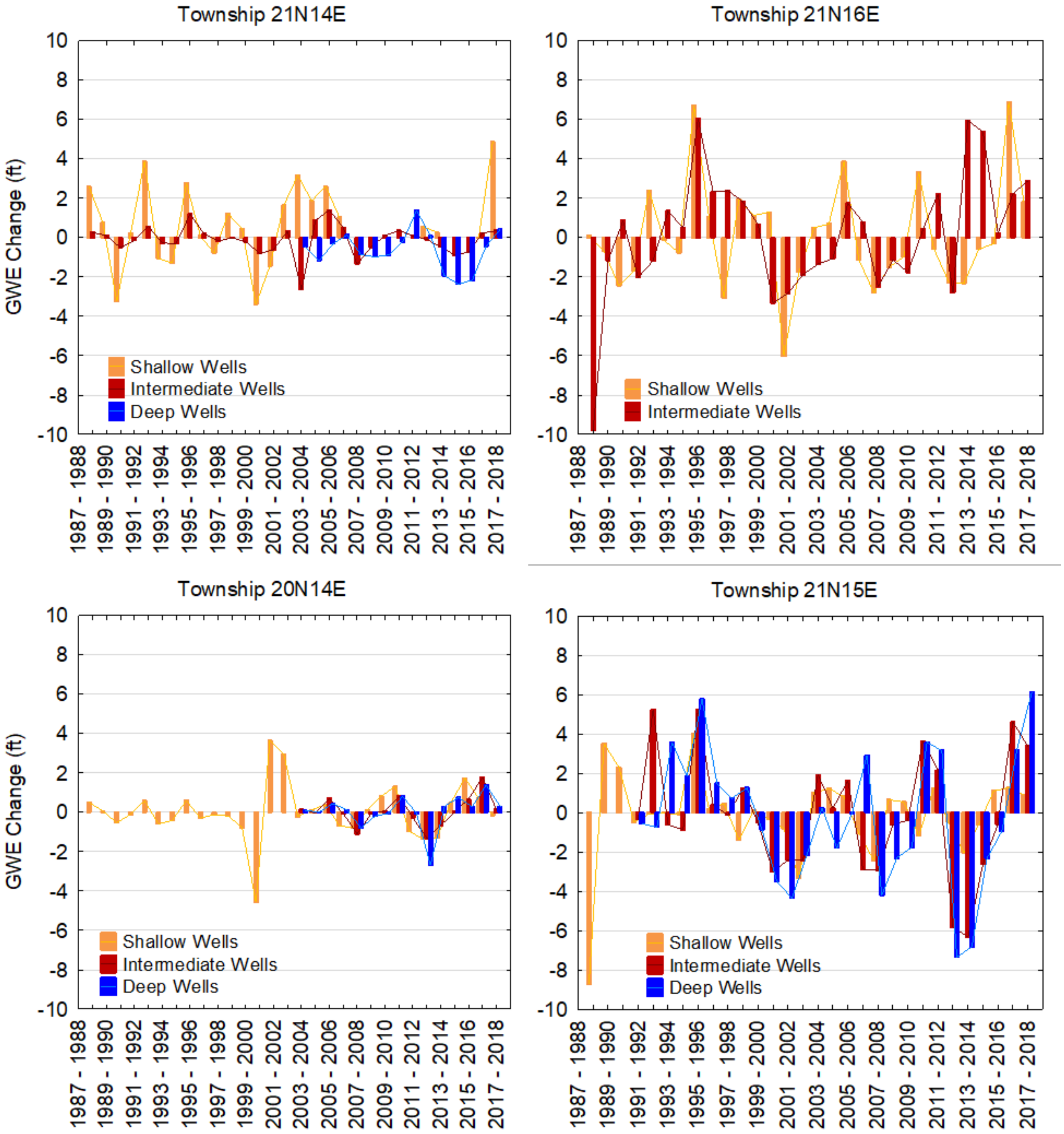


SI Figure 5. Typical long-term groundwater GWE trends for shallow wells in different areas of Sierra Valley.
Historically, shallow wells typically had GWE above ground surface and varied by a couple feet, representative of pre-development conditions. In areas with agricultural pumping (a & b are located east of GVF), shallow GWEs began declining by the 1980s and elicited greater seasonal changes, in the 5 – 10 ft range. Shallow GWEs in areas with agricultural pumping have declined by over 30 ft in some areas. Areas that have had less groundwater pumping and/or are in wetter portions of the valley (e.g. c in the southwestern valley) typically have more stable and higher GWEs.

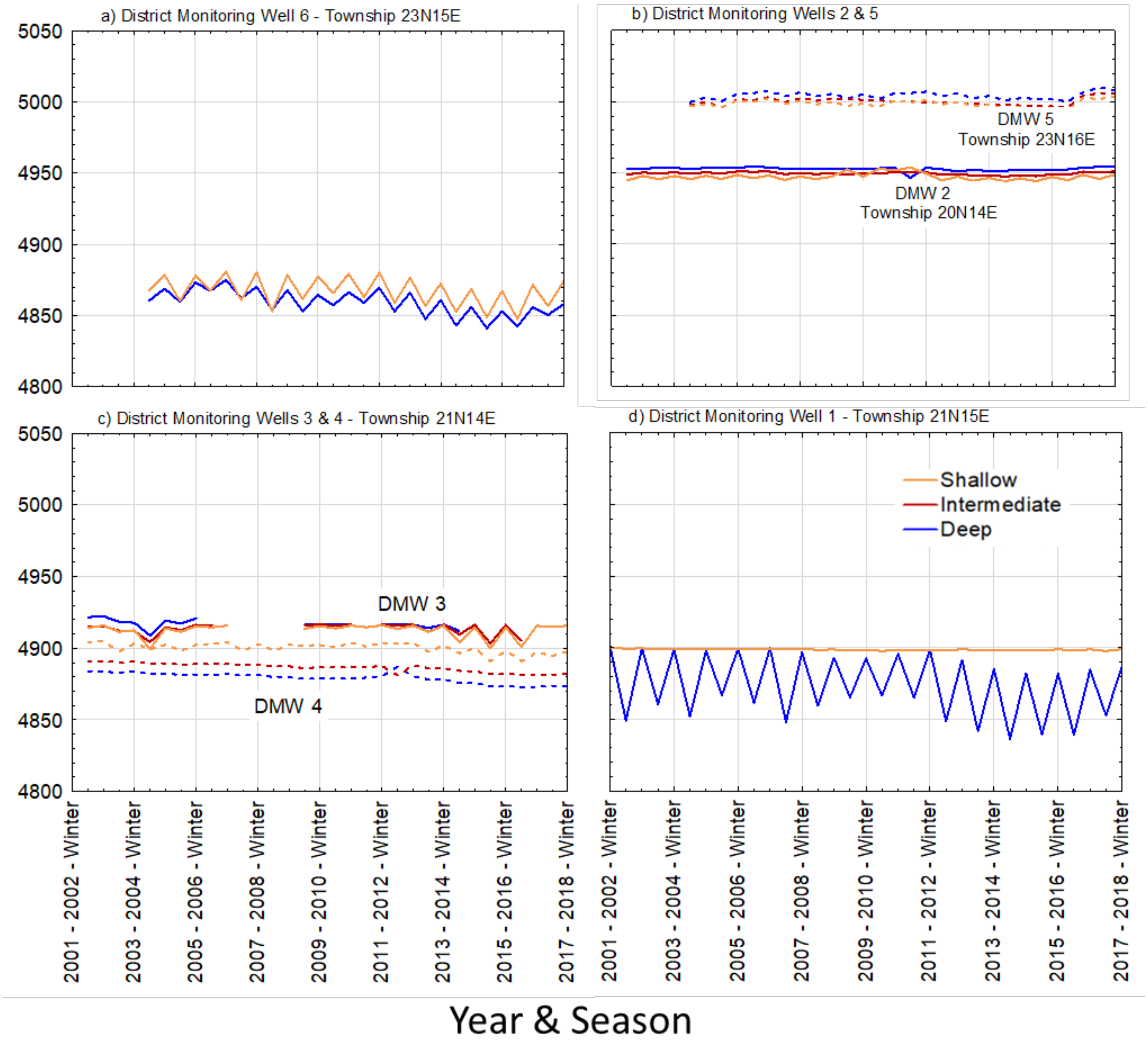


SI Figure 6. Average annual spring groundwater changes since 1990 for three depths in eastern townships.

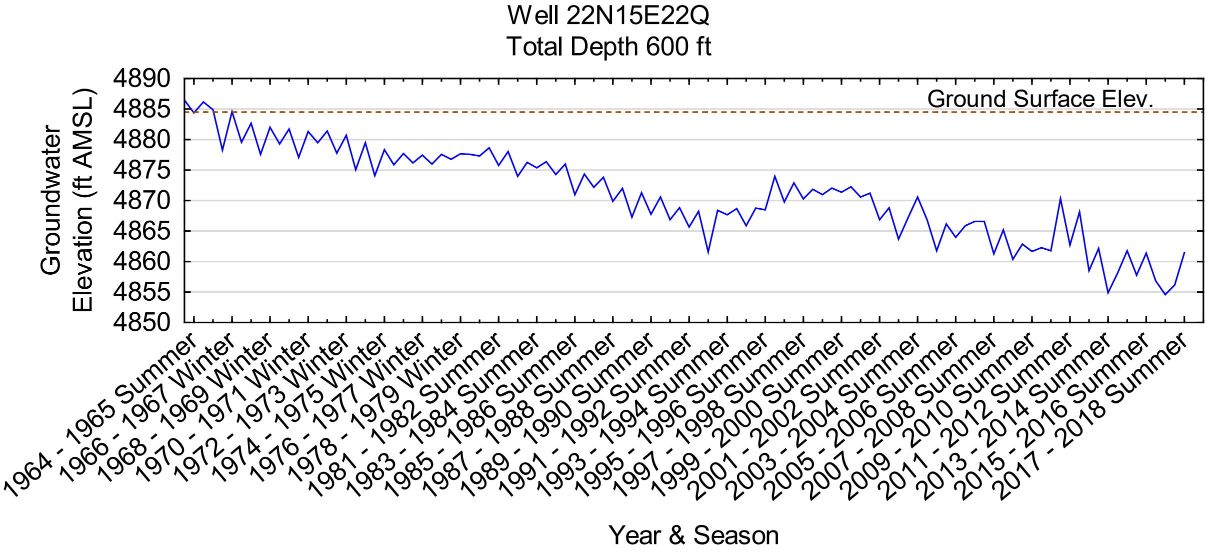
Periods of recharge, particularly in deep wells, are apparent for the most of the 1990s. Since 2000, most years see annual declines, except 2006, 2011 and 2017. Very few eastern valley shallow wells had sufficient accuracy or data points to be included in our analysis wells dataset. Organization of graphs is roughly representative of relative locations in valley.



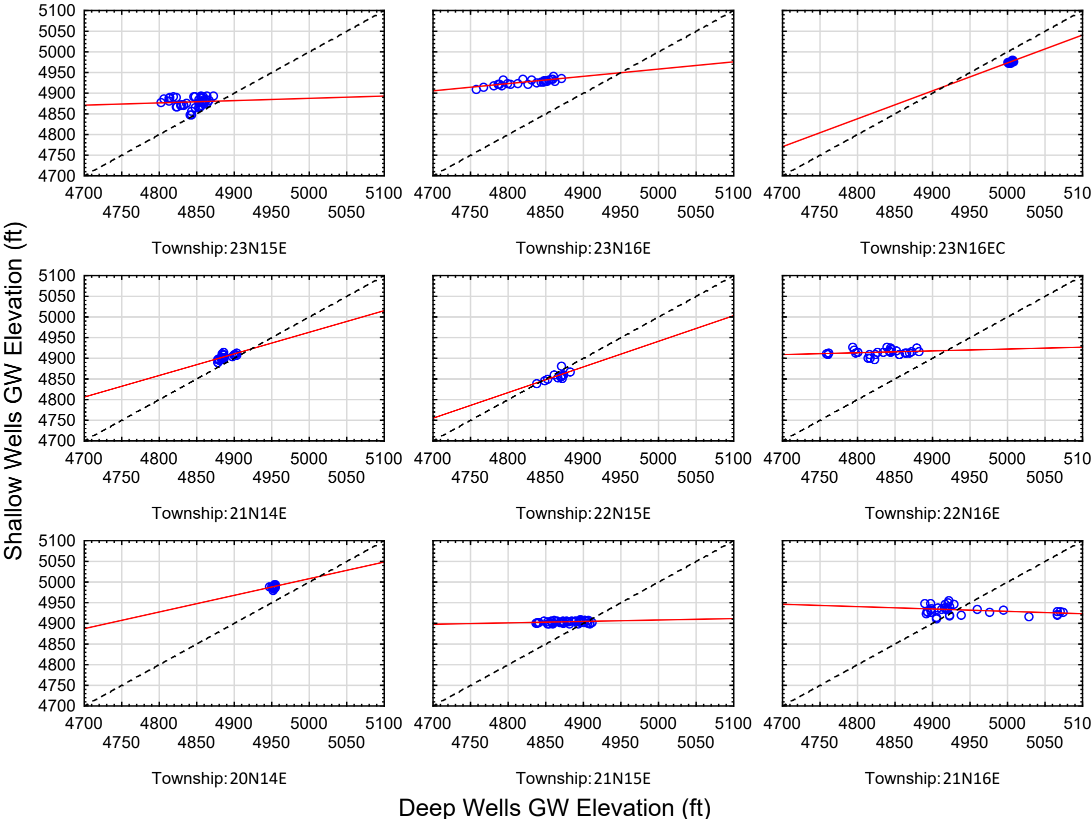
SI Figure 7. Average annual groundwater changes since 1990 for three depths in southwestern and southeastern townships. The southeastern valley (21N15E & 21N16E) have declines in response to pumping, but typically respond to recharge more than townships in the northeastern valley, resulting in slower GWE declines. The southwestern valley (20N14E & 21N14E) typically have smaller annual changes than townships further east. Organization of graphs are NOT representative of relative locations within valley.



