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Preparing for Uncertain Water Futures: An Analysis of Climate Change Impacts on Southern Sierra Nevada Snowpack, Infrastructure Vulnerability, and Implications for San Joaquin Valley Groundwater Management

Kyle Greenspan
Pitzer College

Branwen Williams
Claremont McKenna College

Heather Williams
Pomona College

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An Analysis of Climate Change Impacts on Southern Sierra Nevada Snowpack, Infrastructure Vulnerability, and Implications for San Joaquin Valley Groundwater Management

Researched and Written by Kyle Greenspan,
Pitzer College ‘23

Supported by Professor Branwen Williams
(Claremont McKenna College) and
Professor Heather Williams (Pomona College)

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Abstract: Increased average annual temperatures due to anthropogenic climate change will impact snowpack in the Sierra Nevada region in two ways. First, an increasing share of precipitation will fall as rain instead of snow. Second, snowpack will melt earlier in the season. Earlier runoff driven by precipitation type change and earlier snowmelt necessitates earlier releases of water from dams for flood control. These earlier releases reduce the amount that can be stored for water supply. Analysis of instrumental and model snow water equivalent (SWE) data shows that climate models relied upon in state decision-making capture changes in peak SWE magnitude, but they do not estimate timing of peak SWE well. Future reductions in peak SWE magnitude and vulnerability of surface water storage infrastructure necessitates increased reliance on groundwater basins to store water. Groundwater pumping allocations combined with a replenishment credit can incentivize the diversion of floodwater for underground storage, which would help mitigate economic harm that arises from climate change impacts on snowpack as well as implementation of the 2014 Sustainable Groundwater Management Act.

Chapter One

Climate Change Impacts on
Southern Sierra Nevada Snowpack and
Vulnerability of Surface Water Storage Infrastructure

This chapter explores the physical science of climate change impacts on Sierra Nevada snowpack and the consequences of those impacts for surface water storage infrastructure. Groundwater sustainability plans produced in compliance with the 2014 Sustainable Groundwater Management Act consider climate change impacts on crop water demands (DWR Climate Change Guidance for Groundwater Sustainability Plans, 2018). However, these plans do not consider climate change impacts on snowpack and the surface water that runs off the west slope of the Sierra Nevada mountains. Similarly, the climate change vulnerability assessments produced by the United States Bureau of Reclamation (USBR) and Central Valley Flood Protection Board (CVFPB)–two of the agencies in charge of managing surface water resources and flood control in this region–only allude to the need for increased reliance on groundwater basins to store water. To adapt to new hydrological normals in the San Joaquin Valley in the coming decades, managers of both surface water and groundwater must move towards increased conjunctive use. This means recognizing that (1) the water storage service of snowpack will be diminished, (2) our dams and the reservoirs behind them cannot compensate for these snowpack changes, and (3) both parties–surface water and groundwater managers–must collaborate to store floodwater underground when it is available. Rather than viewing climate change vulnerabilities of surface water storage infrastructure and issues of groundwater sustainability as distinct, these resources must be viewed as one resource and managed together. Over the following two chapters, I argue for increased conjunctive use in California. This change will help us avoid significant economic harms associated with reduced water supplies.

Section I: A three reservoir framework for California water resources management

Three broad types of water storage are relied upon in the state of California: snowpack, dams, and groundwater basins. During the cool, wet times of year–roughly October through March–precipitation falls on the Sierra Nevada mountains as snow. The snowpack accumulates through the winter season until peak snowpack is reached, typically near April 1st. Then, the snowpack melts slowly during the hot, dry times of year–roughly April through September. In this way, Sierra Nevada snowpack provides a regulating ecosystem service. Instead of the water running off the mountains immediately after precipitation falls, the snowpack retains this water and delivers it slowly during the times of year when water is scarcest and people need that water the most. Thus, the snowpack is the state's first type of reservoir, providing intraannual–within a single year–water storage.

Rivers draining the western slope of the Sierra Nevada mountains flow into reservoirs held behind dams. These dams create the second type of water reservoir, with which people have recreated a similar regulating service as the snowpack but with physical infrastructure. Dams provide both intraannual and interannual–across multiple years–water storage. When water is released past these dams into the rivers, streams, and surface water conveyance infrastructure below, most of it reaches its end uses to irrigate crops, serve as municipal and industrial supply, or as instream flows–water left in streams to benefit ecosystems. A fraction of this water evaporates as it is conveyed to these end uses.

When water is applied to crops, some of it is consumed by the plants, but some percolates down into the aquifers. These aquifers are spaces where water is stored in the spaces between sediment underground. Multiple aquifers comprise a groundwater basin (DWR, Groundwater Basics). Aquifers can provide both intrannual and interannual water storage.

This chapter explores climate change impacts on Sierra Nevada snowpack, California's first water reservoir type, and how physical surface water storage infrastructure, California's second reservoir type, are vulnerable to these impacts. Due to likely changes in the regulating service of Sierra Nevada snowpack and vulnerability of physical storage infrastructure to these changes, the state must increasingly rely on the third type of reservoir, groundwater basins.

Section II: Context for climate change impacts on snowpack

Climate describes long-term average weather conditions, while climate change refers to deviation from these long-term average trends. Two broad categories of climate change impacts are changes in temperature and changes in precipitation. For both temperature and precipitation, there can be changes to average annual trends, seasonal trends, or a combination of the two. Additionally, temperature and precipitation vary by region and elevation. This variation must be considered in studies that analyze climate change impacts.

In the Sierra Nevada region, average annual temperatures are expected to increase by 6-9˚F, depending on the level of continued anthropogenic greenhouse gas emissions. The rate of warming is expected to be faster at higher elevations (Dettinger et al. 2018). Conversely, average annual precipitation is not expected to change significantly in the Sierra Nevada region by the end of this century (Dettinger et al. 2018). While average annual precipitation is not expected to change, precipitation extremes–both deluge and drought–are expected to become more extreme as a result of climate change (Dettinger et al. 2018). Increased average annual temperatures in the Sierra Nevada region will cause two important snowpack changes. First, more precipitation will fall as rain instead of snow. Second, snowpack will melt earlier (Dettinger et al. 2018).

Before diving into the scientific literature on Sierra Nevada snowpack climate change impacts and original data analysis that explores snowpack changes, some key takeaways from the state's 2022 California Water Supply Strategy are presented. This provides insight into how the state is thinking about climate change impacts on water resources.

Section III: Key takeaways from the 2022 California Water Supply Strategy

The state describes an expectation of reduced water available for human consumptive uses in the near future because of three climate change impacts, all of which are driven by increased average annual temperatures. [1] First, more water running off the mountains will be absorbed into drier soils. Second, the consumptive use of water by vegetation will increase. Third, more water will be directly lost to the atmosphere via evaporation from surface water storage and conveyance (2022 California Water Supply Strategy). Due to these three climate change impacts, the state anticipates a 10% decline in average annual water supply by 2040. With an annual water supply of 60-90 million acre-feet (maf), this decrease is approximately 6-9 maf annually.[2] To cope with this decrease in water supplies, the state proposes five potential strategies. These include increasing storage space, recycling and reuse, efficiency gains, stormwater capture, and desalination. The state estimates 4 maf of this decline in supplies must be resolved by expanding water storage. Chief among the options proposed to expand storage is increased groundwater replenishment. The state says, "capturing water runoff is needed to help correct decades of over-pumping of groundwater basins" (2022 California Water Supply Strategy). Thus, the state recognizes that capturing floodwater when it is available and moving it to underground storage is a key solution for both unsustainable groundwater use and climate change impacts on surface water resources.

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[1] Consumptive use refers to water consumed by people or ecosystems that is unavailable for reuse.

[2] An acre-foot is the amount of water is takes to fill one acre–roughly a football field–one foot high.

Section IV: A review of the scientific literature addressing climate change impacts on Sierra Nevada snowpack

Temperature change, not precipitation change, is driving snowpack changes in the Western United States (Pierce and Cayan 2013; Figure 1). A common variable used to analyze snowpack changes is snow water equivalent (SWE), which captures the amount of water stored in the snowpack. In most years, peak snowpack occurs near April 1st, so April 1 SWE is used to compare this variable across years.

In addition to knowing how much water is stored in the snowpack, we also want to know what processes drive SWE reductions. One way to unpack these processes is estimating the fraction of precipitation that falls as snow (SFE/P). Decreases in SFE/P would indicate that more precipitation is falling as rain instead of snow, which is also referred to as precipitation type change. A second way to unpack the processes behind SWE reductions is analyzing the fraction of precipitation that remains stored in snowpack on April 1st (SWE/P). Decreases in SWE/P at a faster rate than decreases in SFE/P would indicate that snowpack is melting earlier.

Precipitation type change drives approximately 1.3x more of the decrease in April 1 SWE in the Western United States than earlier snowmelt. Precipitation type change also accounts for a greater share of the decrease in April 1 SWE in warmer locations (Pierce and Cayan 2013). Additionally, SWE/P will likely experience a 40-70% decrease while SFE/P will decrease 25-40% by 2100 in the Western United States (Pierce and Cayan 2013). This indicates that precipitation type change is not the only driver of reduced April 1 SWE. Earlier snowmelt also plays a role (Pierce and Cayan 2013). Finally, significant decreases in SFE/P and SWE/P are expected by 2030 (Pierce and Cayan 2013).

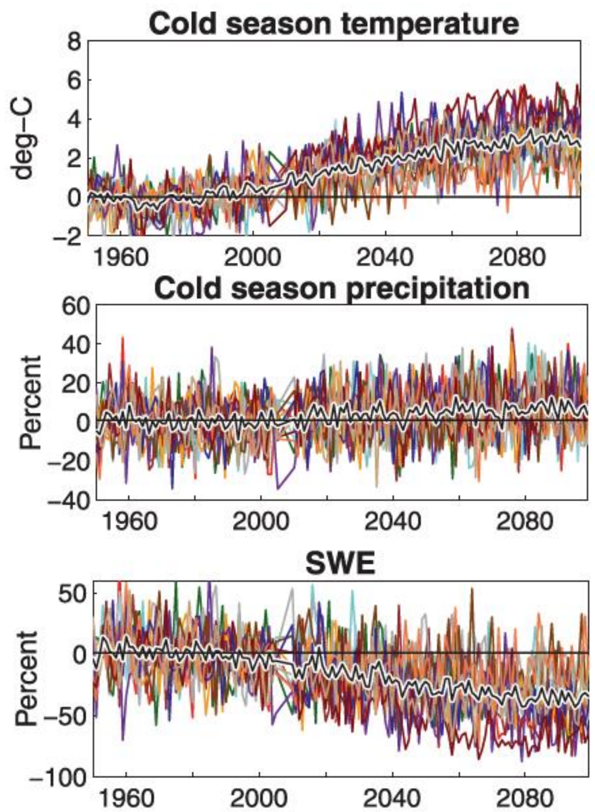

Figure 1: Projected changes in temperature, precipitation, and April 1st SWE due to climate change; each colored line is the output of one climate model; the black line is the average of all model output shown; figure adapted from Pierce and Cayan 2013

Paleoclimate reconstructions are a method used to determine whether the climate we are experiencing differs significantly from historical trends. For example, growth patterns in the rings of trees that grew in the Sierra Nevada between 1500 and 1980 have been used to reconstruct an estimate of April 1 SWE for each year in that period. Reconstructions are compared to instrumental data–measurements that people recorded with equipment–to determine how well the paleoclimate record captures observed phenomena. In the Sierra Nevada SWE reconstruction, there is strong agreement between the paleoclimate record and the instrumental SWE record (Figure 2).

