Modeling California Central Valley Groundwater under the Sustainable Groundwater Management Act

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ABSTRACT

Water demand in California's arid Central Valley has depleted groundwater at a rate of -1.85km^3 per year since the early 1960s with this rate more than doubling in recent drought. In 2014, California State Legislature passed the Sustainable Groundwater Management Act (SGMA) to charge local agencies with ending overdraft in all designated high and medium-risk subbasins by 2040. Many high-risk critically-overdrafted basins lie in the Central Valley. Critics question SGMA's ability to prioritize both local control over groundwater budgets and achieving groundwater sustainability. Two areas of contestation center around 1) Central Valley agencies collectively planning to consume more surface water than is available, and 2) difficulties in collecting recharge. This research builds on Massoud 2018's previously established methodology to create a predictive model for long-term groundwater storage and evaluates the expected impact of local groundwater sustainability plans with and without critiques accounted for. It finds that SGMA could save up to 40.81 million acre-feet of groundwater storage by 2040. Limitations on surface water and recharge will minorly constrain the long-term benefit provided by SGMA.

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INTRODUCTION

Surface and groundwater have supplied urban, environmental, and agricultural water needs for California's Central Valley for decades with agriculture serving as a key player in the region's water budget. In 2014, agriculture consumed 85% of the Central Valley's total water demand. [1] The region produces one quarter of the food grown in the United States including 40% of fruits and nuts.[2] Groundwater levels in the Central Valley have been decreasing at an average rate of 1.85 km^3 since the early 1960s with rate more than doubling throughout drought conditions in recent years.[3] Groundwater depletion persisted even as major surface water canals were built specifically to allow water from the water-rich north to take the burden of supply off of the state's southern aquifers.[4]

As California entered the deepest part of its decades-long megadrought in 2012-2016, historic groundwater pumping[5] depleted aquifer to levels such that parts of the Central Valley saw decreases in watertables [6], drinking water wells going dry[7], high levels of land subsidence [8], and wastewater intrusion. The California Department of Water Resources (DWR) has found that 83% of California's population and 88% of its irrigated acres faced medium to high risks as a result of groundwater depletion.[9] In 2014, the California State Legislature responded by passing the Sustainable Groundwater management Act (SGMA). With SGMA, California became the final state in the American Southwest to pass legislation protecting groundwater.

SGMA aims to use local water agencies to achieve sustainability by 2040.[10] "Recognizing that groundwater is best managed on a local level", SGMA splits aquifers up into subbasins. Newly formed local agencies must submit Groundwater Sustainability Plans (GSPs) for each subbasin. Each GSP must include management methods to avoid six "significant and unreasonable" risks:[11]

1. Depletion of supply from chronic lowering of groundwater levels
2. Reduction of groundwater storage
3. Seawater intrusion
4. Degraded water quality
5. Land subsidence
6. Adverse impacts from depletion of interconnected surface waters

Local agencies can avoid these risks by decreasing water demand, switching to non-groundwater sources to meet existing demand, and increasing groundwater supplies through artificial aquifer recharge.

The first round of GSPs for critically overdrafted basins were due to the California DWR in January 2020, and the Department released GSP evaluations in January 2022. Eleven out of 21 critically overdrafted basins are in the Central Valley.

Only eight GSPs were initially accepted, and none were from Central Valley subbasins.[12] While there are plan-specific critiques of the submitted GSPs regarding the level of accepted risk and where pumping happens within each subbasin,[13] there are also structural concerns with SGMA implementation.

***Figure 1*:** Critically overdrafted subbasins subject to SGMA guidelines. Each subbasin submits a groundwater sustainability plan (GSP) addressing how to end their groundwater overdraft by 2040. *Source: California Department of Water Resources. "Critically Overdrafted Basins." Retrieved Apr 2023.*

One major concern comes from the decentralized nature of SGMA implementation. While this structure is designed to recognize that aquifer characteristics, water supplies, and water demands vary by locale, there are concerns that local agencies developing plans in isolation from one another will not fully account for the water interconnections between subbasins. The Department of Water Resources itself has told water managers that inconsistencies between subbasins will not be considered until the 5 year check-in.[14] This largely comes from a logistical issue: it's impossible to know what the water budget submitted by one's neighboring subbasin might be or how it might plan to use shared water resources. This only becomes more complicated as water trading becomes more widely used in order to match water surpluses to areas with water needs, even as these tools are expected to be able to help contain the economic fallout of water restrictions.[15]