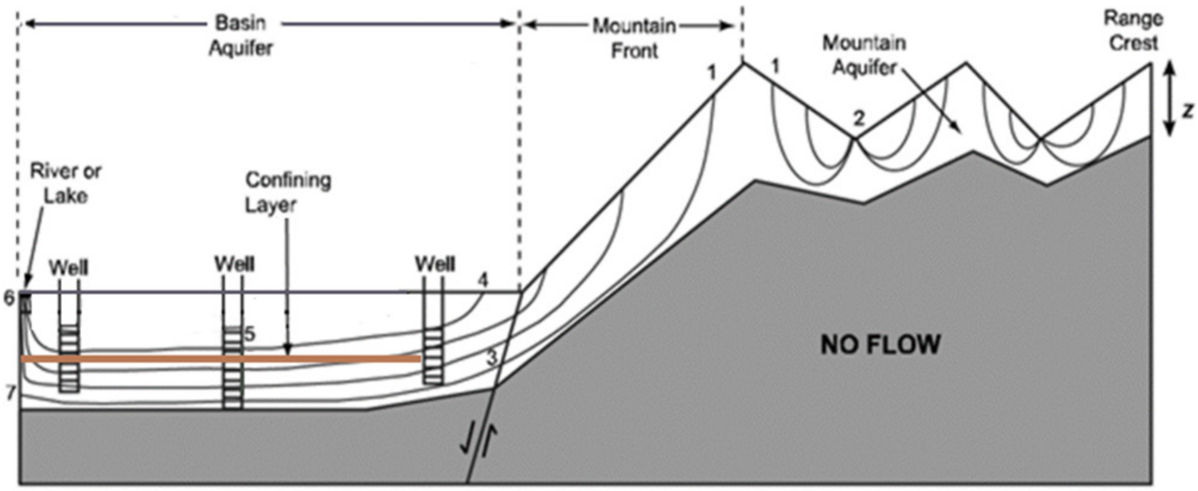
SI Figure 8. Summer- and winter- end GWE averages for SVGMD District Monitoring Wells (DMW).
DMW 2, 3 and 4 are located in the southwest of the valley. DMW 6 is located near Beckwourth, in the north. DMW 1 is located near Loyalton, and its shallow piezometer appears to be drilled into a perched aquifer, isolating it from the effects of pumping seen in the deeper piezometer. DMW 5 is located in the Chilcoot sub-basin. See SI Table 2 for nested piezometer depths.



SI Figure 9. Typical long-term groundwater hydrograph for deep wells in Sierra Valley in locations of groundwater overdraft.
GWE began dropping in the 1960s corresponding with the beginning of groundwater pumping and the construction of Frenchman Dam. GWE in the eastern valley have declined by about 30 feet over the last 50 years.



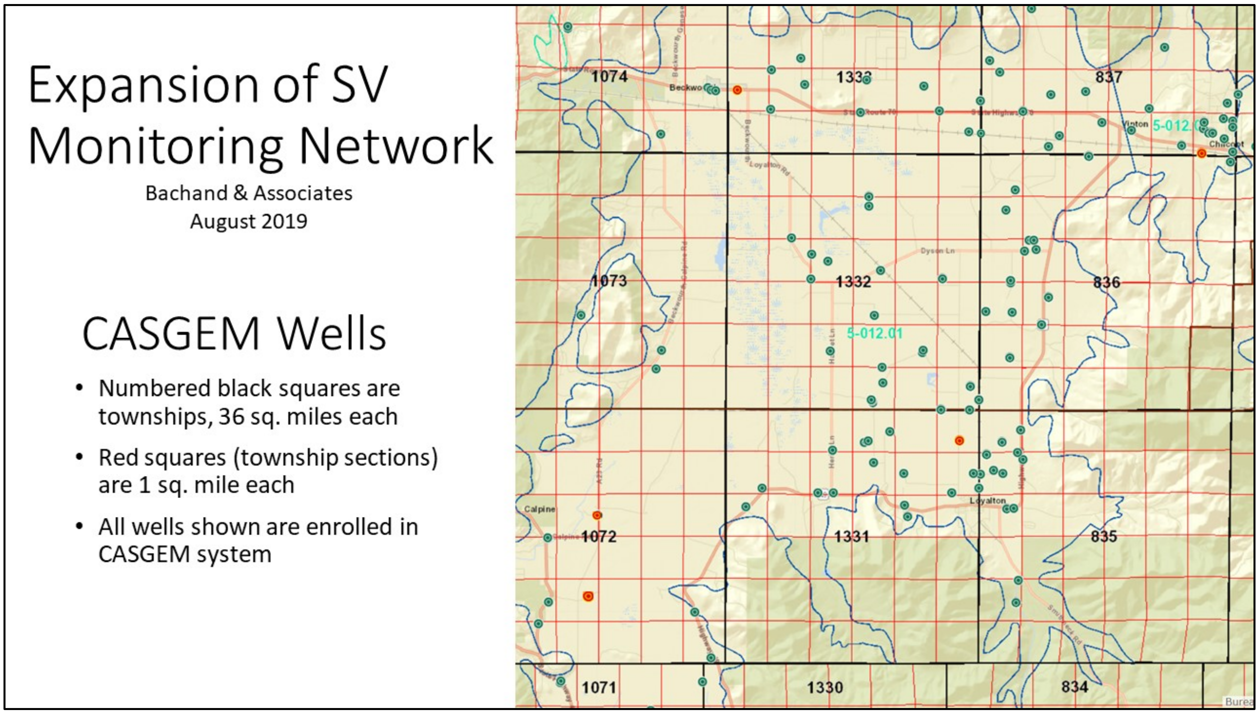
SI Figure 10. Relationship between groundwater elevations in wells above and below 300 ft.
Trend lines (shown in red) with slopes flatter than 1:1 would suggest the deep wells change more, while steeper trend lines would indicate shallow wells have a greater range of elevations. In either case, more than slight deviations from a slope of 1 suggest distinct groundwater regimes. Township 22N15E, in the center of the valley shows a trendline close to unity, though this may be an artifact of having only one shallow well in the township. Township 23N16C is the portion of that township in the Chilcoot sub-basin.



SI Figure 11. Conceptual diagrams of groundwater flow paths.

Recharge and discharge components applied to Sierra Valley: 1 – infiltration of rainfall or snowmelt at high elevation, which may become 2 – discharge to mountain stream, or 3 – recharge to deep layers of basin through mountain front sediments and volcanic or fractured rock; 4 – recharge to shallow layers by infiltration through coarse valley-periphery deposits or direct surface infiltration; 5 – discharge to wells through pumping; 6 – discharge to surface water or evapotranspiration through vegetation; 7 – water that underflows valley floor discharge and may flow into another basin (not likely in Sierra Valley).
z – No Flow Zone depth depends on rock composition and degree of fracturing, which are not homogenous surrounding Sierra Valley. Adapted from Bohm, 2016, originally from Manning and Soloman, 2015.