The amount of water stored in the Sierra Nevada snowpack on April 1st, 2015 was at only 5% of its historical average (Belmecheri et al. 2016, Figure 2). With the exception of error bars on a few select years in the reconstruction, April 1 SWE in 2015 has quite literally no historical precedent since the year 1500. The article in which this SWE reconstruction was published closes with the following: "…the ongoing and projected role of temperature in the amount and duration of California's primary natural water storage system thus foreshadows major future impacts on the state's water supplies" (Belmecheri et al. 2016).

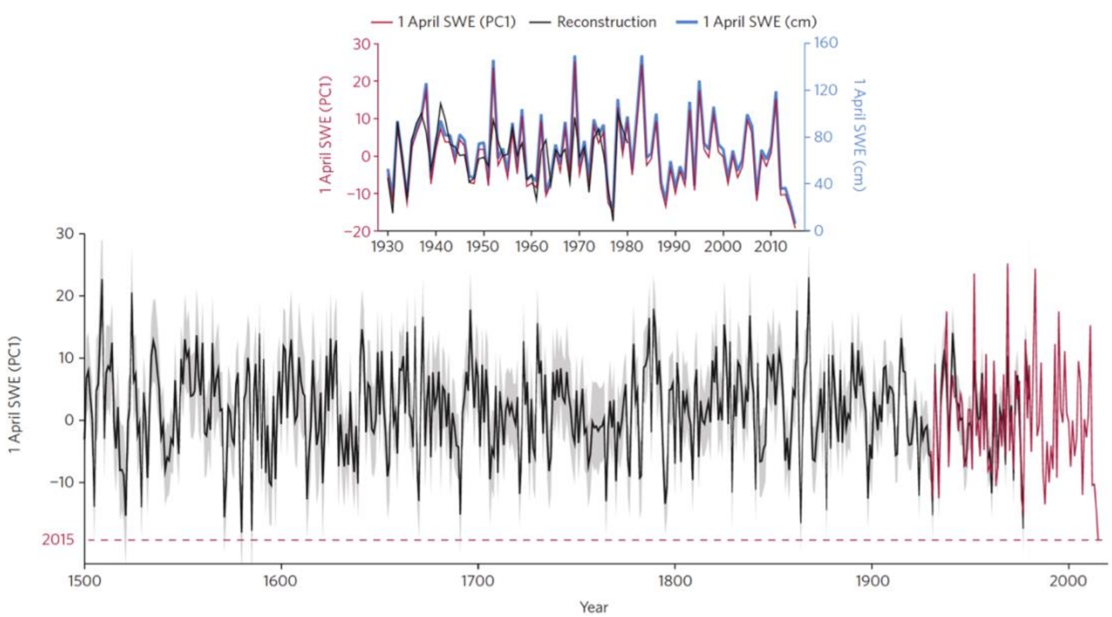

Figure 2: Paleoclimate reconstruction of April 1st water stored in snowpack (SWE); black line shows reconstruction, red line shows instrumental record, grey area is the estimated error in the reconstruction; figure adapted from Belmecheri et al. 2016

Downscaling is a technique used by climate scientists to forecast water variables such as SWE at a scale relevant to local and regional water managers. Large global climate models, commonly referred to as General Circulation Models (GCMs), have coarse spatial resolutions of approximately 100 kilometers (Schwartz et al. 2017). This means the data outputted from these models are only available for 100-kilometer x 100-kilometer squares in a grid. To estimate a variable such as SWE as accurately as possible at the local level, a fine spatial resolution is needed. Downscaling is the process of making the dimensions of the squares for which data is outputted as small as possible.

Downscaling multiple GCMs for multiple emissions scenarios[3], which is called dynamical downscaling, is largely impractical because of high computational costs (Schwartz et al. 2017). Researchers must achieve the benefits of dynamical downscaling without prohibitive computational costs. Statistical downscaling uses regression equations, which are equations that describe the impact that one or more independent variables has on a dependent variable. In the case of statistically downscaling climate models to forecast SWE, the regression equation would describe the historical relationship between precipitation, temperature, and SWE (Schwartz et al. 2017). The problem with statistical downscaling is that it assumes historical relationships between precipitation, temperature, and SWE hold in the future–this is the stationarity assumption.

One solution that incorporates the strengths of both dynamical and statistical downscaling is hybrid downscaling. In hybrid downscaling, the first step is to dynamically downscale a subset of GCMs for one emissions scenario. The output from this abbreviated dynamical downscaling process is used to build a statistical model–a collection of regression equations–that mimics the dynamical model behavior. Then, SWE is estimated for all GCMs and emission scenarios using the statistical model that was built using the output from the abbreviated dynamical downscaling process (Schwartz et al. 2017). The result of hybrid downscaling is a SWE dataset that incorporates both the physical credibility of dynamical downscaling and the computational efficiency of statistical downscaling (Schwartz et al. 2017).

A study that used downscaling techniques to estimate future April 1 SWE found that 36% of historical April 1 SWE will remain by 2100 under a high-emissions scenario and 70% will remain under a realistic emissions scenario.[4] They also found that the main driver of April 1

[3] Emission scenarios are potential future worlds that we will all be living in, specifically referencing the concentrations of heat-trapping gases–commonly referred to greenhouse gases–in the atmosphere of each hypothetical future world.

[4] The realistic emissions scenario, also called RCP4.5, assumes some mitigation of greenhouse gas emissions occurs, while the high-emissions scenario, also called RCP8.5, assumes little to no mitigation of greenhouse gas emissions occurs.

SWE reductions at middle elevations (~6,500-10,000 feet elevation) is precipitation type change, while the main driver of April 1 SWE reduction at high elevations (above 10,000 feet) is earlier snowmelt (Sun et al. 2019; Figure 3).

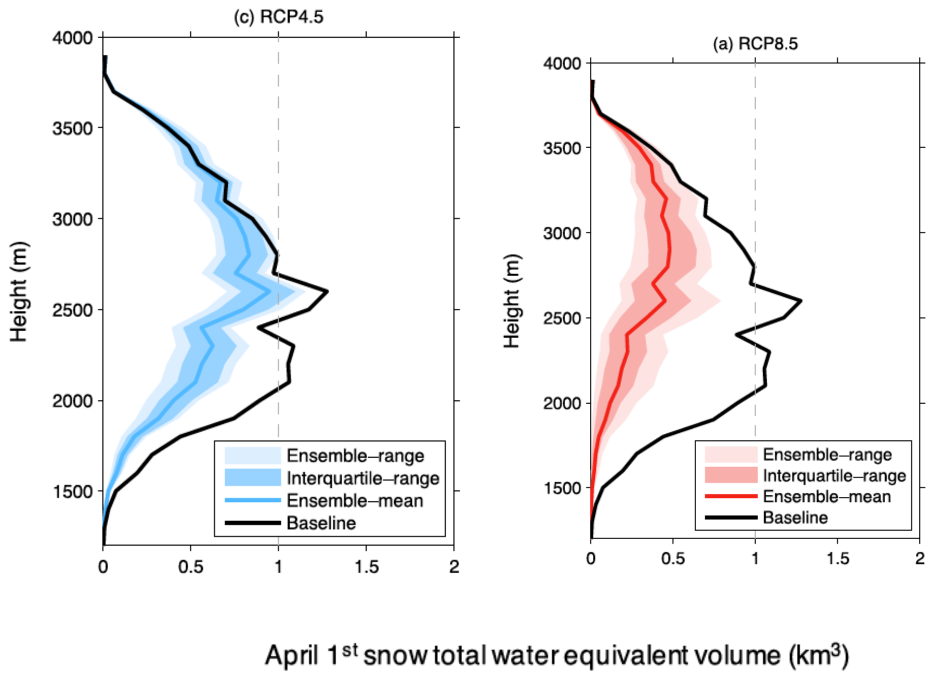

Figure 3: April 1st SWE by emissions scenario and elevation; figure adapted from Sun et al. 2019

Downscaling techniques can also be used to forecast variables other than SWE. For example, a result of precipitation type change and earlier snowmelt is earlier surface water runoff (Schwartz et al. 2017). This is the water that results when the snowpack melts and water flows downhill towards the Central Valley. One way to analyze surface water runoff timing is estimating the date by which half of cumulative surface water runoff has occurred (R_{50}). Between 6,500 feet and 9,000 feet elevation, R_{50} is approximately 80 days earlier under a high-emissions scenario and 40 days earlier under a realistic emissions scenario. This analysis used climate model output at a 3-kilometer spatial resolution (Schwartz et al. 2017; Figure 4).

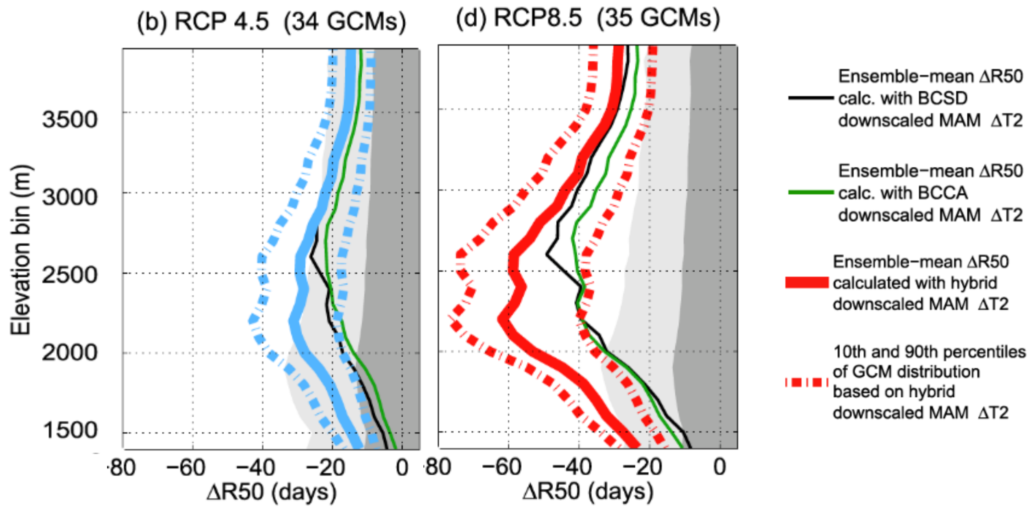

Figure 4: R50 advancement by emissions scenario and elevation; figure adapted from Schwartz et al. 2017

Intrannual snowpack processes, such as the timing of peak snowpack accumulation and the melt rate, are also important because the ability of California's physical water storage infrastructure to meet demand for water depends on runoff timing. SWE triangle analysis allows researchers to visualize intrannual snowpack processes (Rhoades et al. 2018a; Figure 5). The x-axis shows each month of the water year, from October to September. The y-axis shows SWE. Each curve on the plot shows accumulation and melt of snowpack in a single year. Using SWE triangle methods, researchers found that the peak accumulation date will occur approximately four weeks earlier in the Sierra Nevada region under a high-emissions scenario by the end of this century (Rhoades et al. 2018).