Coordination is particularly a problem when it comes to surface water, where the local groundwater agencies may claim to cut back on groundwater dependence by turning to surface water supplies without listing their legal rights to said surface water. This raises the concern that surface water is double-counted, the same cubic feet of water claimed by separate GSPs. The Public Policy Institute of California found that "more new water sources are claimed in GSPs than exists within the Central Valley Region".[16]

The second regional concern regarding SGMA implementation is the portrayal of the region's capacity to capture precipitation as groundwater recharge. Increasing recharge accounts for 42.7% of the Central Valley GSPs' planned water supply increases.[17] For this to be carried out as envisioned, recharge basins must be built so that the water can percolate down into the aquifer instead of being shunted out to sea, conveyance systems must be built to carry water to the recharge basins, and agencies must obtain the legal right to this water and prove that their use of this water for recharge does not affect another agency's downstream water right. With climate models predicting that California will see more of its precipitation through extreme precipitation events largely in the northern part of the state,[18,19] effective precipitation capture increasingly relies on building new infrastructure. The degree to which California will be able to overcome these challenges is yet unknown.

This thesis considered the plans submitted by the Central Valley's critically overdrafted basins in the first round of GSP submissions to predict their combined impact on Central Valley groundwater overdraft by 2040. This research studied the impact for several scenarios: one where GSPs are taken on face value and management plans have the expected groundwater savings; one where surface water supplies are capped to the amount Public Policy Institute of California finds is available in the region; and several scenarios where surface water is capped and artificial recharge is limited to 50%, 70%, and 90% of reported effect. While the actual amount of recharge that can be supported is yet undetermined, these represent three different scenarios that can help facilitate planning. This study aims to improve the understanding of the Sustainable Groundwater Management Act's impact on Central Valley groundwater levels and to quantify the effect of SGMA's structural limitations.

In order to model the effects of GSP implementation, this study used a groundwater modeling method developed in Massoud et al[20], estimating parts of the Central Valley's annual hydrologic budget by water-use sector and then calculating the cumulative impact of groundwater consumption from this. The estimates are derived through precipitation anomaly. In their paper, Massoud et al reported that their model calculations adequately match historical data from the Central Velley Hydrologic Model.[21] Massoud et al's methodology provides a way to use publicly available data to create estimates of groundwater consumption, a quantity notoriously hard to measure, much less predict. By creating an empirical model, Massoud et al is able to account for the impact of standard anthropogenic water uses despite the behavior-based nature of these actions. This study will add in the effect of GSP management strategies to model the long-term quantitative impact of these behavioral changes.

METHODS

The purpose of the model is to simulate changes in groundwater storage under historic and future conditions. This research found the historical relationships between precipitation and water budget sectors so as to use precipitation forecasts under climate change scenarios in Representative Concentration Pathways (RCP) 4.5 and 8.5 to estimate future water budgets and derive their impact on groundwater storage. This research draws on the groundwater storage change methodology established by Massoud et al and extends it to integrate GSPs to consider the previously unaccounted for effects of SGMA.

In the next sections, the methodology for estimating groundwater depletion will be outlined, then the modeled depletion will be compared against historical measurements, and finally future depletion will be predicted in scenarios with and without GSP management plans.

A. Modeling Groundwater Storage from Precipitation and Groundwater Budgets

This research uses a methodology developed by Massoud et al to empirically predict future groundwater change. That methodology will first be outlined here before it is expanded for the specific aims of this research.

This research relies on linear models that related precipitation anomaly and water budget sectors to estimate annual groundwater consumption. The net flow of groundwater in and out of storage each year is determined using consumption alongside Massoud et al's equation for groundwater recharge.

The linear models utilized precipitation anomaly and the correlations between precipitation anomaly and water budget sectors. Nine different supply and demand sectors are considered. For supply, the sectors are: Recycle & Reused Water, Groundwater, Local Water, Conveyance, Surface Storage. For demand, these sectors are: Urban, Agricultural, Wild Flows, Environmental Flows.