10.3 Appendix C – CASGEM Well Selection Approach to Expand Groundwater Network

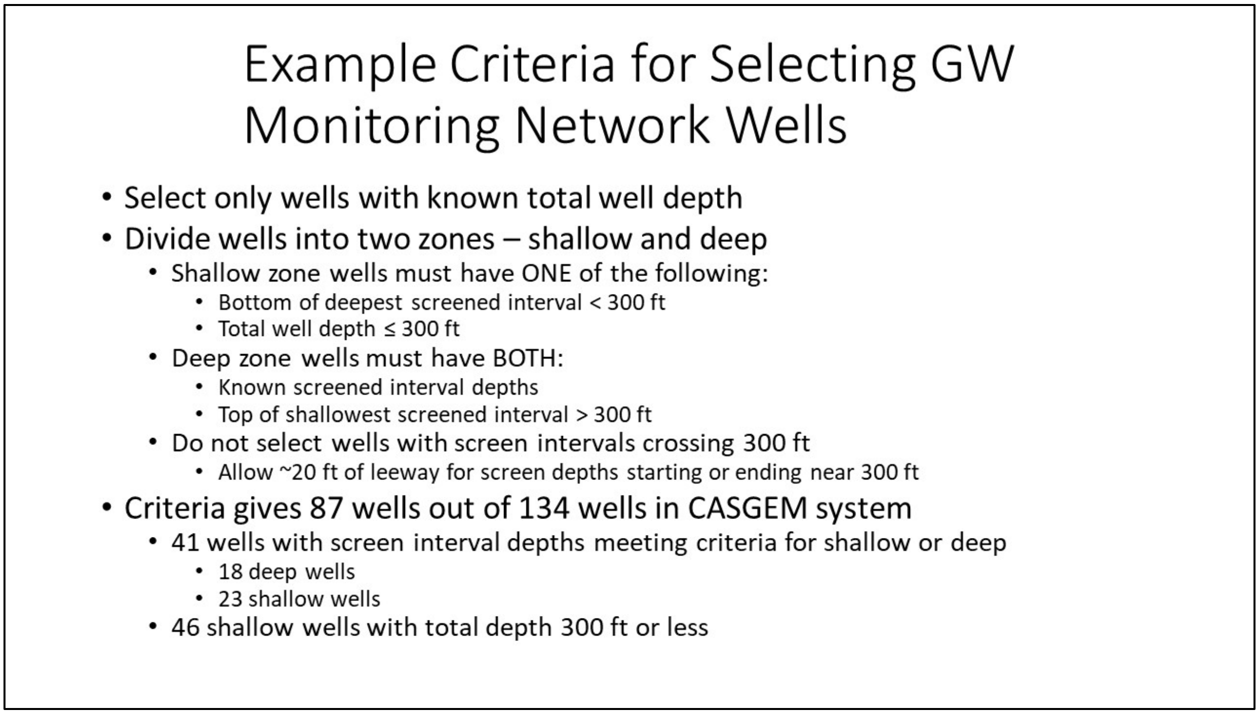


Expansion of SV Monitoring Network

Bachand & Associates
August 2019

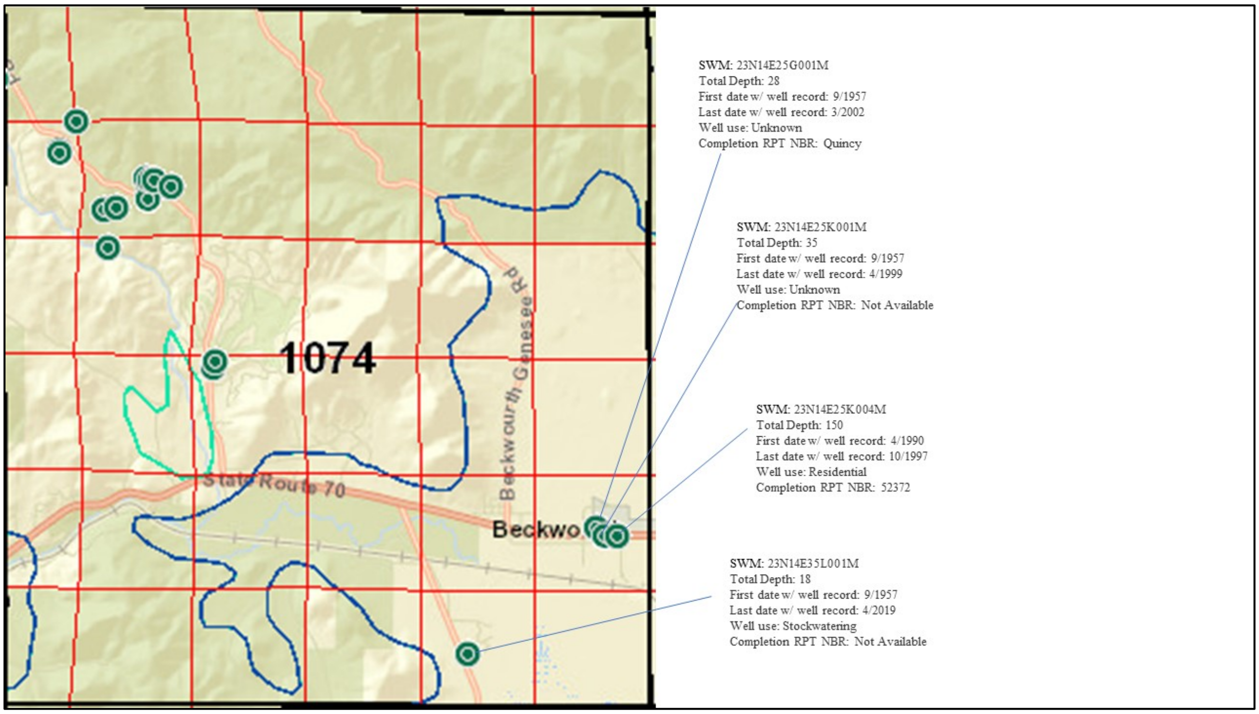
CASGEM Wells

- Numbered black squares are townships, 36 sq. miles each
- Red squares (township sections) are 1 sq. mile each
- All wells shown are enrolled in CASGEM system



Example Criteria for Selecting GW Monitoring Network Wells

- Select only wells with known total well depth
- Divide wells into two zones – shallow and deep
  - Shallow zone wells must have ONE of the following:
    - Bottom of deepest screened interval < 300 ft
    - Total well depth ≤ 300 ft
  - Deep zone wells must have BOTH:
    - Known screened interval depths
    - Top of shallowest screened interval > 300 ft
  - Do not select wells with screen intervals crossing 300 ft
    - Allow ~20 ft of leeway for screen depths starting or ending near 300 ft
- Criteria gives 87 wells out of 134 wells in CASGEM system
  - 41 wells with screen interval depths meeting criteria for shallow or deep
    - 18 deep wells
    - 23 shallow wells
  - 46 shallow wells with total depth 300 ft or less

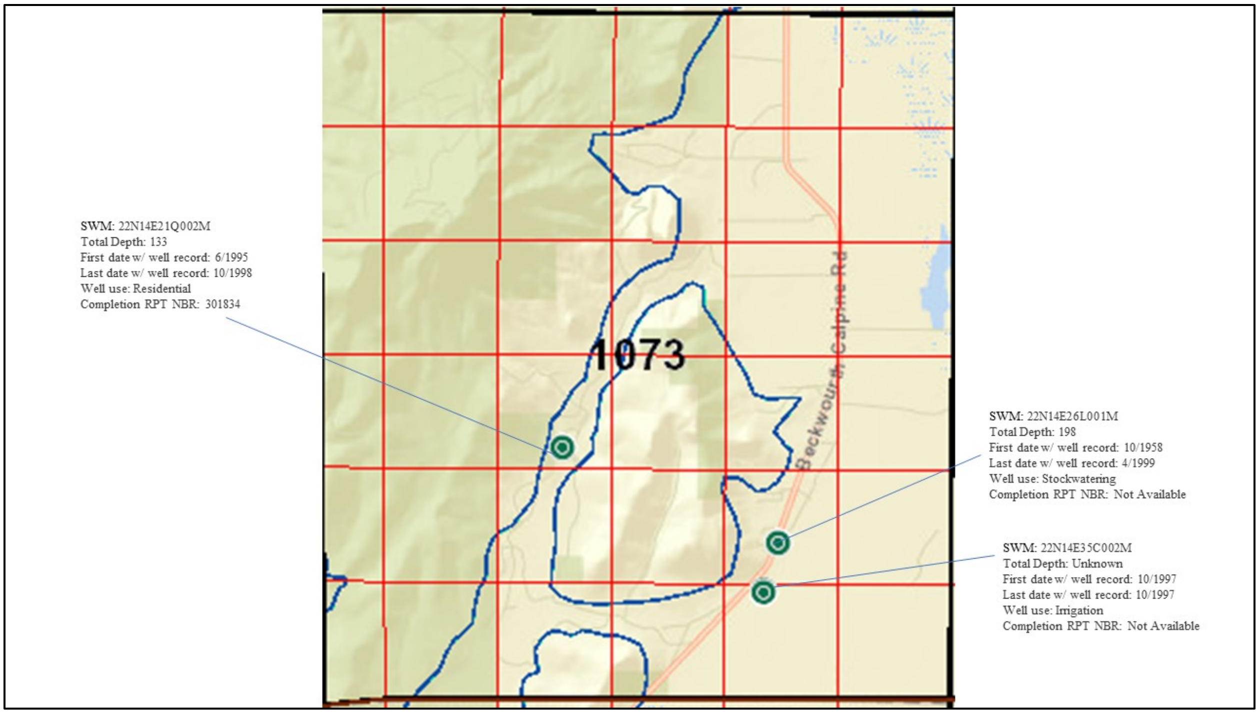


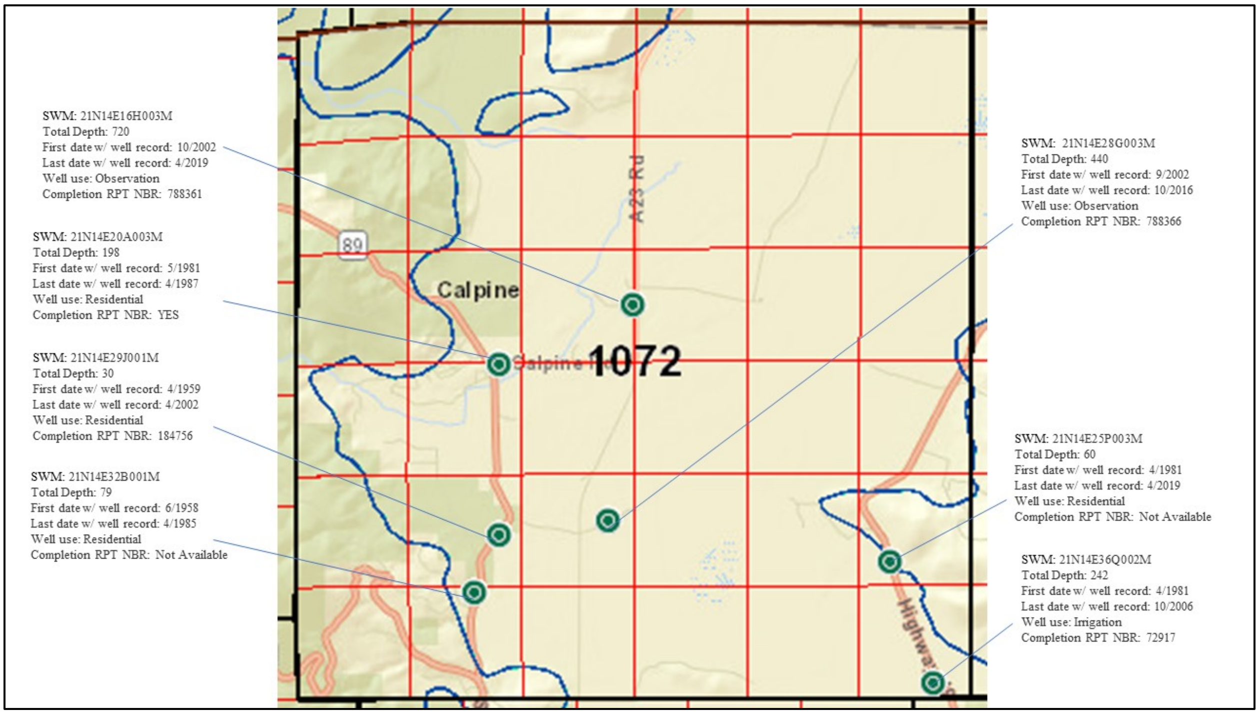
SWM: 23N14E25G001M
Total Depth: 28
First date w/ well record: 9/1957
Last date w/ well record: 3/2002
Well use: Unknown
Completion RPT NBR: Quincy

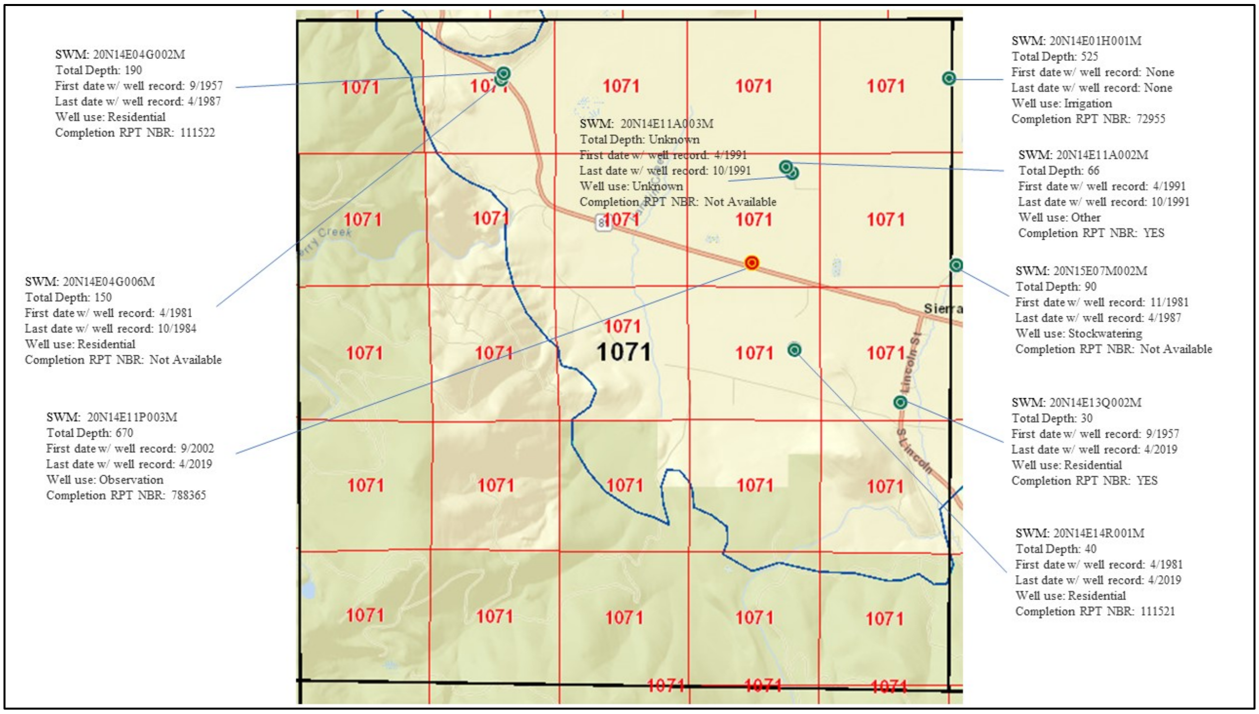
SWM: 23N14E25K001M
Total Depth: 35
First date w/ well record: 9/1957
Last date w/ well record: 4/1999
Well use: Unknown
Completion RPT NBR: Not Available

SWM: 23N14E25K004M
Total Depth: 150
First date w/ well record: 4/1990
Last date w/ well record: 10/1997
Well use: Residential
Completion RPT NBR: 52372

SWM: 23N14E35L001M
Total Depth: 18
First date w/ well record: 9/1957
Last date w/ well record: 4/2019
Well use: Stockwatering
Completion RPT NBR: Not Available


SWM: 22N14E21Q002M
Total Depth: 133
First date w/ well record: 6/1995
Last date w/ well record: 10/1998
Well use: Residential
Completion RPT NBR: 301834
1073
Beckwourth Calpine Rd
SWM: 22N14E26L001M
Total Depth: 198
First date w/ well record: 10/1958
Last date w/ well record: 4/1999
Well use: Stockwatering
Completion RPT NBR: Not Available
SWM: 22N14E35C002M
Total Depth: Unknown
First date w/ well record: 10/1997
Last date w/ well record: 10/1997
Well use: Irrigation
Completion RPT NBR: Not Available