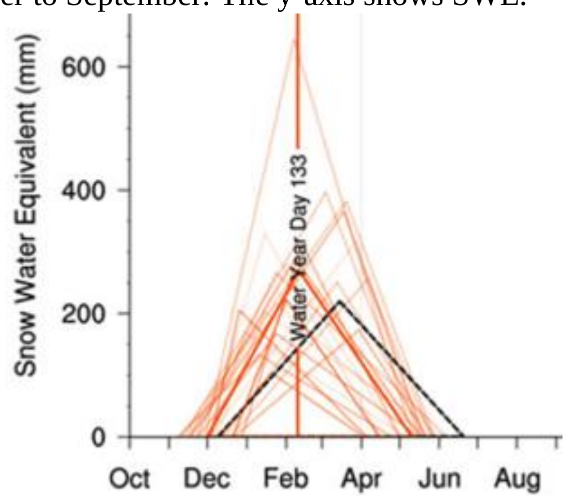

Figure 5: Example SWE triangle plots; each colored triangle represents snowpack accumulation and melt within one year; average SWE triangle for each plot is emboldened; dashed triangle is the historical comparison; colored vertical line represents estimated peak accumulation date (day in the water year); faint vertical line shows April 1st (historical peak accumulation date); figure adapted from Rhoades et al. 2018a

As a result of changes in intraannual snowpack processes, more of each year's water supply is likely to arrive at the reservoirs held behind dams simultaneously earlier in the spring. The analysis presented in the subsequent section follows SWE triangle analysis methods using SWE data with a finer spatial resolution, as compared to the data used in similar previous analyses (Rhoades et al. 2018b).

Section V: Multimetric Analysis of Climate Change Impacts on Snowpack in Southern Sierra Nevada Watersheds Overlying the San Joaquin Valley

The analysis presented in this section aims to understand how the water storage service of Southern Sierra Nevada snowpack will change in the coming decades. It is likely that snowpack in this region will no longer store as much water into the dry times of the year as it once did because of climate change impacts. This means that more of each year's surface water supplies will arrive at once, rather than being distributed over multiple months with gradual snowmelt. This analysis is novel because it incorporates both the intrannual aspects of SWE triangle analysis and the fine spatial resolution of climate model output prepared for California's Fourth Climate Change Assessment. To my knowledge, previous studies have not used these methods of intrannual analysis with SWE data at the 6-kilomseter spatial resolution for the Southern Sierra Nevada.

Three questions are explored in this section. First, how well do climate models relied upon in the state decision-making capture intrannual snowpack processes? To answer this question, climate model output are compared to instrumental data in a historical period. Second, how is the amount of water stored in Southern Sierra Nevada snowpack expected to change by the end of this century under realistic and high emission scenarios? To answer this question, two SWE triangle analyses for a future period are

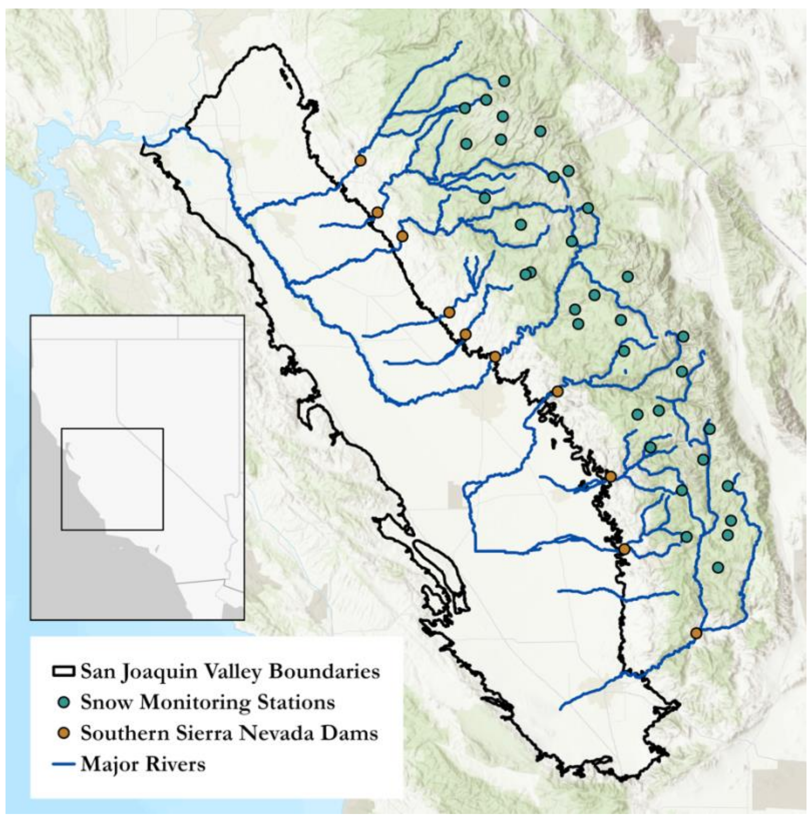

Figure 6: locations of the 34 snow monitoring stations used in this analysis; data sources are the Natural Resources Conservation Service (location of snow sensors), California Natural Resources Agency (rivers and streams), and the California Open Data Portal (county boundaries)

presented. Finally, estimates of April 1 SWE from this analysis are compared to the results of the aforementioned scientific literature.

Three major steps were followed to set up this analysis. First, instrumental SWE data were obtained for 34 snow monitoring stations in the Southern Sierra Nevada for the period 1985-2005 (Figure 7). Second, SWE data outputted from four downscaled climate models were obtained for the entire Sierra Nevada region as rasters, which are images that store values as the color of each pixel. These rasters were "hole punched" at the location of each monitoring station, a process that extracted SWE values for the 6-kilometer x 6-kilometer squares that contain the monitoring stations. The result of this process is paired SWE values, one instrumental and one model output, for each of 34 locations in the Sierra Nevada. The paired SWE values can be directly compared.

The comparison of instrumental data and model output in the historical period yielded two key findings. The climate models included in this analysis estimate that the peak accumulation date occurs, on average, at March 1st during this period, not April 1st (Figure 7b). This indicates that the included climate models are not skillful at capturing SWE timing. Second, peak SWE–the top of the triangles–estimated by these models is similar to the average peak SWE in the instrumental data (Figure 7b). This suggests that the included models are skillful at capturing magnitude, even if there are limitations in their ability to capture timing. One

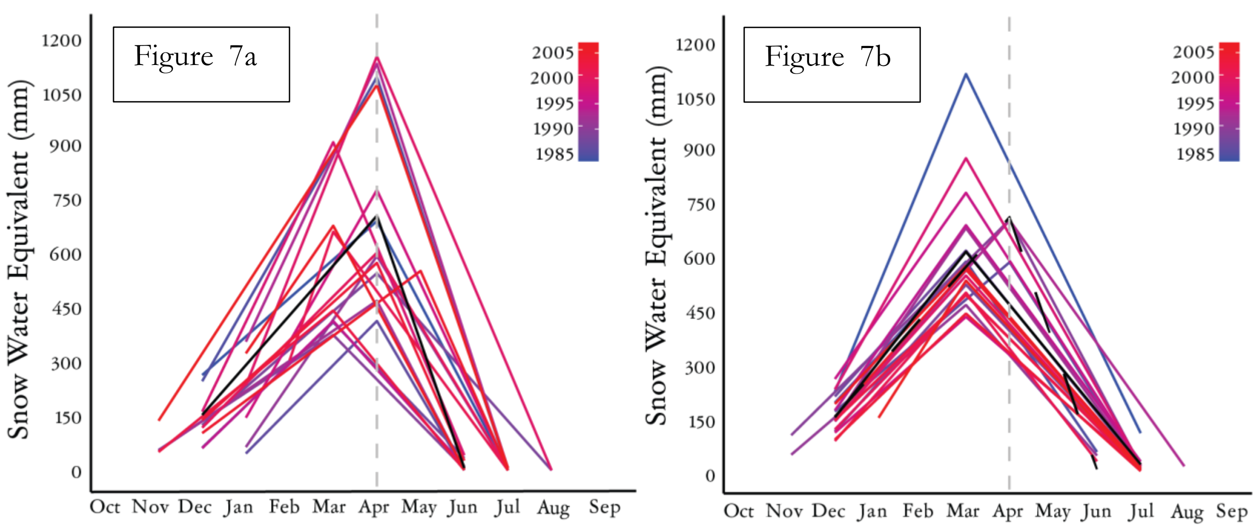

Figure 7: (a) Average monthly instrumental SWE values at 34 monitoring stations in the Southern Sierra Nevada, bolded black triangle shows the average of the component SWE triangles, vertical dashed line shows April 1st, data source for instrumental SWE data is California Cooperative Snow Surveys via NWCC; (b) average monthly SWE model output values at 34 monitoring stations in the Southern Sierra Nevada, bolded black triangle shows the average of the component SWE triangles, dashed black triangle shows the average of instrumental SWE triangles shown in (a), vertical dashed line shows April 1st, data source for SWE model output is the Scripps Institution of Oceanography via Cal-Adapt

possibility for why the models fail to capture the April 1st peak accumulation date is the use of monthly data in this analysis. Climate model output for SWE was only available as monthly data. Similar to spatial resolution, temporal resolution that is too coarse can be limiting. Daily data may better capture intrannual snowpack processes (Rhoades et al. 2018, Maurer et al. 2010).

Despite the fact that these models are not skillful at capturing SWE timing with monthly data, the changes in SWE magnitude they show likely illustrate the effects of precipitation type change. Even in a future world where some mitigation of greenhouse gas emissions occurs, snowpack will store less water (Figure 8a). Additionally, each additional unit of warming results in additional SWE reductions (Figure 8b).