SWM: 21N14E16H003M
Total Depth: 720
First date w/ well record: 10/2002
Last date w/ well record: 4/2019
Well use: Observation
Completion RPT NBR: 788361
SWM: 21N14E20A003M
Total Depth: 198
First date w/ well record: 5/1981
Last date w/ well record: 4/1987
Well use: Residential
Completion RPT NBR: YES
SWM: 21N14E29J001M
Total Depth: 30
First date w/ well record: 4/1959
Last date w/ well record: 4/2002
Well use: Residential
Completion RPT NBR: 184756
SWM: 21N14E32B001M
Total Depth: 79
First date w/ well record: 6/1958
Last date w/ well record: 4/1985
Well use: Residential
Completion RPT NBR: Not Available
89
Calpine
A23 Rd
1072
SWM: 21N14E28G003M
Total Depth: 440
First date w/ well record: 9/2002
Last date w/ well record: 10/2016
Well use: Observation
Completion RPT NBR: 788366
SWM: 21N14E25P003M
Total Depth: 60
First date w/ well record: 4/1981
Last date w/ well record: 4/2019
Well use: Residential
Completion RPT NBR: Not Available
SWM: 21N14E36Q002M
Total Depth: 242
First date w/ well record: 4/1981
Last date w/ well record: 10/2006
Well use: Irrigation
Completion RPT NBR: 72917



SWM: 20N14E04G002M
Total Depth: 190
First date w/ well record: 9/1957
Last date w/ well record: 4/1987
Well use: Residential
Completion RPT NBR: 111522

SWM: 20N14E04G006M
Total Depth: 150
First date w/ well record: 4/1981
Last date w/ well record: 10/1984
Well use: Residential
Completion RPT NBR: Not Available

SWM: 20N14E11P003M
Total Depth: 670
First date w/ well record: 9/2002
Last date w/ well record: 4/2019
Well use: Observation
Completion RPT NBR: 788365

SWM: 20N14E11A003M
Total Depth: Unknown
First date w/ well record: 4/1991
Last date w/ well record: 10/1991
Well use: Unknown
Completion RPT NBR: Not Available

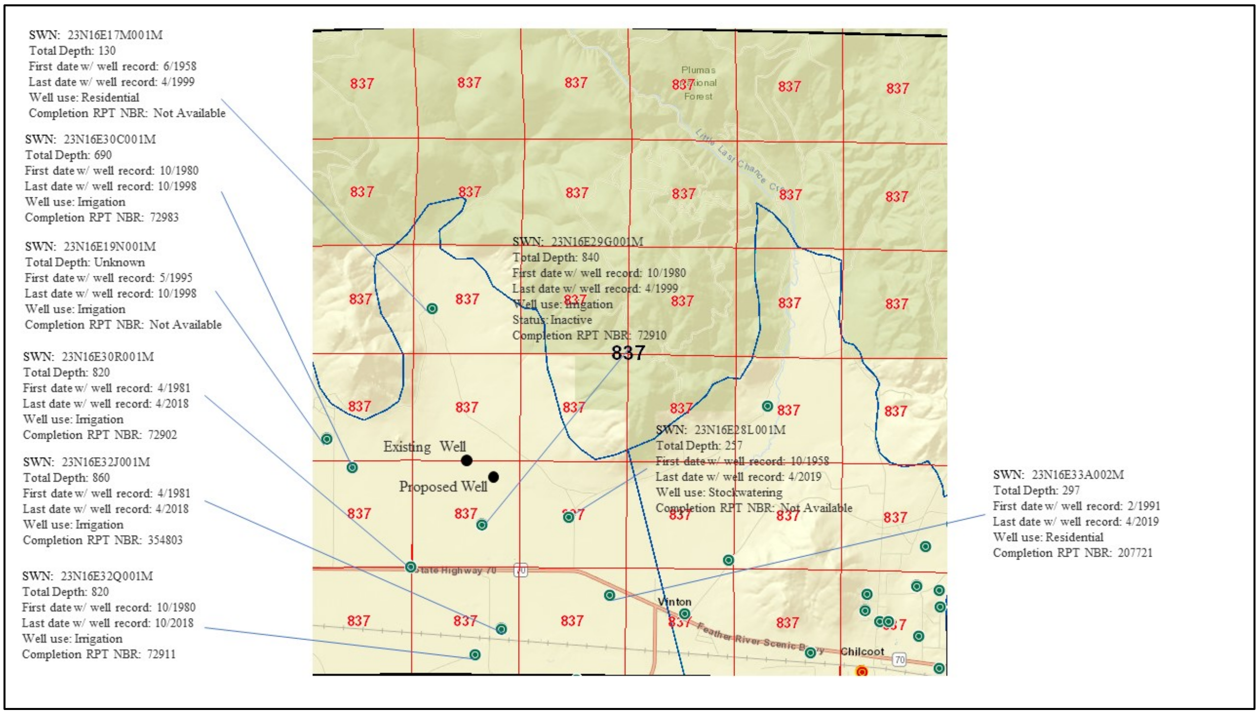
SWM: 20N14E01H001M
Total Depth: 525
First date w/ well record: None
Last date w/ well record: None
Well use: Irrigation
Completion RPT NBR: 72955

SWM: 20N14E11A002M
Total Depth: 66
First date w/ well record: 4/1991
Last date w/ well record: 10/1991
Well use: Other
Completion RPT NBR: YES

SWM: 20N15E07M002M
Total Depth: 90
First date w/ well record: 11/1981
Last date w/ well record: 4/1987
Well use: Stockwatering
Completion RPT NBR: Not Available

SWM: 20N14E13Q002M
Total Depth: 30
First date w/ well record: 9/1957
Last date w/ well record: 4/2019
Well use: Residential
Completion RPT NBR: YES

SWM: 20N14E14R001M
Total Depth: 40
First date w/ well record: 4/1981
Last date w/ well record: 4/2019
Well use: Residential
Completion RPT NBR: 111521



SWN: 23N16E17M001M
Total Depth: 130
First date w/ well record: 6/1958
Last date w/ well record: 4/1999
Well use: Residential
Completion RPT NBR: Not Available

SWN: 23N16E30C001M
Total Depth: 690
First date w/ well record: 10/1980
Last date w/ well record: 10/1998
Well use: Irrigation
Completion RPT NBR: 72983

SWN: 23N16E19N001M
Total Depth: Unknown
First date w/ well record: 5/1995
Last date w/ well record: 10/1998
Well use: Irrigation
Completion RPT NBR: Not Available

SWN: 23N16E30R001M
Total Depth: 820
First date w/ well record: 4/1981
Last date w/ well record: 4/2018
Well use: Irrigation
Completion RPT NBR: 72902

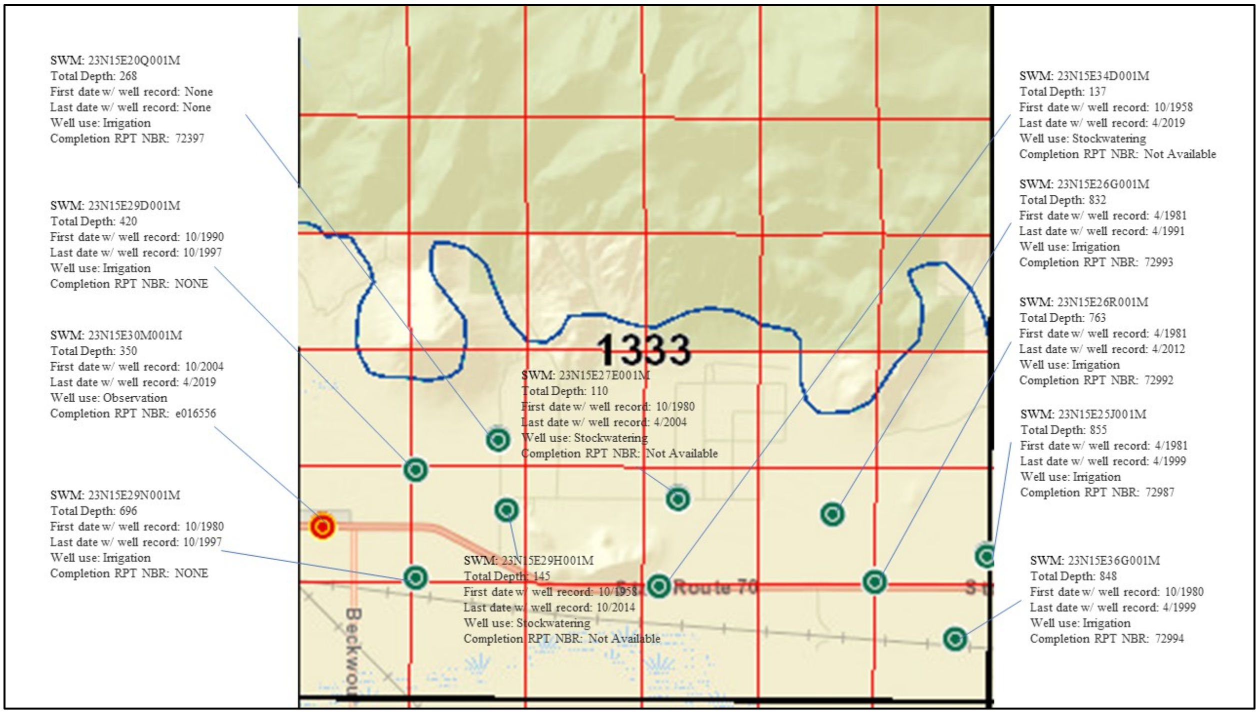
SWN: 23N16E32J001M
Total Depth: 860
First date w/ well record: 4/1981
Last date w/ well record: 4/2018
Well use: Irrigation
Completion RPT NBR: 354803

SWN: 23N16E32Q001M
Total Depth: 820
First date w/ well record: 10/1980
Last date w/ well record: 10/2018
Well use: Irrigation
Completion RPT NBR: 72911

SWN: 23N16E29G001M
Total Depth: 840
First date w/ well record: 10/1980
Last date w/ well record: 4/1999
Well use: Irrigation
Status: Inactive
Completion RPT NBR: 72910

SWN: 23N16E28L001M
Total Depth: 257
First date w/ well record: 10/1958
Last date w/ well record: 4/2019
Well use: Stockwatering
Completion RPT NBR: Not Available

SWN: 23N16E33A002M
Total Depth: 297
First date w/ well record: 2/1991
Last date w/ well record: 4/2019
Well use: Residential
Completion RPT NBR: 207721



SWM: 23N15E20Q001M
Total Depth: 268
First date w/ well record: None
Last date w/ well record: None
Well use: Irrigation
Completion RPT NBR: 72397

SWM: 23N15E29D001M
Total Depth: 420
First date w/ well record: 10/1990
Last date w/ well record: 10/1997
Well use: Irrigation
Completion RPT NBR: NONE

SWM: 23N15E30M001M
Total Depth: 350
First date w/ well record: 10/2004
Last date w/ well record: 4/2019
Well use: Observation
Completion RPT NBR: e016556

SWM: 23N15E29N001M
Total Depth: 696
First date w/ well record: 10/1980
Last date w/ well record: 10/1997
Well use: Irrigation
Completion RPT NBR: NONE

SWM: 23N15E27E001M
Total Depth: 110
First date w/ well record: 10/1980
Last date w/ well record: 4/2004
Well use: Stockwatering
Completion RPT NBR: Not Available

SWM: 23N15E29H001M
Total Depth: 145
First date w/ well record: 10/1958
Last date w/ well record: 10/2014
Well use: Stockwatering
Completion RPT NBR: Not Available

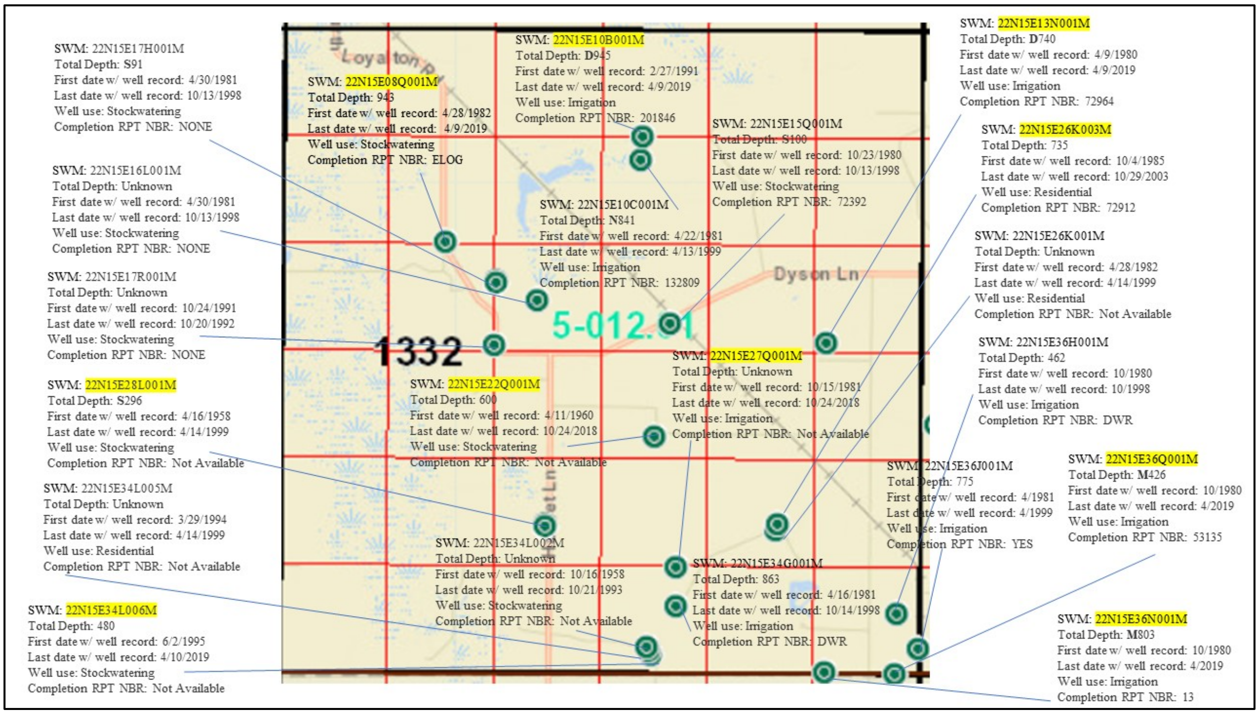
SWM: 23N15E34D001M
Total Depth: 137
First date w/ well record: 10/1958
Last date w/ well record: 4/2019
Well use: Stockwatering
Completion RPT NBR: Not Available

SWM: 23N15E26G001M
Total Depth: 832
First date w/ well record: 4/1981
Last date w/ well record: 4/1991
Well use: Irrigation
Completion RPT NBR: 72993

SWM: 23N15E26R001M
Total Depth: 763
First date w/ well record: 4/1981
Last date w/ well record: 4/2012
Well use: Irrigation
Completion RPT NBR: 72992

SWM: 23N15E25J001M
Total Depth: 855
First date w/ well record: 4/1981
Last date w/ well record: 4/1999
Well use: Irrigation
Completion RPT NBR: 72987

SWM: 23N15E36G001M
Total Depth: 848
First date w/ well record: 10/1980
Last date w/ well record: 4/1999
Well use: Irrigation
Completion RPT NBR: 72994



SWM: 22N15E17H001M
Total Depth: S91
First date w/ well record: 4/30/1981
Last date w/ well record: 10/13/1998
Well use: Stockwatering
Completion RPT NBR: NONE

SWM: 22N15E16L001M
Total Depth: Unknown
First date w/ well record: 4/30/1981
Last date w/ well record: 10/13/1998
Well use: Stockwatering
Completion RPT NBR: NONE

SWM: 22N15E17R001M
Total Depth: Unknown
First date w/ well record: 10/24/1991
Last date w/ well record: 10/20/1992
Well use: Stockwatering
Completion RPT NBR: NONE

SWM: 22N15E28L001M
Total Depth: S296
First date w/ well record: 4/16/1958
Last date w/ well record: 4/14/1999
Well use: Stockwatering
Completion RPT NBR: Not Available

SWM: 22N15E34L005M
Total Depth: Unknown
First date w/ well record: 3/29/1994
Last date w/ well record: 4/14/1999
Well use: Residential
Completion RPT NBR: Not Available

SWM: 22N15E34L006M
Total Depth: 480
First date w/ well record: 6/2/1995
Last date w/ well record: 4/10/2019
Well use: Stockwatering
Completion RPT NBR: Not Available

SWM: 22N15E08Q001M
Total Depth: 943
First date w/ well record: 4/28/1982
Last date w/ well record: 4/9/2019
Well use: Stockwatering
Completion RPT NBR: ELOG

SWM: 22N15E10B001M
Total Depth: **D**945
First date w/ well record: 2/27/1991
Last date w/ well record: 4/9/2019
Well use: Irrigation
Completion RPT NBR: 201846

SWM: 22N15E15Q001M
Total Depth: S100
First date w/ well record: 10/23/1980
Last date w/ well record: 10/13/1998
Well use: Stockwatering
Completion RPT NBR: 72392

SWM: 22N15E10C001M
Total Depth: N841
First date w/ well record: 4/22/1981
Last date w/ well record: 4/13/1999
Well use: Irrigation
Completion RPT NBR: 132809

SWM: 22N15E22Q001M
Total Depth: 600
First date w/ well record: 4/11/1960
Last date w/ well record: 10/24/2018
Well use: Stockwatering
Completion RPT NBR: Not Available

SWM: 22N15E27Q001M
Total Depth: Unknown
First date w/ well record: 10/15/1981
Last date w/ well record: 10/24/2018
Well use: Irrigation
Completion RPT NBR: Not Available

SWM: 22N15E34L002M
Total Depth: Unknown
First date w/ well record: 10/16/1958
Last date w/ well record: 10/21/1993
Well use: Stockwatering
Completion RPT NBR: Not Available

SWM: 22N15E34G001M
Total Depth: 863
First date w/ well record: 4/16/1981
Last date w/ well record: 10/14/1998
Well use: Irrigation
Completion RPT NBR: DWR

SWM: 22N15E13N001M
Total Depth: **D**740
First date w/ well record: 4/9/1980
Last date w/ well record: 4/9/2019
Well use: Irrigation
Completion RPT NBR: 72964

SWM: 22N15E26K003M
Total Depth: 735
First date w/ well record: 10/4/1985
Last date w/ well record: 10/29/2003
Well use: Residential
Completion RPT NBR: 72912

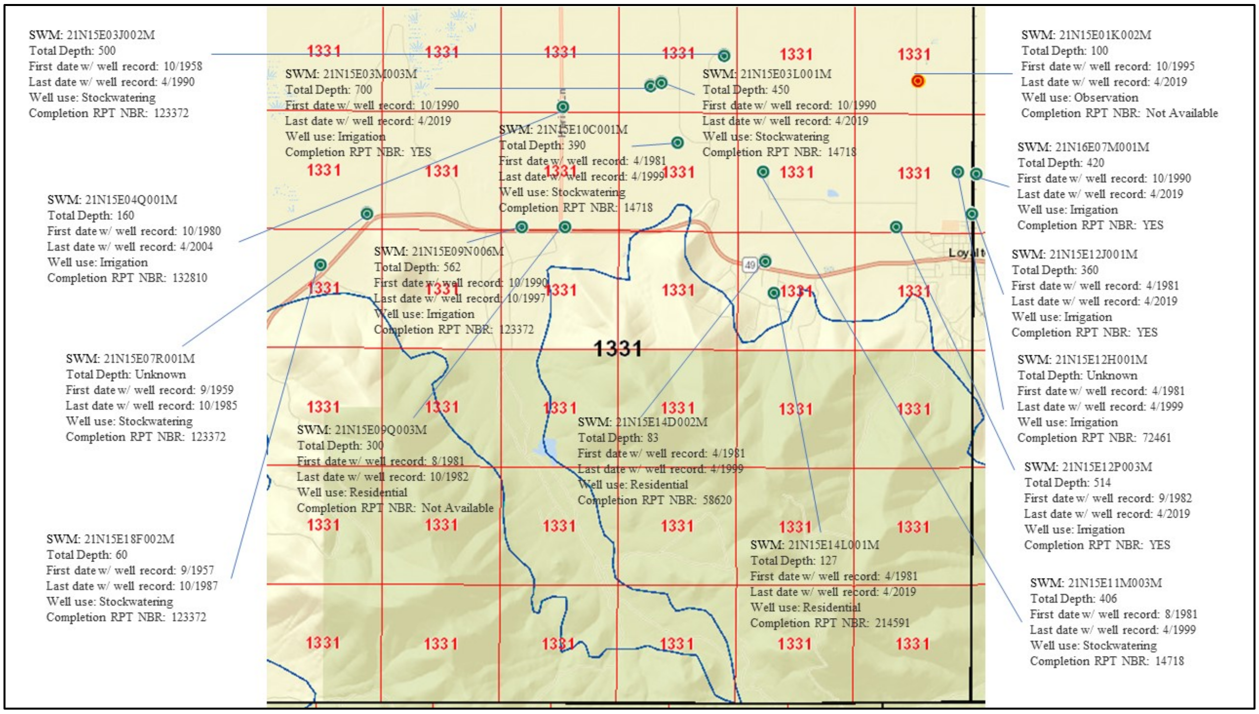
SWM: 22N15E26K001M
Total Depth: Unknown
First date w/ well record: 4/28/1982
Last date w/ well record: 4/14/1999
Well use: Residential
Completion RPT NBR: Not Available

SWM: 22N15E36H001M
Total Depth: 462
First date w/ well record: 10/1980
Last date w/ well record: 10/1998
Well use: Irrigation
Completion RPT NBR: DWR

SWM: 22N15E36J001M
Total Depth: 775
First date w/ well record: 4/1981
Last date w/ well record: 4/1999
Well use: Irrigation
Completion RPT NBR: YES

SWM: 22N15E36Q001M
Total Depth: **M**426
First date w/ well record: 10/1980
Last date w/ well record: 4/2019
Well use: Irrigation
Completion RPT NBR: 53135

SWM: 22N15E36N001M
Total Depth: **M**803
First date w/ well record: 10/1980
Last date w/ well record: 4/2019
Well use: Irrigation
Completion RPT NBR: 13



SWM: 21N15E03J002M
Total Depth: 500
First date w/ well record: 10/1958
Last date w/ well record: 4/1990
Well use: Stockwatering
Completion RPT NBR: 123372

SWM: 21N15E04Q001M
Total Depth: 160
First date w/ well record: 10/1980
Last date w/ well record: 4/2004
Well use: Irrigation
Completion RPT NBR: 132810

SWM: 21N15E07R001M
Total Depth: Unknown
First date w/ well record: 9/1959
Last date w/ well record: 10/1985
Well use: Stockwatering
Completion RPT NBR: 123372

SWM: 21N15E18F002M
Total Depth: 60
First date w/ well record: 9/1957
Last date w/ well record: 10/1987
Well use: Stockwatering
Completion RPT NBR: 123372

SWM: 21N15E03M003M
Total Depth: 700
First date w/ well record: 10/1990
Last date w/ well record: 4/2019
Well use: Irrigation
Completion RPT NBR: YES

SWM: 21N15E10C001M
Total Depth: 390
First date w/ well record: 4/1981
Last date w/ well record: 4/1999
Well use: Stockwatering
Completion RPT NBR: 14718

SWM: 21N15E09N006M
Total Depth: 562
First date w/ well record: 10/1990
Last date w/ well record: 10/1997
Well use: Irrigation
Completion RPT NBR: 123372

SWM: 21N15E09Q003M
Total Depth: 300
First date w/ well record: 8/1981
Last date w/ well record: 10/1982
Well use: Residential
Completion RPT NBR: Not Available

SWM: 21N15E03L001M
Total Depth: 450
First date w/ well record: 10/1990
Last date w/ well record: 4/2019
Well use: Stockwatering
Completion RPT NBR: 14718

SWM: 21N15E14D002M
Total Depth: 83
First date w/ well record: 4/1981
Last date w/ well record: 4/1999
Well use: Residential
Completion RPT NBR: 58620

SWM: 21N15E14L001M
Total Depth: 127
First date w/ well record: 4/1981
Last date w/ well record: 4/2019
Well use: Residential
Completion RPT NBR: 214591

SWM: 21N15E01K002M
Total Depth: 100
First date w/ well record: 10/1995
Last date w/ well record: 4/2019
Well use: Observation
Completion RPT NBR: Not Available