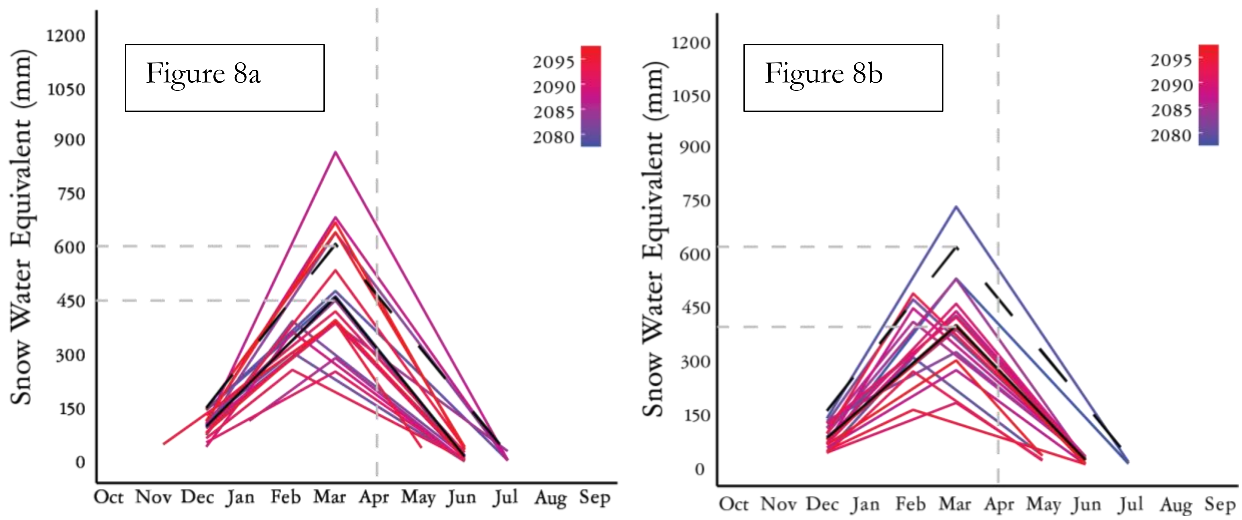

Figure 8: (a) SWE triangle estimating future intrannual snowpack processes in a realistic emissions scenario (RCP4.5), bolded black triangle shows the average of the component SWE triangles, dashed black triangle shows the average of model output SWE triangles for the historical period shown in Figure 7b; (b) SWE triangle estimating future intrannual snowpack processes in a high-emissions scenario (RCP8.5), bolded black triangle shows the average of the component SWE triangles, dashed black triangle shows the average of model output SWE triangles for the historical period shown in Figure 7b

Estimates of April 1 SWE in the coming decades produced using the same dataset as the SWE triangle analysis above are consistent with the scientific literature (Table 1). The climate models used in this analysis underestimate April 1 SWE, as compared to the instrumental record. Underestimation of April 1 SWE may be driven by extremely wet years. Climate models capture average annual trends better than they capture annual extremes. Extremely wet years in the instrumental record likely drive higher April 1 SWE values (Figure 9a). Underestimation of April 1 SWE values is preferable to overestimation because it indicates that the models used in this analysis provide conservative estimates of future SWE. Snowpack will likely store more water than these models indicate it will, making the model output suitable for planning purposes. Finally, even in a future world in which we have mitigated some greenhouse gas emissions (RCP4.5), Californians must contend a diminished snowpack water storage service (Figure 9b).

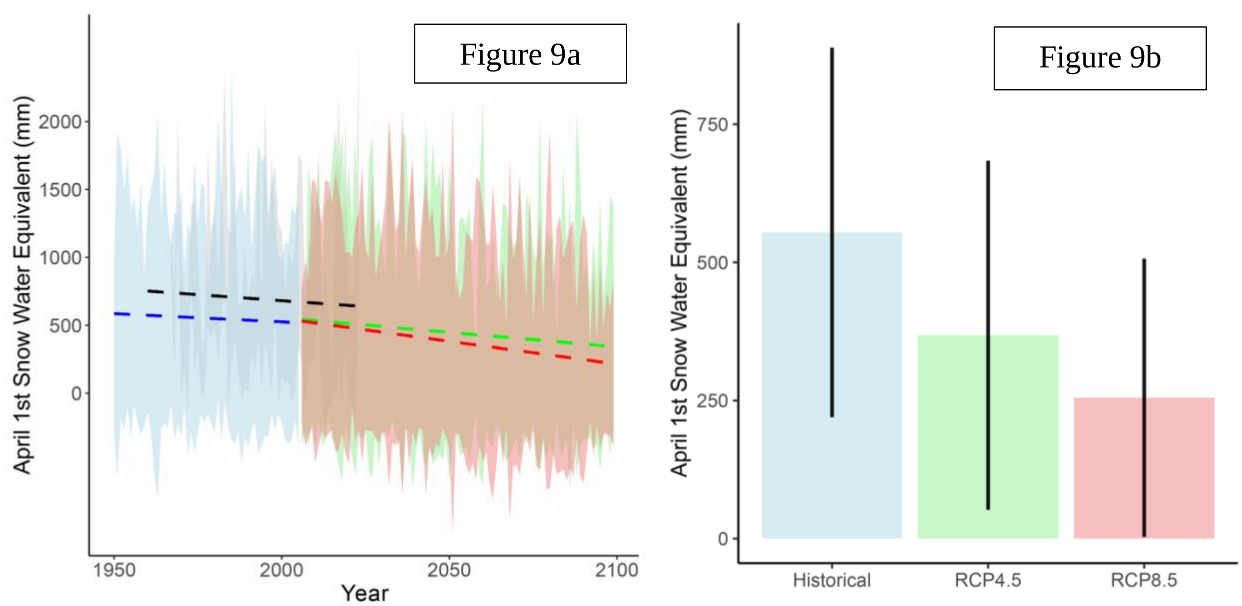

Figure 9: (a) April 1 SWE in historical and future periods, including both model output and the instrumental record; shaded areas show 95% confidence intervals, the black line represents the instrumental data that is available within this period, colored lines show model output, trendlines are shown in lieu of the SWE data because variability in the data obscures trends; (b) average model output for April 1 SWE in the historical period (1985-2005) and future period (2079-2099) considering two emission scenarios, error bars are twice the standard deviation

Table 1: Comparison of the data used in this analysis (Greenspan et al. 2023) and the scientific literature that discusses climate change impacts on Western United States or Sierra Nevada snowpack

Paper Authors and Year	**Study Region**	**Variable(s) of Interest**	**Spatial Resolution (km)**	**Historical Period**	**Forecast Period**	**% Δ SWE, RCP 8.5******
Pierce and Cayan 2013	Western United States	April 1st SWE, SWE/P, SFE/P	14	1976-2005	2070-2099	-70%
Li et al. 2017	Western United States	April 1st SWE	6.5	1960-2005	2006-2100	-64%
Schwartz et al. 2017	Sierra Nevada	R50*	3	1991-2000	2091-2100	n/a
Rhoades et al. 2018	Sierra Nevada	April 1st SWE**	12, 25, 50***	1985-2005	2039-2059; 2079-2099	-79%
Sun et al. 2019	Sierra Nevada	April 1st SWE	3	1991-200	2091-2100	-64%
Greenspan et al. 2023	Southern Sierra Nevada	April 1st SWE	6	1985-2005	2079-2099	-54%
*R50 definition is provided in the text describing findings from Schwartz et al. 2017						
**Rhoades et al. 2018 also analyzes intraanual snowpack variables; this analysis follows their intraannual analysis methods						
***The spatial resolution of downscaled GCMs used to forecast SWE in Rhoades et al. 2018 varies						
****This column reports the percent reduction in April 1st SWE, comparing the average for the historical period and the average for the future period in the high-emissions scenario (RCP8.5)						

Section VI: Climate change vulnerability of surface water storage infrastructure

Climate change impacts on Southern Sierra Nevada snowpack matter because the surface water storage infrastructure downstream is vulnerable to changes in runoff timing. The dams and reservoirs along the west slope of the Sierra Nevada serve multiple purposes (Figure 6). One purpose of these dams and reservoirs is storing water during wet periods so that it can be supplied to users during dry periods. Another purpose of this surface water storage infrastructure is flood control. Water supply managers seek to maximize the amount of water stored in each reservoir because they are responsible for maintaining the reliability of this supply, even in the face of multiyear drought. Flood control managers seek to minimize the amount of water stored in each reservoir because they are responsible for protecting lives and property downstream, even in the face of wet years with repeated storms. This tension between water supply and flood control priorities is key to understanding the climate change vulnerabilities of the dams and reservoirs overlying the San Joaquin Valley. In this section, key concepts from climate change vulnerability assessments prepared by the United States Bureau of Reclamation (USBR) and Central Valley Flood Protection Board (CVFPB) are presented.

In their report addressing climate change impacts on surface water storage infrastructure in the San Joaquin River Basin (a portion of the San Joaquin Valley), USBR highlights earlier runoff as a key vulnerability. Specifically, USBR expects peak runoff to occur more than one month earlier in some watersheds (USBR 2015). Three key concepts are helpful to understand USBR's concern regarding earlier runoff. First, flood rule curves are the water storage and release rules established by the United States Army Corps of Engineers (USACE). Rule curves are specific to each dam and reservoir. Second, the flood-conservation pool is the maximum level of reservoir storage that must be maintained for flood control purposes. The flood-conservation pool level is set by the rule curves. Third, carryover storage is the water stored in reservoirs at the end of September, which is the end of the water year. USBR must maintain sufficient carryover storage for several years of drought (USBR 2015). To respond to earlier runoff and avoid exceeding the flood-conservation pool level set by USACE's rule curves, USBR will need to release water earlier. Earlier release of water reduces carryover storage.

In the 2022 Central Valley Flood Protection Plan, CVFPB emphasizes regional differences in the effect of climate change on flood magnitudes in California.[5] Flood magnitudes are expected to increase more in the San Joaquin Valley than in the Sacramento Valley (CVFPB 2022; Figure 10). This difference in climate change impacts on flood magnitude is driven by differences in precipitation type change. Due to increasing temperatures, the freezing elevation–above which precipitation falls as snow and below which precipitation falls as rain–in the Sacramento River Basin is expected to increase from 5,000 feet elevation without climate change to 8,500 feet elevation in a high-emissions scenario. The freezing elevation in the San Joaquin River Basin is expected to increase from 8,000 feet without climate change to 12,000 feet in a high-emissions scenario (CVFPB 2022). Thus, the Southern Sierra Nevada and the San Joaquin Valley are especially vulnerability to shifts in runoff timing that will diminish future surface water supplies.

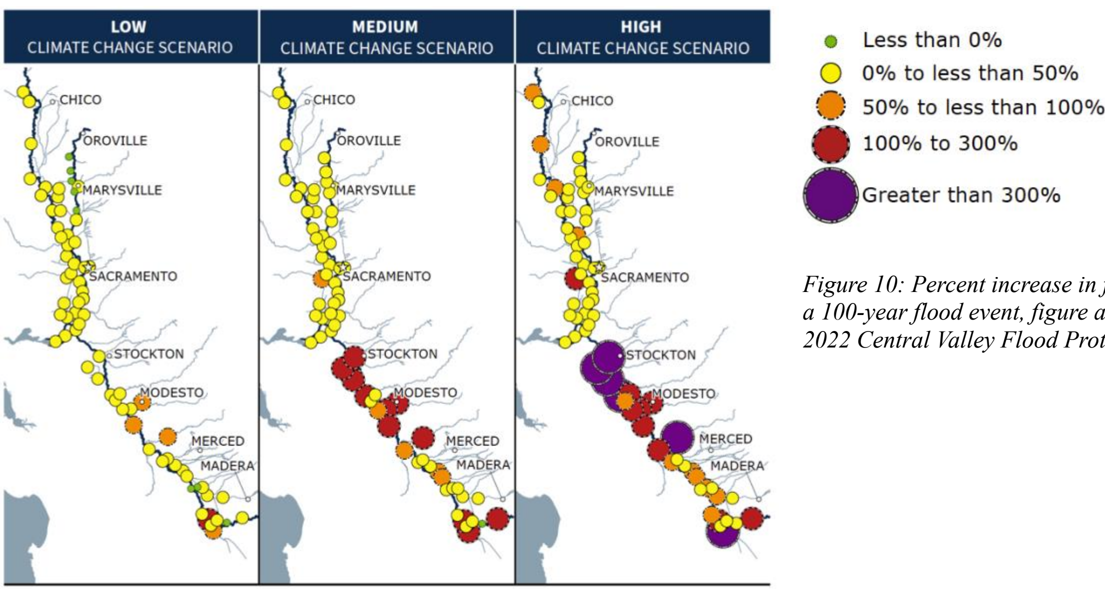

Figure 10: Percent increase in flood magnitudes of a 100-year flood event, figure adapted from the 2022 Central Valley Flood Protection Plan

[5] Flood magnitude describes the amount of water that arrives simultaneously.