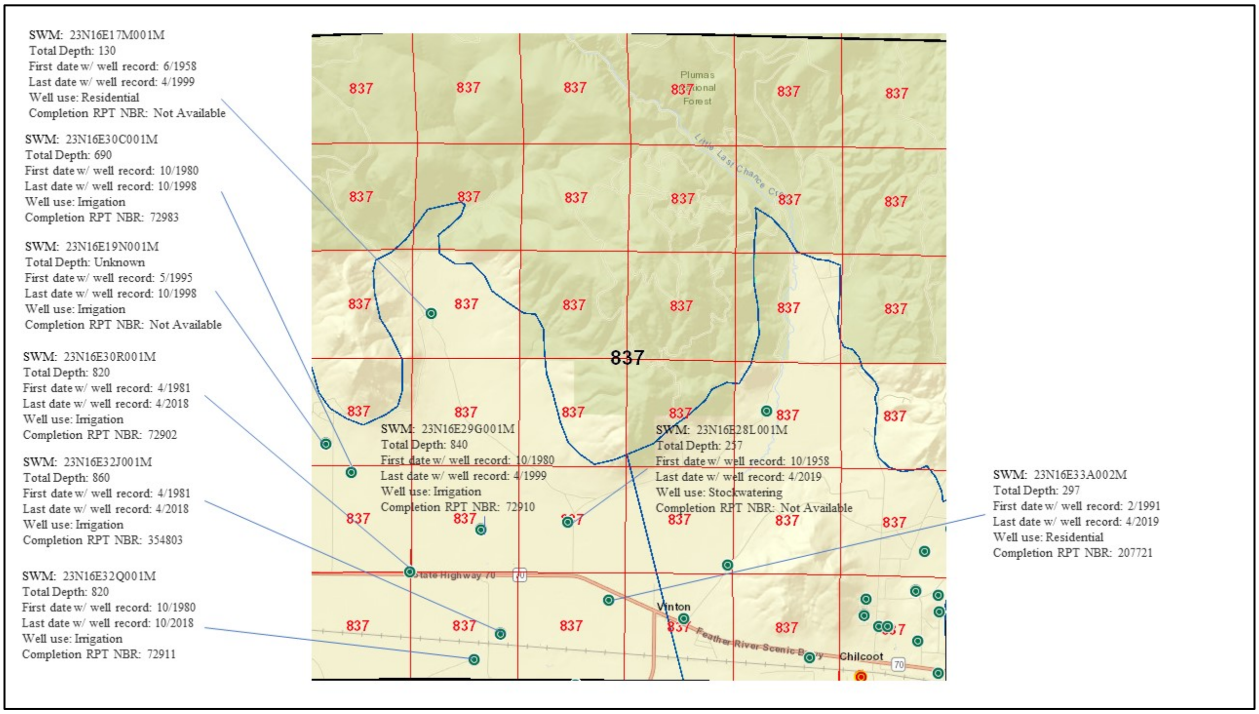
SWM: 21N16E07M001M
Total Depth: 420
First date w/ well record: 10/1990
Last date w/ well record: 4/2019
Well use: Irrigation
Completion RPT NBR: YES

SWM: 21N15E12J001M
Total Depth: 360
First date w/ well record: 4/1981
Last date w/ well record: 4/2019
Well use: Irrigation
Completion RPT NBR: YES

SWM: 21N15E12H001M
Total Depth: Unknown
First date w/ well record: 4/1981
Last date w/ well record: 4/1999
Well use: Irrigation
Completion RPT NBR: 72461

SWM: 21N15E12P003M
Total Depth: 514
First date w/ well record: 9/1982
Last date w/ well record: 4/2019
Well use: Irrigation
Completion RPT NBR: YES

SWM: 21N15E11M003M
Total Depth: 406
First date w/ well record: 8/1981
Last date w/ well record: 4/1999
Well use: Stockwatering
Completion RPT NBR: 14718



SWM: 23N16E17M001M
Total Depth: 130
First date w/ well record: 6/1958
Last date w/ well record: 4/1999
Well use: Residential
Completion RPT NBR: Not Available

SWM: 23N16E30C001M
Total Depth: 690
First date w/ well record: 10/1980
Last date w/ well record: 10/1998
Well use: Irrigation
Completion RPT NBR: 72983

SWM: 23N16E19N001M
Total Depth: Unknown
First date w/ well record: 5/1995
Last date w/ well record: 10/1998
Well use: Irrigation
Completion RPT NBR: Not Available

SWM: 23N16E30R001M
Total Depth: 820
First date w/ well record: 4/1981
Last date w/ well record: 4/2018
Well use: Irrigation
Completion RPT NBR: 72902

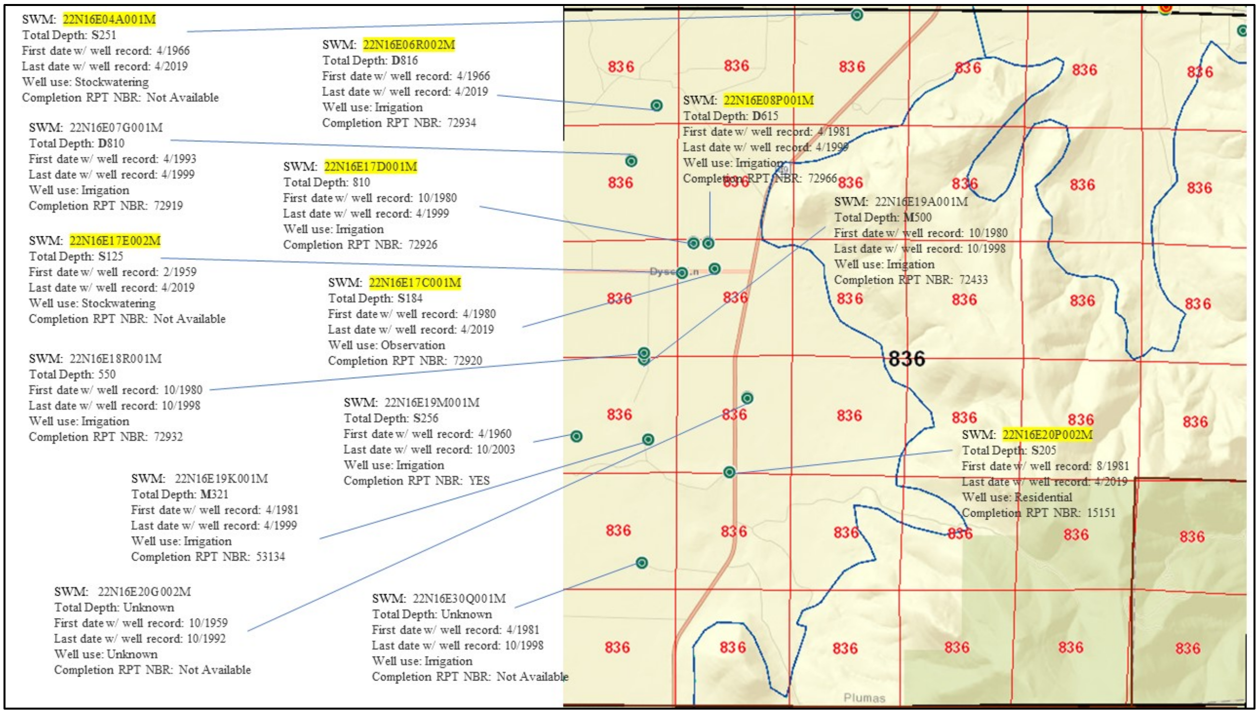
SWM: 23N16E32J001M
Total Depth: 860
First date w/ well record: 4/1981
Last date w/ well record: 4/2018
Well use: Irrigation
Completion RPT NBR: 354803

SWM: 23N16E32Q001M
Total Depth: 820
First date w/ well record: 10/1980
Last date w/ well record: 10/2018
Well use: Irrigation
Completion RPT NBR: 72911

SWM: 23N16E29G001M
Total Depth: 840
First date w/ well record: 10/1980
Last date w/ well record: 4/1999
Well use: Irrigation
Completion RPT NBR: 72910

SWM: 23N16E28L001M
Total Depth: 257
First date w/ well record: 10/1958
Last date w/ well record: 4/2019
Well use: Stockwatering
Completion RPT NBR: Not Available

SWM: 23N16E33A002M
Total Depth: 297
First date w/ well record: 2/1991
Last date w/ well record: 4/2019
Well use: Residential
Completion RPT NBR: 207721



SWM: 22N16E04A001M
Total Depth: S251
First date w/ well record: 4/1966
Last date w/ well record: 4/2019
Well use: Stockwatering
Completion RPT NBR: Not Available

SWM: 22N16E06R002M
Total Depth: D816
First date w/ well record: 4/1966
Last date w/ well record: 4/2019
Well use: Irrigation
Completion RPT NBR: 72934

SWM: 22N16E08P001M
Total Depth: D615
First date w/ well record: 4/1981
Last date w/ well record: 4/1999
Well use: Irrigation
Completion RPT NBR: 72966

SWM: 22N16E07G001M
Total Depth: D810
First date w/ well record: 4/1993
Last date w/ well record: 4/1999
Well use: Irrigation
Completion RPT NBR: 72919

SWM: 22N16E17D001M
Total Depth: 810
First date w/ well record: 10/1980
Last date w/ well record: 4/1999
Well use: Irrigation
Completion RPT NBR: 72926

SWM: 22N16E19A001M
Total Depth: M500
First date w/ well record: 10/1980
Last date w/ well record: 10/1998
Well use: Irrigation
Completion RPT NBR: 72433

SWM: 22N16E17E002M
Total Depth: S125
First date w/ well record: 2/1959
Last date w/ well record: 4/2019
Well use: Stockwatering
Completion RPT NBR: Not Available

SWM: 22N16E17C001M
Total Depth: S184
First date w/ well record: 4/1980
Last date w/ well record: 4/2019
Well use: Observation
Completion RPT NBR: 72920

SWM: 22N16E18R001M
Total Depth: 550
First date w/ well record: 10/1980
Last date w/ well record: 10/1998
Well use: Irrigation
Completion RPT NBR: 72932

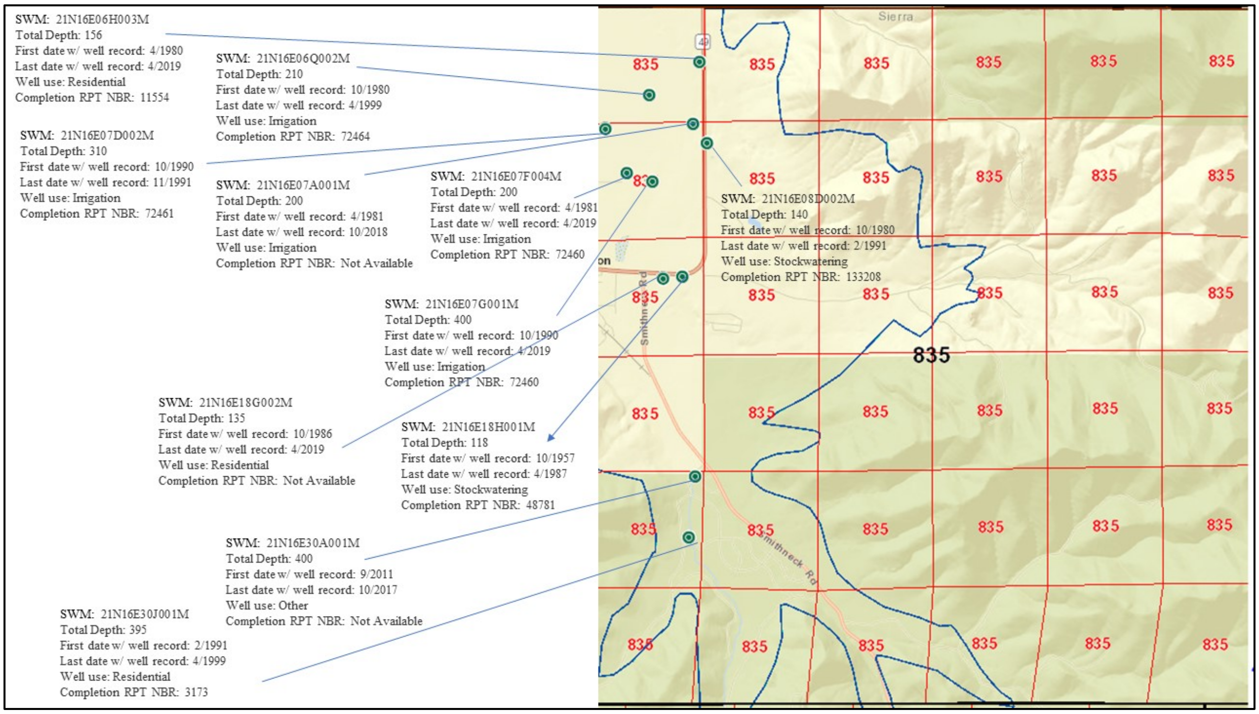
SWM: 22N16E19M001M
Total Depth: S256
First date w/ well record: 4/1960
Last date w/ well record: 10/2003
Well use: Irrigation
Completion RPT NBR: YES