Section VII: Concluding thoughts about the shift towards increased conjunctive use

This research attempts to link two bodies of research. In one sphere, there are climate scientists, hydrologists, surface water managers, and others who are calling attention to changes in the way snowpack stores water as well as the vulnerabilities of dams and reservoirs to these changes. In another sphere, groundwater users, groundwater managers, groundwater sustainability plan authors, and others are working to find an equitable path toward sustainable groundwater use in the San Joaquin Valley. USBR and CVFPB both highlight groundwater management changes as key climate change adaptation strategies due to the vulnerabilities of surface water storage infrastructure (USBR 2016, CVFPB 2022). However, these surface water supply and flood control managers do not fully acknowledge the challenges of altering groundwater management policy in their reports. Similarly, groundwater sustainability plan authors quantify the impacts of climate change on crop water demands, but they do not account for climate change impacts on snowpack and surface water resources. Groundwater managers must plan for climate change impacts on overlying watersheds, not just crop water demands. Likewise, surface water managers must recognize the extreme challenges that come with scaling up groundwater recharge efforts. In the world of California water resources management, climate change is forcing us towards thinking of our surface water and groundwater resources as one resource.

Chapter Two

Implications of Climate Change Impacts on Surface Water for San Joaquin Valley Groundwater Management

Climate change impacts on snowpack are not the only constraint that California water managers face in the coming decades. Implementation of the 2014 Sustainable Groundwater Management Act (SGMA) will also reduce water supplies. These dual constraints on water in our state present an opportunity. Implementation of local policy in the San Joaquin Valley that establishes groundwater pumping allocations and provides a credit for groundwater replenishment when floodwater is available has the potential to both facilitate adaptation to altered runoff timing and reduce the economic harms of SGMA compliance.

Figure 11: San Joaquin Valley boundaries and Madera County

Section I presents data on surface water availability in the San Joaquin Valley, which provides context for the importance of groundwater in the region's water supply. Section II explores the history of groundwater use regulation in California and the new powers granted to groundwater managers under SGMA. Section III explores how groundwater managers in the San Joaquin Valley are responding to SGMA, including their estimation of sustainable quantities of groundwater use and the actions they believe are needed to achieve groundwater sustainability goals. Section IV provides key takeaways from the research of Public Policy Institute of California's (PPIC) Water Policy Center, which points out areas where groundwater sustainability planning can be improved in the San Joaquin Valley. Section V details the groundwater pumping allocation and replenishment credit approach, based on a series of interviews with groundwater managers in Madera County (Figure 11).

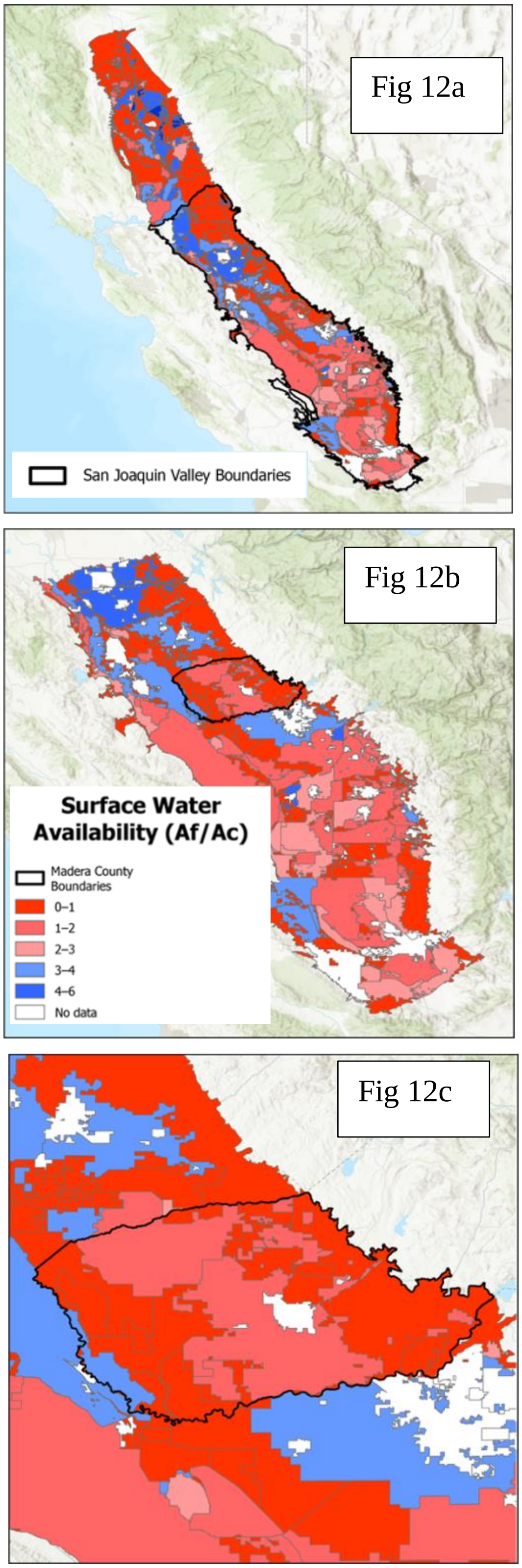

Figure 12: Surface water availability (acre-feet/acre) in (a) the Central Valley, (b) the San Joaquin Valley, and (c) Madera County

Section I: Surface Water Availability

Surface water resources are not distributed evenly in the San Joaquin Valley. Rather, water rights and conveyance infrastructure create a patchwork of surface water haves and have nots (Figure 12). Areas that are rich in surface water are less likely to have groundwater sustainability problems because they do not need to pump as much groundwater for their crops. Because these areas have conveyance infrastructure to move surface water to agricultural land, they are typically better equipped to divert floodwater for groundwater replenishment when it is available. Conversely, other areas receive little to no surface water. These areas are highly susceptible to mandatory land fallowing as SGMA is implemented over the next decade because of their high dependence on groundwater to irrigate crops. They are also typically not well-equipped to capture floodwater and move it to cropland for groundwater replenishment. Additionally, areas that depends solely on groundwater to irrigate crops are called white areas. Under SGMA, counties are responsible for managing groundwater sustainability efforts in white areas. Madera County contains a large portion of these white areas (Figure 12c). Over a series of interviews, I have learned how the Madera County groundwater sustainability agencies are attempting to reduce groundwater pumping in their management area. Key takeaways from these interviews are presented in section V.

Section II: History of Groundwater Use Regulation in California, New Powers Granted to GSAs

In 1914, the State of California enacted the Water Commission Act, which established licensing for surface water use (SWRCB, Water Commission Act). However, the State left groundwater use unregulated for another century. Four legal mechanisms emerged to regulate groundwater use at the local level, prior to state-level regulations. These mechanisms include adjudication, county ordinance, groundwater management plans (GMPs), and Special Act Districts.

The superior courts of California became the venue to address disagreements over groundwater pumping via a process known as adjudication beginning in the 1940s (Dennis et al. 2020). Adjudication effectively resolves pumping conflicts but is a lengthy, costly process that is not well suited to the San Joaquin Valley because it requires a highly accurate accounting of all groundwater system inflows and outflows. All currently adjudicated groundwater basins are in urban Southern California (SGMA Data Viewer, Adjudicated Basin Annual Reporting).

The second way groundwater use was regulated at the local level prior to SGMA is Special Act Districts. These districts are formed in response to a specific groundwater problem, such as seawater intrusion, for a specific location by an act of the state legislature. Most Special Act Districts are in coastal areas (Langridge et al. 2016).

A third approach to local regulation of groundwater use is county ordinance. In such an ordinance, one county bans the export of groundwater to another county. As of 2015, 30 of the state's 58 counties had groundwater ordinances (Water Education Foundation SGMA Handbook).

A fourth approach to local groundwater regulation is GMPs. The 1992 Groundwater Management Act provided local water managers

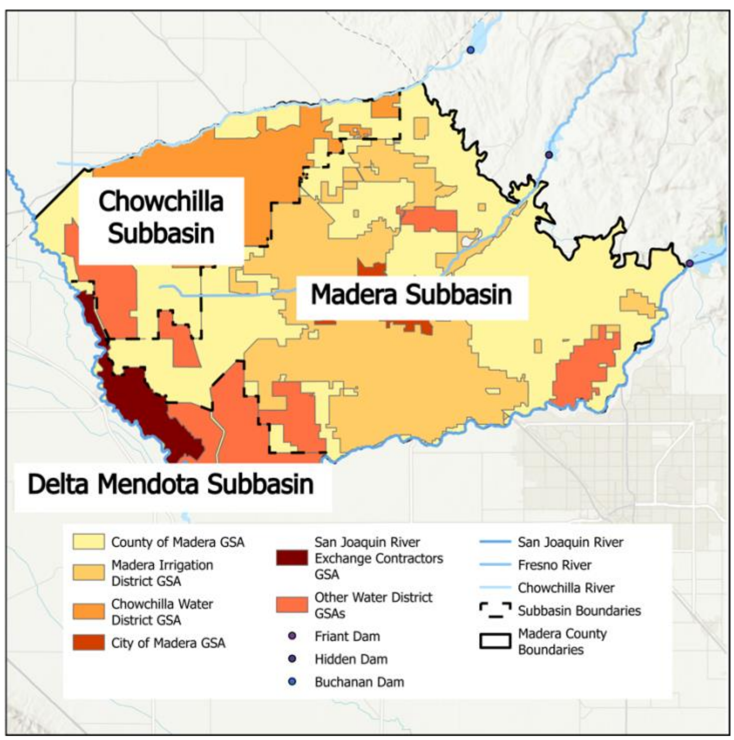

Figure 13: Subbasin and groundwater sustainability agency boundaries in Madera County

with the authority to collect fees tied to volumes of groundwater pumped in order to fund implementation of GMPs (Dennis et al. 2020; California Legislative Information, Water Code Section 10750). By 2014, there were 149 GMPs developed, but the 1992 act incorporated no mandate to achieve a sustainability goal and local entities did not get all the tools they needed to effectively manage their jurisdiction's groundwater (Water Education Foundation SGMA Handbook).

The critical overdraft designation is a useful concept to understand other aspects of SGMA. Overdraft refers to a multiyear, persistent trend of groundwater system outflows exceeding groundwater system inflows. To determine which subbasins are critically overdrafted, the California Department of Water Resources (DWR) started with a list of critically overdrafted subbasins produced by the agency as part of Bulletin 118's 1980 edition.[6] DWR then defined a base period that included a representative amount of wet and dry years.[7] They chose 1989-2009. Finally, DWR evaluated the subbasins on the 1980 list over the baseline period to determine whether one or more undesirable results occurred (Maven's Notebook, Critical Overdraft Designation). Undesirable results refer to consequences of groundwater overdraft. They include chronic lowering of groundwater levels, reduction of groundwater storage, land subsidence, seawater intrusion, depletion of interconnected surface water, and degraded groundwater quality.

In 2014, SGMA provided more legal tools to local water managers charged with managing groundwater in their jurisdiction. Under SGMA, newly created groundwater sustainability agencies (GSAs) have the authority to limit groundwater pumping where current levels of pumping causes any of the undesirable results. This power previously was limited to 15 Special Act Districts (Langridge et al. 2016, Nelson and Perrone 2016, Water Education Foundation SGMA Handbook). GSAs can be formed by either one local entity, such as a water district, or multiple local entities. Likewise, groundwater sustainability plans (GSPs) can be authored by one GSA or multiple GSAs. For example, the San Joaquin Valley contains 11 critically overdrafted subbasins. Six of these subbasins are fragmented with multiple GSPs. Five of these subbasins are governed by a single GSP (PPIC, San Joaquin Valley Project and Actions

[6] Bulletin 118 is the state's groundwater report, which compiles subbasin maps, geological information, and management details.
[7] For more information of classification of wet years and dry years, see the following: (DWR, Water Year Hydrologic Classification Indices).

Dataset). Subbasin and GSA boundaries in Madera County provide another example of this complexity (Figure 13).

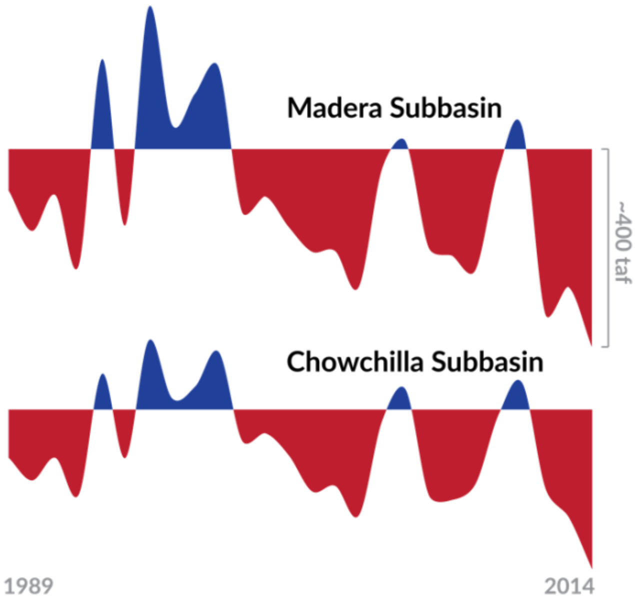

Figure 13: Groundwater system inflows and outflows for Madera and Chowchilla subbasins, taf is thousand acre-feet, data source is PPIC water budget dataset

Section III: An Analysis of How Local Groundwater Managers are Responding to SGMA

Each GSP contains information about the extent of overdraft in the plan area and how the GSAs plan to address this overdraft. Most plans also contain annual data for groundwater system inflows and outflows for some period of record. For Madera and Chowchilla subbasins, the two subbasins that comprise most of Madera County, groundwater system outflows exceed groundwater system inflows in most years (Figure 14).

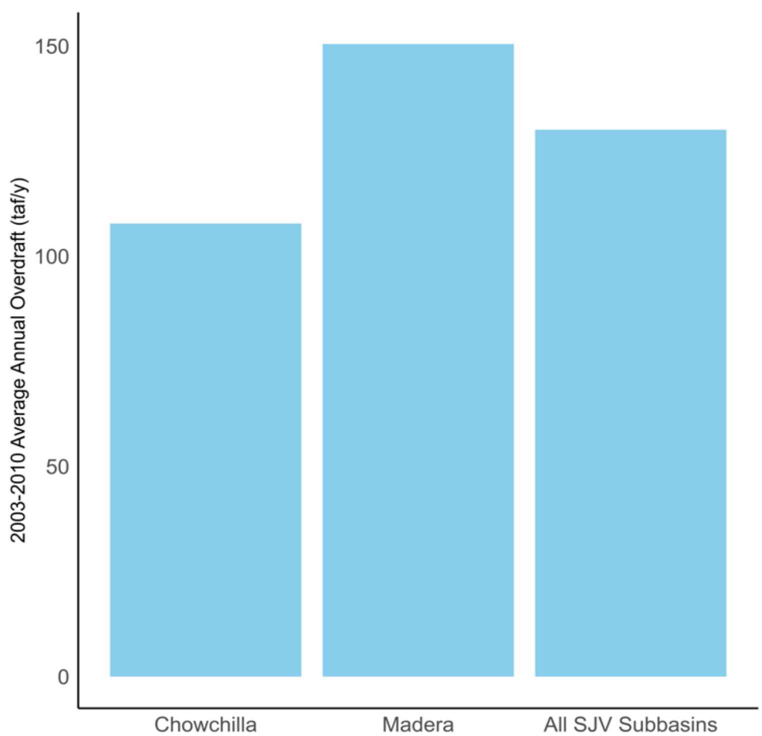

Figure 14: Average annual overdraft, median used for all San Joaquin Valley (SJV) subbasins because Kern County Subbasin is a strong outlier with extremely large amounts of annual overdraft, data source is PPIC water budget dataset

To compare overdraft in Madera Subbasin and Chowchilla Subbasin to other subbasins, a common set of years that contains a balanced amount of wet and dry years must be used. Average annual overdraft in Madera and Chowchilla subbasins is near the median value for all critically

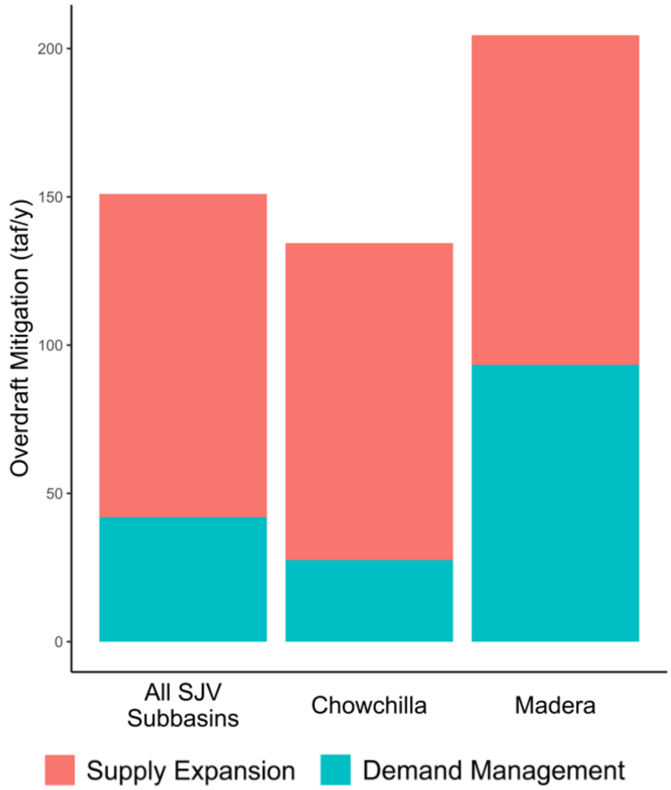

Figure 15: Overdraft mitigation by supply side and demand side efforts. Supply side projects aim to expand surface water supplies. Demand management actions aim to reduce demand for groundwater. Data source is PPIC San Joaquin Valley Projects and Actions Dataset.

overdrafted San Joaquin Valley subbasins (Figure 15).

GSPs include a portfolio of efforts to mitigate groundwater overdraft, including projects that aim to expand surface water supplies and management actions that aim to reduce demand for groundwater. Most subbasins are relying on a portfolio of efforts that heavily emphasize securing new supplies of surface water. Conversely, Madera subbasin emphasizes demand management actions (Figure 16). Because Madera subbasin contains a large portion of white areas–areas with no surface water–Madera County GSA has quickly developed a set of actions to reduce demand for groundwater. The demand management strategies of the Madera County GSAs and other county GSAs can provide a blueprint for groundwater demand management throughout the San Joaquin Valley.

Section IV: Key Takeaways from PPIC Research Regarding the Transition to Groundwater Sustainability in the San Joaquin Valley

There is a stark contrast between the demand reductions that San Joaquin Valley groundwater managers have planned and the demand reductions that must occur to comply with SGMA. For the period 1988-2017, annual overdraft was two million acre-feet, which is approximately 11% of water use in the valley (Hanak et al. 2019). PPIC estimates that new supplies of surface water can only address approximately one-quarter of this overdraft; the rest must come from reductions in agricultural groundwater demand (Hanak et al. 2019). However, the groundwater sustainability plans for the 11 critically overdrafted subbasins in the San Joaquin Valley assume that new supplies of surface water will address approximately threequarters of the overdraft. This disconnect points to a need for revised demand management strategies in San Joaquin Valley GSPs.

The optimal path forward involves a balanced portfolio of efforts, including cost-effective new supplies of surface water, new surface water trading arrangements, and beneficial uses of land that would otherwise be fallowed. Even with gains in new supplies, approximately 500,000 acres of land will likely need to be fallowed in the San Joaquin Valley to comply with SGMA (Hanak et al. 2023). In the worst-case scenario, without substantial new supplies of surface water, nearly 900,000 acres will likely need to be fallowed (Escriva-Bou et al. 2023). For context, in 2018 there were 4.5 million acres of irrigated cropland in the San Joaquin Valley (Escriva-Bou et al. 2023). Acquisition of cost-effective sources of new surface water would minimize the fallowing that needs to occur. Given the scarcity of surface water in the San Joaquin Valley, capturing water during storms and moving it underground is likely to be the most cost-effective source of new supplies (Hanak et al. 2019). The main barriers to this objective are (1) lack of coordination between surface water reservoir and groundwater recharge managers, (2) limited infrastructure to move floodwater to farmland suitable for recharge, (3) permitting requirements administered by the State Water Resources Board and California Department of Fish and Wildlife, and (4) an insufficient quantity of growers as well as groundwater managers that are sufficiently organized to take water (Mount et al. 2023). Additionally, new surface water trading arrangements would minimize the cost of land fallowing that needs to occur (Hanak et al. 2019, Escriva-Bou et al. 2023). Surface water trading is important because it allows water to move to its highest value use, thus minimizing the costs of fallowing land. Trading could occur at the local or valley-wide level; increased levels of flexibility further reduces costs (Hanak et al. 2019, Escriva-Bou et al. 2023). Finally, beneficial uses of land that would otherwise be fallowed would also reduce the costs of SGMA compliance. Alternatives for otherwise fallowed lands include solar development, water-limited agriculture, and habitat restoration, among other uses (Hanak et al. 2023, Escriva-Bou et al. 2023).[8] A

[8] For more details on alternative uses of formerly irrigated lands, refer to Hanak et al. 2023 Managing Water and Farmland Transitions in the San Joaquin Valley.

balance of cost-effective new supplies, new water trading arrangements, and new beneficial uses for formerly irrigated lands will minimize the costs of achieving groundwater sustainability.

Groundwater pumping allocations–assigning a maximum groundwater pumping quantity to each grower–are a foundational step for both acquisition of cost-effective new supplies of surface water and flexible reduction of demand for groundwater. Allocations incorporate the scarcity of the resource into policy, a long overdue step in San Joaquin Valley groundwater management. When paired with a credit for groundwater replenishment, pumping allocations incentivize growers to use their land for groundwater replenishment when floodwater is available. Additionally, allocations set the foundation for flexible demand management because pumping allocations can be traded as groundwater becomes scarcer, helping to minimize the cost of land fallowing. The next section explores how the Madera County GSAs set up their allocation system and situates their approach in a broad picture of groundwater demand management approaches in the San Joaquin Valley.