SWM: 22N16E20P002M
Total Depth: S205
First date w/ well record: 8/1981
Last date w/ well record: 4/2019
Well use: Residential
Completion RPT NBR: 15151

SWM: 22N16E19K001M
Total Depth: M321
First date w/ well record: 4/1981
Last date w/ well record: 4/1999
Well use: Irrigation
Completion RPT NBR: 53134

SWM: 22N16E20G002M
Total Depth: Unknown
First date w/ well record: 10/1959
Last date w/ well record: 10/1992
Well use: Unknown
Completion RPT NBR: Not Available

SWM: 22N16E30Q001M
Total Depth: Unknown
First date w/ well record: 4/1981
Last date w/ well record: 10/1998
Well use: Irrigation
Completion RPT NBR: Not Available



SWM: 21N16E06H003M
Total Depth: 156
First date w/ well record: 4/1980
Last date w/ well record: 4/2019
Well use: Residential
Completion RPT NBR: 11554

SWM: 21N16E06Q002M
Total Depth: 210
First date w/ well record: 10/1980
Last date w/ well record: 4/1999
Well use: Irrigation
Completion RPT NBR: 72464

SWM: 21N16E07D002M
Total Depth: 310
First date w/ well record: 10/1990
Last date w/ well record: 11/1991
Well use: Irrigation
Completion RPT NBR: 72461

SWM: 21N16E07A001M
Total Depth: 200
First date w/ well record: 4/1981
Last date w/ well record: 10/2018
Well use: Irrigation
Completion RPT NBR: Not Available

SWM: 21N16E07F004M
Total Depth: 200
First date w/ well record: 4/1981
Last date w/ well record: 4/2019
Well use: Irrigation
Completion RPT NBR: 72460

SWM: 21N16E08D002M
Total Depth: 140
First date w/ well record: 10/1980
Last date w/ well record: 2/1991
Well use: Stockwatering
Completion RPT NBR: 133208

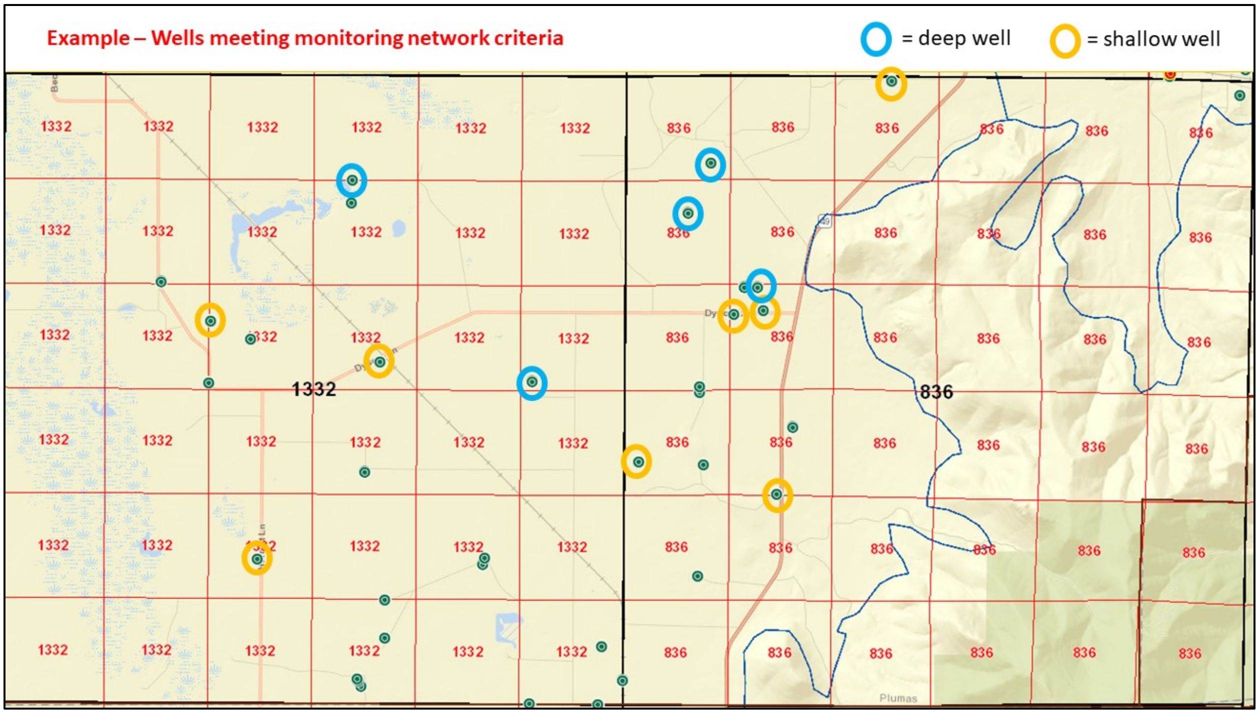
SWM: 21N16E07G001M
Total Depth: 400
First date w/ well record: 10/1990
Last date w/ well record: 4/2019
Well use: Irrigation
Completion RPT NBR: 72460

SWM: 21N16E18G002M
Total Depth: 135
First date w/ well record: 10/1986
Last date w/ well record: 4/2019
Well use: Residential
Completion RPT NBR: Not Available

SWM: 21N16E18H001M
Total Depth: 118
First date w/ well record: 10/1957
Last date w/ well record: 4/1987
Well use: Stockwatering
Completion RPT NBR: 48781

SWM: 21N16E30A001M
Total Depth: 400
First date w/ well record: 9/2011
Last date w/ well record: 10/2017
Well use: Other
Completion RPT NBR: Not Available

SWM: 21N16E30J001M
Total Depth: 395
First date w/ well record: 2/1991
Last date w/ well record: 4/1999
Well use: Residential
Completion RPT NBR: 3173


Example – Wells meeting monitoring network criteria
= deep well
= shallow well
1332
836
Plumas

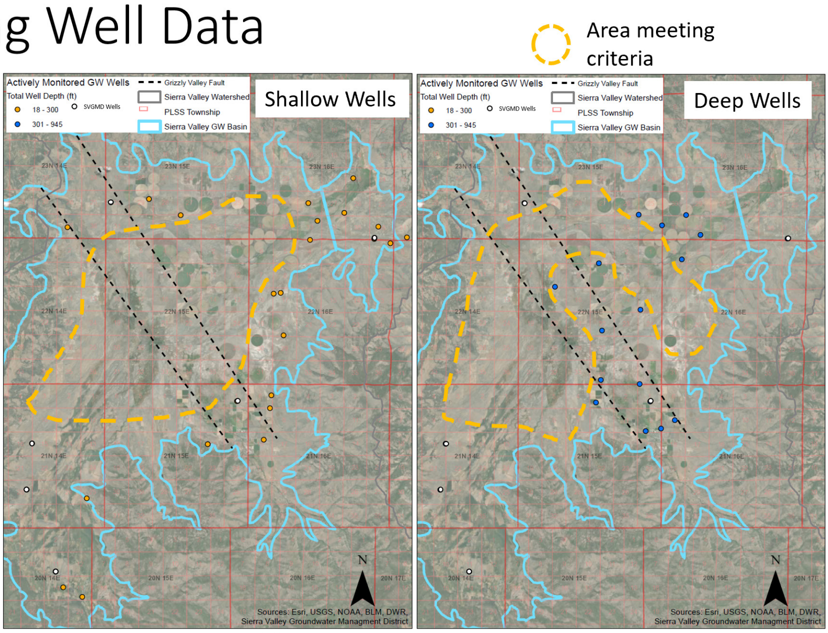
10.4 Appendix D – Eastern Valley SGMA Considerations

Eastern Valley Monitoring Well Site Selection

- Site Selection Based on Four Criteria:
  - Areas lacking accurate well data
  - Areas with high-volume pumping
  - Land subsidence zone
  - Groundwater elevation depression zone
- Further considerations
  - Site accessibility

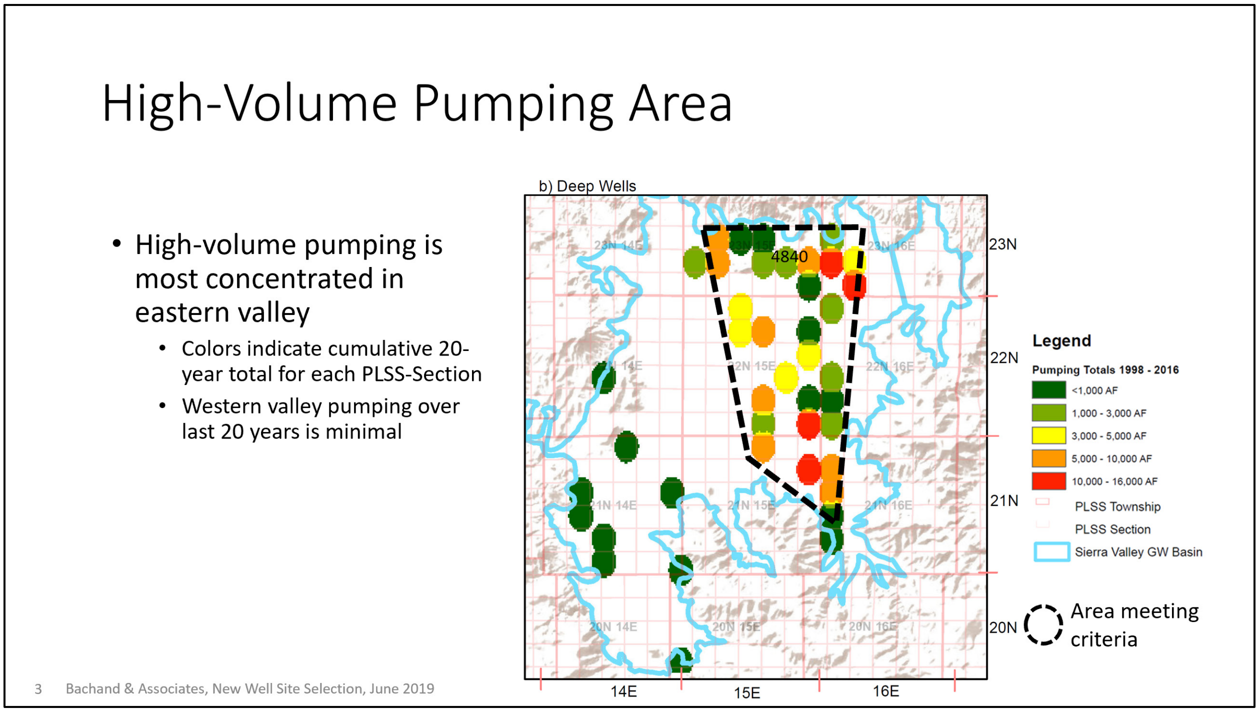
Areas Lacking Well Data

- Actively-monitored well coverage is incomplete
  - No nested piezometer in eastern Valley
  - No shallow wells in center of valley
  - Large portion of western valley has no recent well data
- Well density is critical for accurate contour mapping



Sources: Esri, USGS, NOAA, BLM, DWR, Sierra Valley Groundwater Managment District