Section V: Groundwater Demand Management in Madera County and the San Joaquin Valley

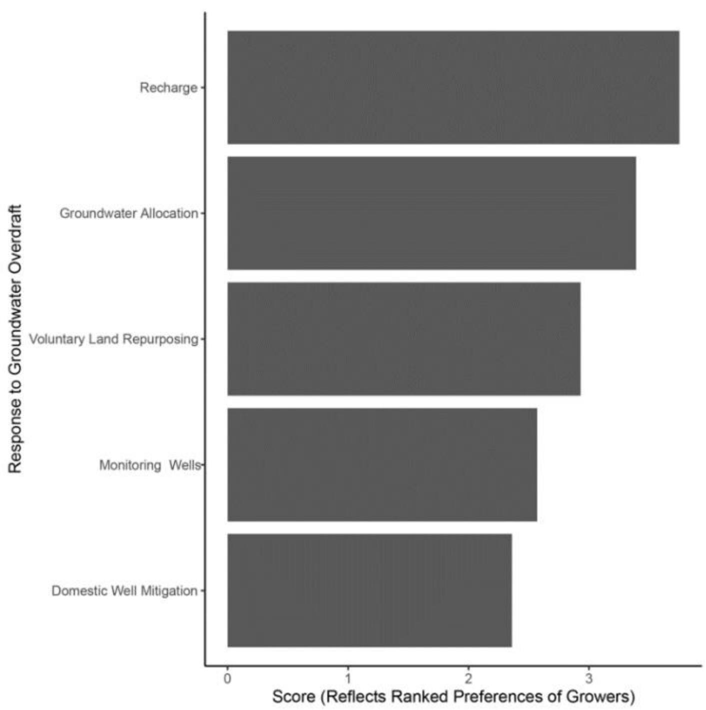

Figure 17: Madera County grower preferences for responses to groundwater overdraft, data acquired from Madera County Department of Water and Natural Resources

Madera County's groundwater pumping allocation system is a model that can be followed by other groundwater managers in the San Joaquin Valley to incentivize on-farm groundwater replenishment when floodwater is available. Two pieces of evidence indicate early success of Madera County's approach. First, growers in Madera County prefer recharge–synonymous with groundwater replenishment–and pumping allocations to alternative actions such as land fallowing and metering pumped quantities (Figure 17). Second, in response to two

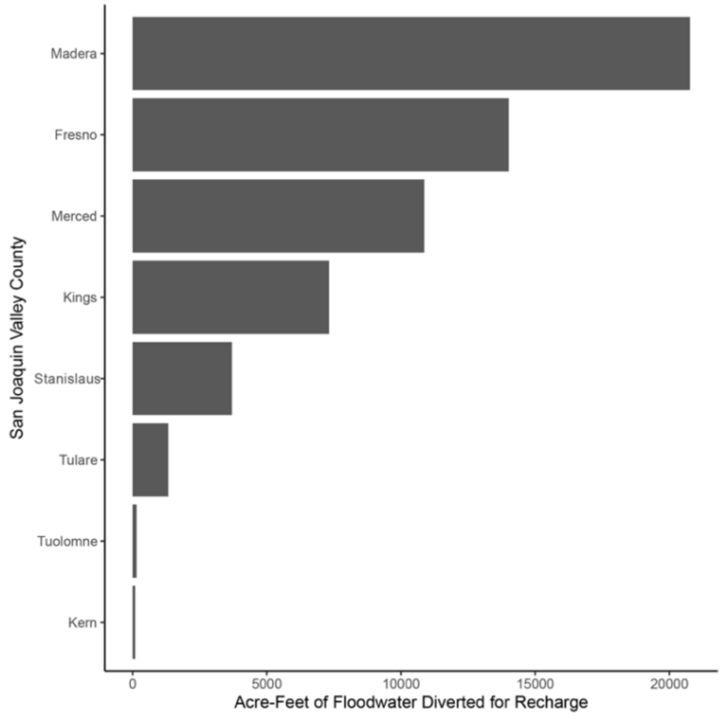

Figure 18: Volumes of water diverted in spring 2023 under executive orders by San Joaquin Valley county, data is from State Water Resources Control Board and was summarized by county in August 2023 LunchMAR presentation by Madera County Department of Water and Natural Resources

executive orders that temporarily withdrew permitting requirements in spring 2023, Madera County entities diverted more floodwater than any other county in the San Joaquin Valley (Figure 18). The large diverted volumes can mostly be attributed to the fact that Madera County has a flood control arm (most other San Joaquin Valley counties do not). However, the large diverted volumes also demonstrate that growers can and will divert floodwater onto their land for groundwater replenishment when provided with incentives to do so.

The ability of GSAs to sustainably manage groundwater will depend on stable revenue sources. Grant funding, a current financing source, is not sustainable. The Madera County GSAs

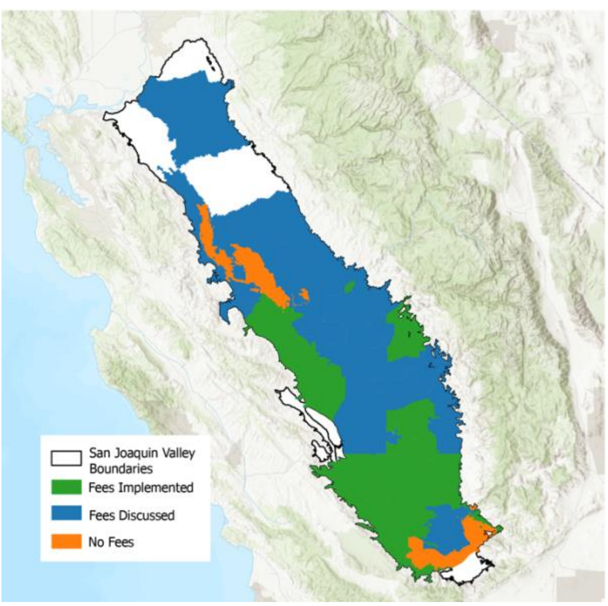

Figure 19: GSP areas that have implemented fees in at least one GSA or discuss fees in their GSP

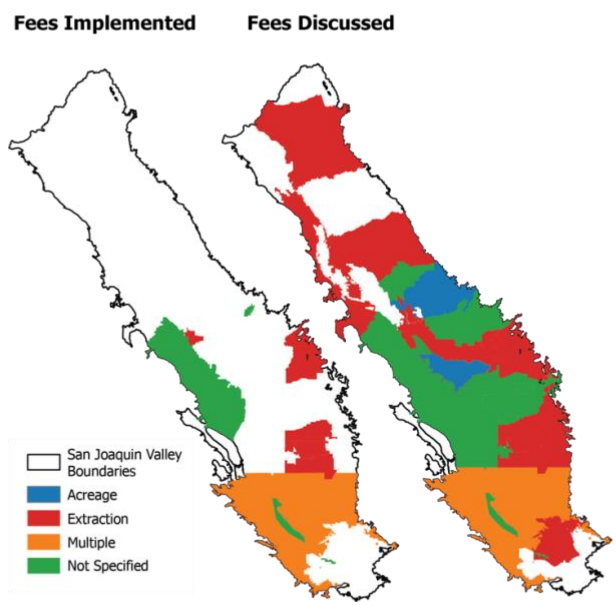

Figure 20: type of fee in GSP areas where fees have been implemented, all GSP areas that discuss fees in their plan

Table 2: sustainable yield and transition water quanties by year in the Madera County GSAs, Delta-Mendota subbasin omitted, table adapted from Madera County resolutions

Year	Madera Subbasin		Chowchilla Subbasin	
	SY	TW	SY	TW
2020	90,000	101,000	22,500	60,500
2021	90,000	98,980	22,500	59,290
2022	90,000	96,960	22,500	58,080
2023	90,000	94,940	22,500	56,870
2024	90,000	92,920	22,500	55,660
2025	90,000	90,900	22,500	54,450

have implemented a fee that is based on irrigated acreage, which is preferable due to the stability of the revenue source. Fees tied to volumes pumped vary year-to-year, which makes for a volatile revenue source. Few other San Joaquin Valley GSPs for critically overdrafted subbasins have implemented fees (Figure 19).[9] Among the set of GSPs that have discussed implementing fees, an amount tied to volumes of groundwater pumped is preferred (Figure 20). To determine which lands are irrigated, Madera County relies on evapotranspiration data measured from satellites (Resolution 2021-069). Madera County chose a fee of $246 per acre per year, which reflects the average cost of service in a given year (Resolution 2022-086).

The next steps to establish pumping allocations in Madera County included establishing (1) the total amount of water available for pumping in each year, (2) the areas in which trading of pumping allocations will be allowed, and (3) the method by which compliance with pumping allocations will be monitored. First, the Madera County GSAs have defined two categories of water. The

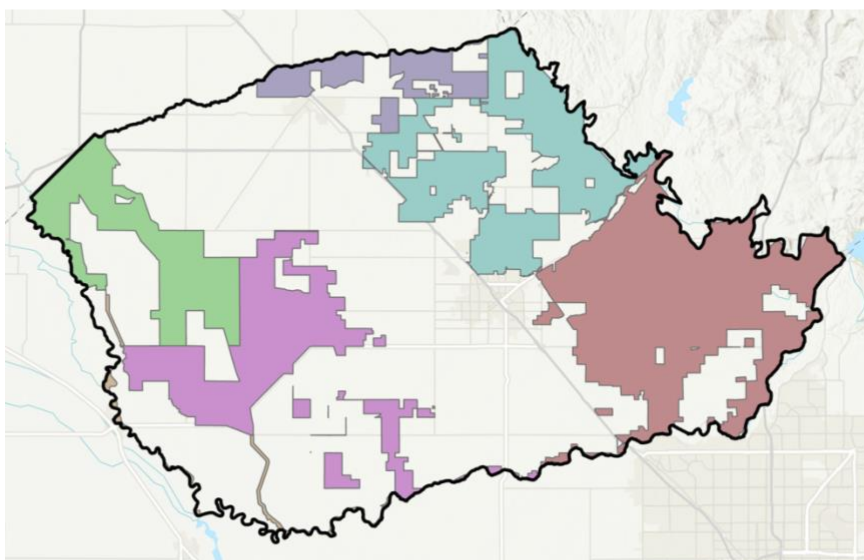

Figure 21: farm unit zones in Madera County, data acquired from Madera County Department of Water and Natural Resources

[9] Data caveat for figures 19, 20, 22-24: these figures are based on data acquired from UC Berkeley's Department of Agricultural and Resource Economics SGMA Demand Management Action Database. Data are available at the groundwater sustainability plan (GSP) level. Because GSPs can be authored by multiple groundwater sustainability agencies (GSAs), the maps shown in these figures are overestimates of the areas in which the strategy has been implemented or discussed. For example, Figure 22 shows GSP areas that have implemented and discussed allocations. The green areas indicate that allocations have been implemented, but in many cases only a portion of the GSAs in the green area have implemented allocations.

Table 4: Allocations of sustainable yield and transition water by acre in Madera County GSA portions of Madera and Chowchilla subbasins, table adapted from Madera County resolutions

Madera County GSA: Madera Subbasin							
	GSA Allocations (af/yr)		Per-Acre Allocation (inches/ac/yr)				
Year	SY	TW	B-SY	Re-SY	TW	Total for Irr.	Total Non-irr.
2020	90,000	113,000	6	7	16.0	28.7	0
2021		110,740			15.6	28.3	0
2022		108,480			15.3	28.0	0
2023		106,220			15.0	27.7	0
2024		103,960			14.7	27.4	0
2025		101,700			14.4	27.1	0
Irrigated Acres = 85,000			Can access B-SY, Re-SY and TW				
Non-Irr. Opt-in acres = 0			Can access only B-SY and Re-SY				
Total GSA acres = 185,000							

Madera County GSA: Chowchilla Subbasin							
	GSA Allocations (af/yr)		Per-Acre Allocation (inches/ac/yr)				
Year	SY	TW	B-SY	Re-SY	TW	Total for Irr.	Total Non-irr.
2020	22,500	63,400	6	1.1	20.0	27.1	0
2021		62,132			19.6	26.7	0
2022		60,864			19.2	26.3	0
2023		59,596			18.8	25.9	0
2024		58,328			18.4	25.5	0
2025		57,060			18.0	25.1	0
Irrigated Acres = 38,000			Can access B-SY, Re-SY and TW				
Non-Irr. Opt-in acres = 0			Can access only B-SY and Re-SY				
Total GSA acres = 45,000							

first category is sustainable yield, which is the average amount of groundwater that can be pumped each year while maintaining groundwater sustainability. The second category is transition water, which is the amount of pumping that is allowed to occur in excess of sustainable yield. Transition water amounts decrease each year (Table 2). The goal is to have pumped quantities equal sustainable yield in 2040, the year by which full compliance with SGMA must be achieved. Second, the Madera County GSAs allow trading of pumping allocations within farm unit zones (Figure 21). A parcel is a collection of acres, while a farm unit is a collection of parcels bound by common management. A farm unit zone is an aggregation of these farm units based on proximity. Prohibition of pumping allocation trades between farm unit zones minimizes the concentration of undesireable results in specific areas. Third, the evapotranspiration of water applied to crops (ETAW), as measured by the company Land IQ, is the default method of measuring groundwater pumping (Resolution 2021-113, Resolution 2022, 192). Pumping can be estimated from ETAW because water lost to the atmosphere from plants is equivalent to the sum of applied water and precipitation, less the fraction of applied water that infiltrates without being used by the plant. In white areas, all applied water is pumped groundwater. No surface water is applied to crops in these areas. The advantages of using ETAW as a proxy for groundwater pumping include the fine scale of the data–it can be obtained at the field level–and the fact that it overcomes the data limitations of inadequate metering on groundwater wells. Ideally, meters would provide the exact pumped quantities, but the Madera County GSAs lack a good accounting of agricultural wells, and meter data is not available from most wells. Challenges in developing an accurate accounting of agricultural wells and monitoring pumped quantities exist in numerous locations dependent on groundwater throughout the world, usually due to a lack of capacity to register wells and enforce metering (Molle and Closas 2020).

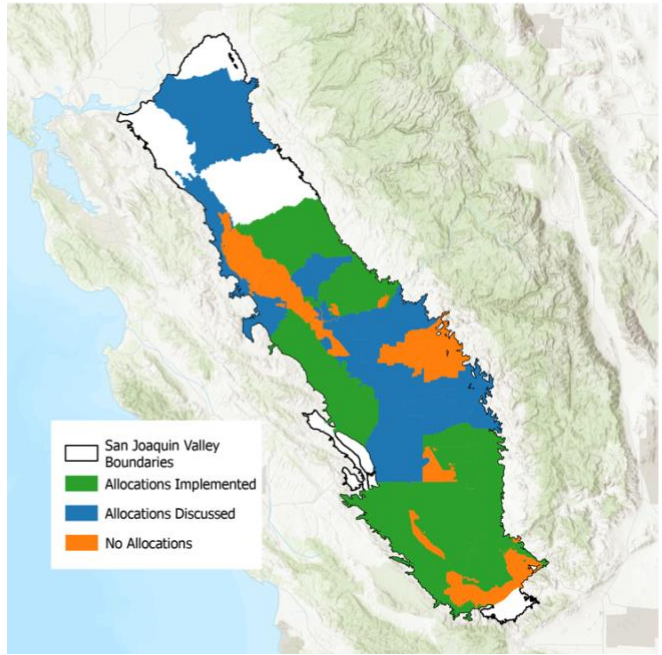

Figure 22: GSP areas in critically overdrafted San Joaquin Valley subbasins that have implemented allocations or discussed allocations in their GSP

The final steps to establish allocations were to define which lands are eligible for a pumping allocation, how the total pumping allocation will be divided up among eligible lands, and the penalty that will be assessed for over-pumping. Lands that are eligible for a pumping allocation include lands that are currently irrigated or have been irrigated at any point since January 1st, 2015 (Resolution 2021-069). Pumping allocations are divided up by irrigated

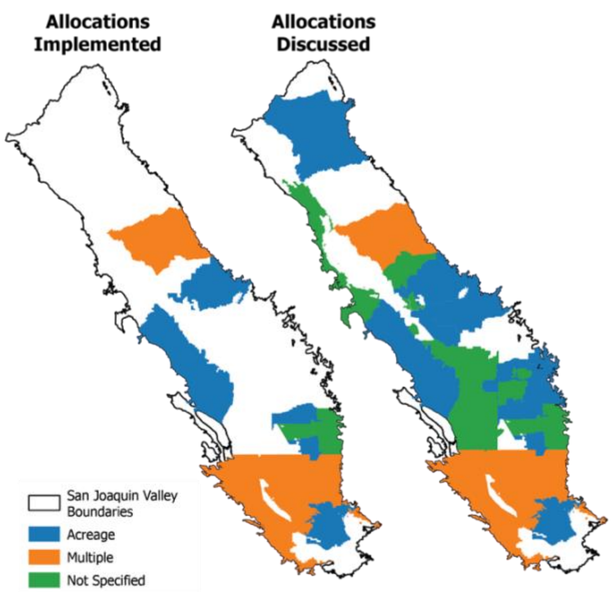

Figure 23: The factor used to divide up pumping allocations in GSP areas that have implemented allocations and the areas of GSPs that have only discussed the possibility of allocations

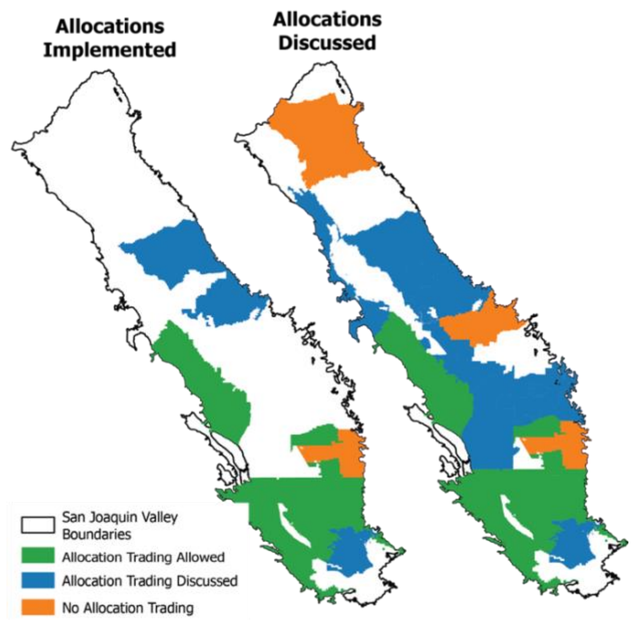

Figure 24: GSP areas that allow allocation trading, only includes GSP areas that have implemented allocations and the areas of GSPs that have discussed the possibility of allocations

acre (Table 4). When ETAW measurements show that a grower is out of compliance with the allocations, a penalty of $100 per acre-foot is assessed in 2023. This penalty increases by $100 per acre-foot each year until it reaches the maximum penalty of $500 per acre-foot (Resolution 2022-143, Resolution 2022-145).

The allocations approach of the Madera County GSAs presents one potential pathway for other GSAs in the San Joaquin Valley to effectively and fairly reduce demand for groundwater. Few San Joaquin Valley GSAs have implemented allocations, while many discuss the potential for allocations in their GSPs (Figure 22). Among the GSPs that have discussed implementing allocations in their GSPS, most prefer the use of acreage as the basis for dividing up allocations, similar to the Madera County GSAs (Figure 23). Among the GSAs that have implemented allocations, most allow some trading of those allocations (Figure 24). In addition, when pumping allocations are paired with a credit for groundwater replenishment, growers are incentivized to divert floodwater onto their land when it is available. A credit allows growers to increase their pumping allocation for later dry periods if they replenish groundwater when floodwater is available. Madera County has suggested a partial credit that accounts for lateral flows in the groundwater basin and evaporative loss that occurs when floodwater is spread on cropland (Madera's Successful Response to EO N-4-23, 2023).

The Sustainable Groundwater Management Act (SGMA) has provided new tools to local groundwater managers (GSAs), but many of these managers have not planned for the reduction in groundwater demand that must occur. Areas that receive little to no surface water, such as the areas managed by the Madera County GSAs, have quickly developed plans to reduce demand for groundwater because their ability to comply with SGMA depends on their ability to reduce groundwater pumping. The pumping allocations system developed by the Madera County GSAs provides a blueprint for other GSAs in the San Joaquin Valley to reduce demand for groundwater. Groundwater pumping allocations and groundwater replenishment credits can enable both SGMA compliance with minimized economic cost and adaptation to altered surface water availability under climate change. For allocations and credits to achieve these goals, surface water and groundwater managers must collaborate to store floodwater underground when it is available. Rather than viewing climate change vulnerabilities of surface water storage infrastructure and issues of groundwater sustainability as distinct, these resources must be viewed as one resource and managed together.

Appendix A: Snow Water Equivalent Data Analysis Methods

Instrumental snow water equivalent data were obtained from the National Water and Climate Center (NWCC) for the California Cooperative Snow Survey Network. Climate model output for snow water equivalent (SWE) were obtained from the Scripps Institution of Oceanography via Cal-Adapt. Four climate models were chosen based on how well they represent California climate. Those models are HADGEM2-ES, CNRM-CM5, CanESM2, and MIROC5 (Cal-Adapt, What climate models should I use in my analysis?). The 34 snow monitoring stations included in the instrumental dataset were chosen based on data availability for the period 1985-2005. SWE data were extracted from the rasters obtained from Cal-Adapt for the exact locations of those 34 monitoring stations using the Extract Multi Values to Points tool in ArcGIS Pro. Instrumental and model SWE data were compared using snow water equivalent triangle methods (Rhoades et al. 2018a). The values used to define the SWE triangles were (1) the peak value, (2) the first value that exceeds 10% of the peak each year, and (2) the last value that exceeds 10% of the peak in each year. Future changes in SWE were estimated by plotting future data under two emissions scenarios alongside the average historical SWE triangle produced using model data.

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