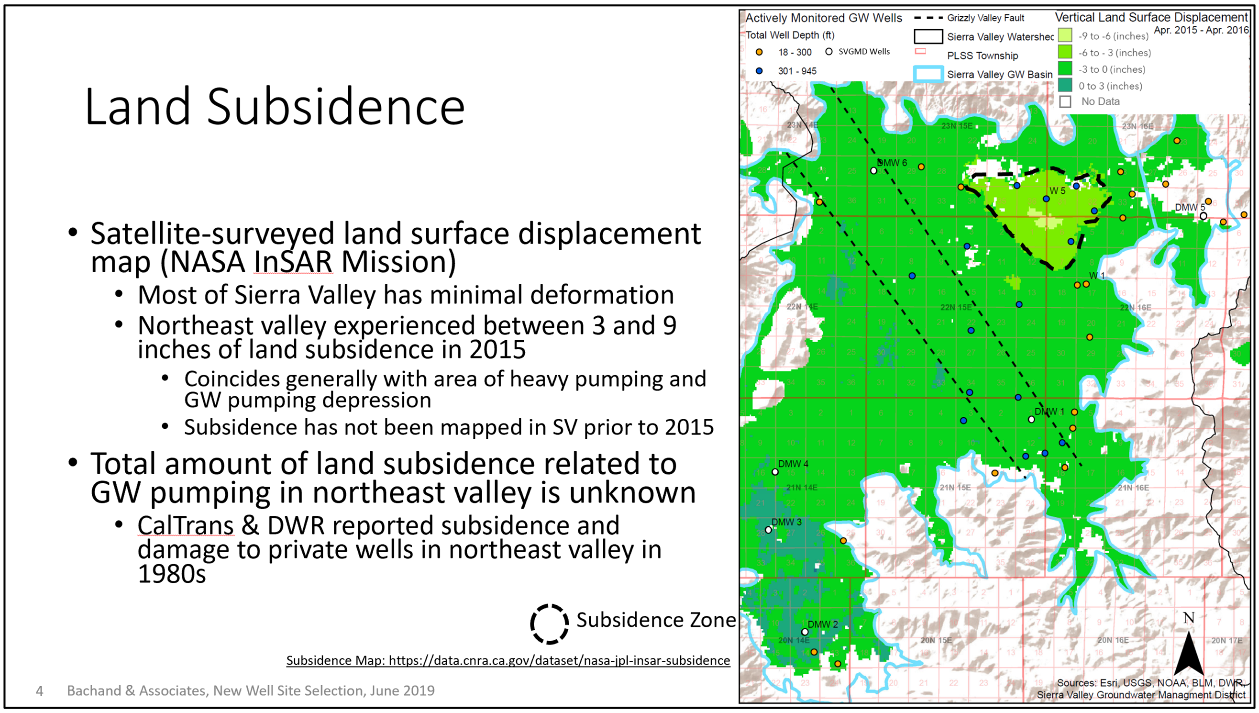
Notes:
1. Wells shown have been monitored at least once since 2010
2. DMW are nested piezometers and typically have multiple depths



High-Volume Pumping Area

- High-volume pumping is most concentrated in eastern valley
  - Colors indicate cumulative 20-year total for each PLSS-Section
  - Western valley pumping over last 20 years is minimal

3 Bachand & Associates, New Well Site Selection, June 2019

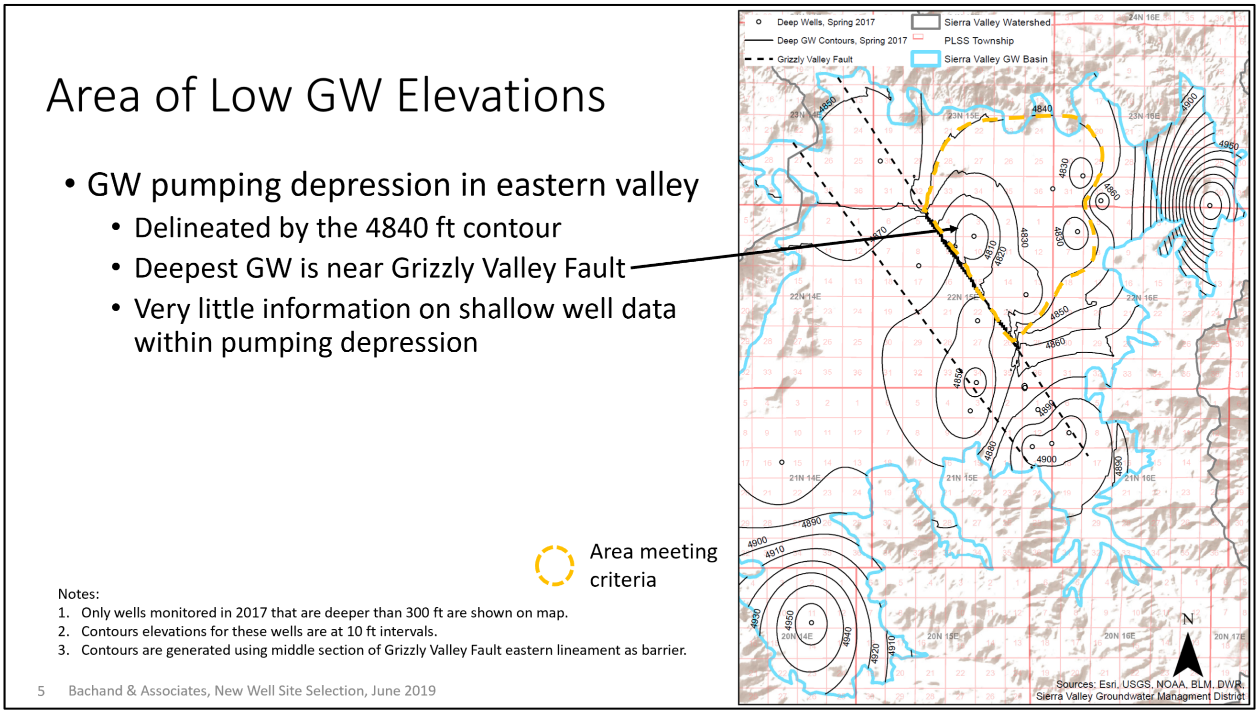


Land Subsidence

- Satellite-surveyed land surface displacement map (NASA InSAR Mission)
  - Most of Sierra Valley has minimal deformation
  - Northeast valley experienced between 3 and 9 inches of land subsidence in 2015
    - Coincides generally with area of heavy pumping and GW pumping depression
    - Subsidence has not been mapped in SV prior to 2015
- Total amount of land subsidence related to GW pumping in northeast valley is unknown
  - CalTrans & DWR reported subsidence and damage to private wells in northeast valley in 1980s

Subsidence Map: https://data.cnra.ca.gov/dataset/nasa-jpl-insar-subsidence

4 Bachand & Associates, New Well Site Selection, June 2019



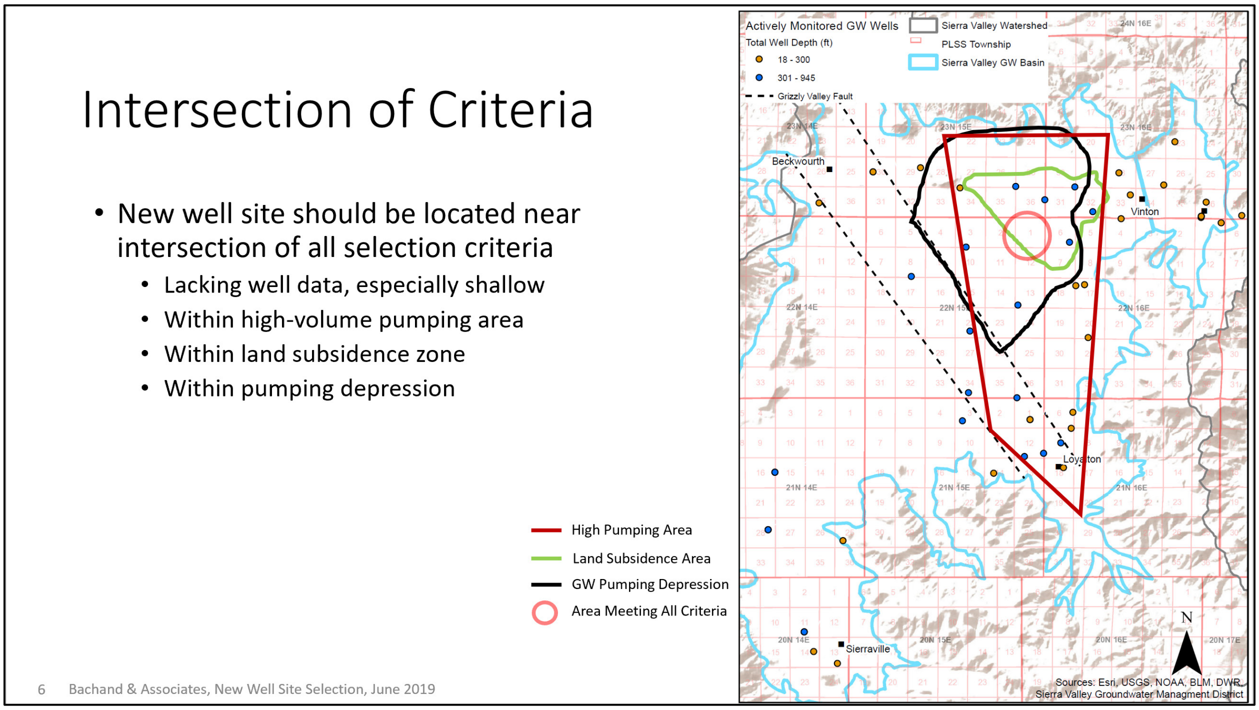
Area of Low GW Elevations

- GW pumping depression in eastern valley
  - Delineated by the 4840 ft contour
  - Deepest GW is near Grizzly Valley Fault
  - Very little information on shallow well data within pumping depression

Area meeting criteria

Notes:
1. Only wells monitored in 2017 that are deeper than 300 ft are shown on map.
2. Contours elevations for these wells are at 10 ft intervals.
3. Contours are generated using middle section of Grizzly Valley Fault eastern lineament as barrier.

5 Bachand & Associates, New Well Site Selection, June 2019

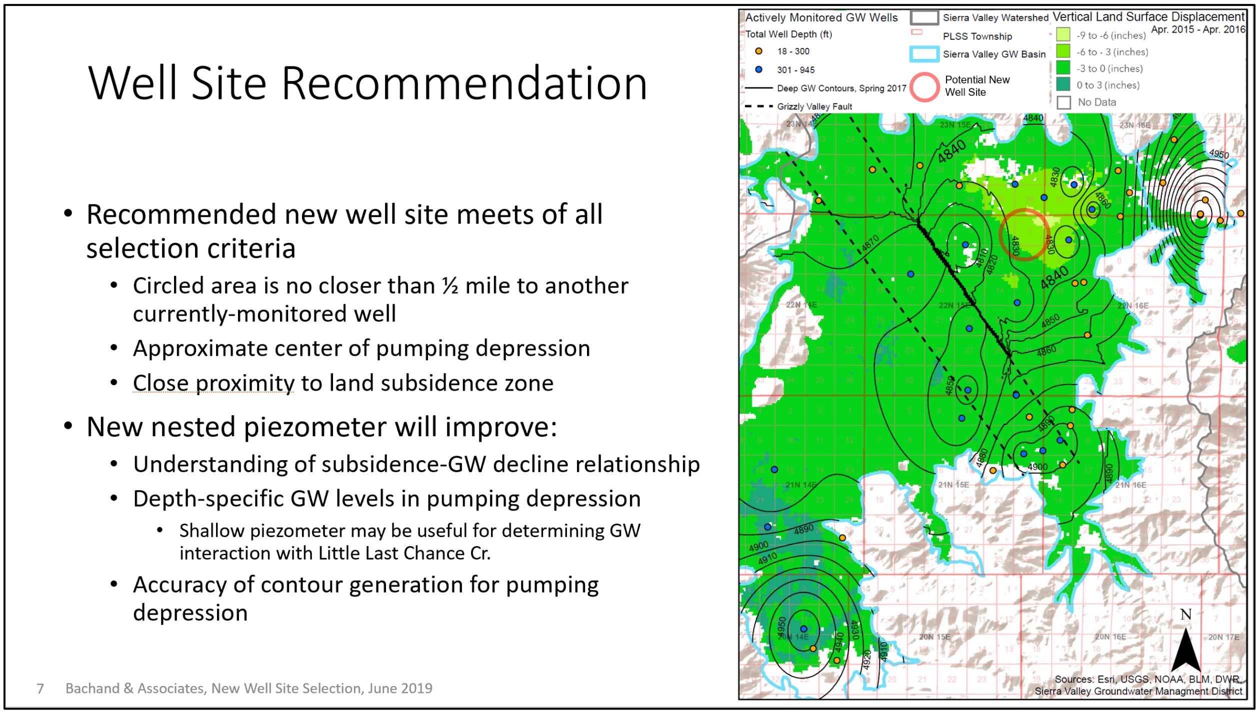


Intersection of Criteria

- New well site should be located near intersection of all selection criteria
  - Lacking well data, especially shallow
  - Within high-volume pumping area
  - Within land subsidence zone
  - Within pumping depression

High Pumping Area
Land Subsidence Area
GW Pumping Depression
Area Meeting All Criteria

6 Bachand & Associates, New Well Site Selection, June 2019



Well Site Recommendation

- Recommended new well site meets of all selection criteria
  - Circled area is no closer than ½ mile to another currently-monitored well
  - Approximate center of pumping depression
  - Close proximity to land subsidence zone
- New nested piezometer will improve:
  - Understanding of subsidence-GW decline relationship
  - Depth-specific GW levels in pumping depression
    - Shallow piezometer may be useful for determining GW interaction with Little Last Chance Cr.
  - Accuracy of contour generation for pumping depression

7 Bachand & Associates, New Well Site Selection, June 2019

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