Each sector has an associated linear model with the form

$$Sector(t) = m * PP(t) + b \qquad (1)$$

where *Sector(t)* is the annual amount associated with each sector; for example, the quantity of water supplied by the groundwater sector in the year is represented as *GWpump(t)*. The values *m* and *b* are sector-specific parameters, and *PP(t)* is the value of the precipitation anomaly for year *t*.

After all *Sector(t)* equations were estimated, the water budget for each year was balanced. The sum of water demand sectors was divided by the sum of water supply sectors. The values for each of the supply sectors were then multiplied by this scale factor to make total supply meet total demand each year. This assumes that managers are more likely change water supply to meet demand than vice versa. Each supply sector would be impacted by this scaling, though this study is only concerned with the impact on the groundwater sector.

Then, annual recharge was found following Massoud et al's method. Massoud et al separated recharge into two components: α for precipitation recharge, and $\beta(t)$ for anthropogenic recharge from agriculture and percolation from surface reservoirs.

$$GWRecharge(t) = \alpha * PP(t) + \beta(t) \quad (2)$$

$$\alpha = 4.3\ km^3$$

$$\beta(t) = -0.6 * PP(t) + 6.9$$

Massoud et al derived this equation specifically for California's Central Valley using a Markov chain Monte Carlo simulation method to find the value for α and a linear model for β.

In the final step to find groundwater storage, the annual net flows of water were summed together to show the cumulative impact of managing groundwater. Annual groundwater storage change is given by:

$$\Delta GW\ Storage(t) = GW\ Recharge(t) - GW\ pump(t) \quad (3)$$

$$GW\ Storage\ (t) = GW\ Storage\ (t-1) + \Delta GW\ Storage \quad (4)$$

Data Organization

Precipitation and water budget data are the two types of data used throughout the model. The data sets are spatially bounded in different ways. *PP(t),* the precipitation anomaly values used throughout the model, were derived based on Central Valley-wide precipitation data to represent

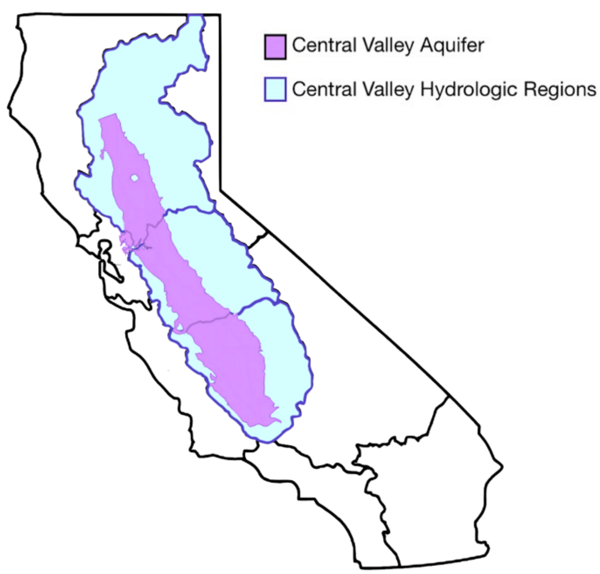

Figure 2: Precipitation data is derived from all three Central Valley Hydrologic regions (blue). These regions are, from north to south, Sacramento River, San Joaquin River, and Tulare Lake. The location of the Central Valley Aquifer is shown in purple.

the hydrologic interconnections between hydrologic regions (regions can be seen in *Figure 2*). Because northern water is imported to the south, southern water use is affected by whether or not the northern area had more or less precipitation than average.[22]

Water budget data, on the other hand, was separated by hydrologic region. Water budget data reflects what the water was used for. The different climate conditions for the regions make each hydrologic region's response to extended drought distinct.

B. Modeling Historical Data

i) Precipitation and Water Budget Sector Correlations

In this research, recent data were added in to update Massoud et al's results, and the exact sector groupings of supply and demand were altered to better match GSP management categories.

To model precipitation anomaly affecting the Central Valley, and to factor in the strong hydrologic interconnections between regions, precipitation data from the Sacramento River, San Joaquin Valley, and Tulare Lake hydrologic regions were used. Parameter-Elevation Regressions on Independent Slopes Model (PRISM) precipitation data for 1998-2016 was used to estimate precipitation for these years. The precipitation data for the three regions was normalized by the region's 30-year average, also provided by PRISM.[23] This yielded the precipitation anomaly for each year.

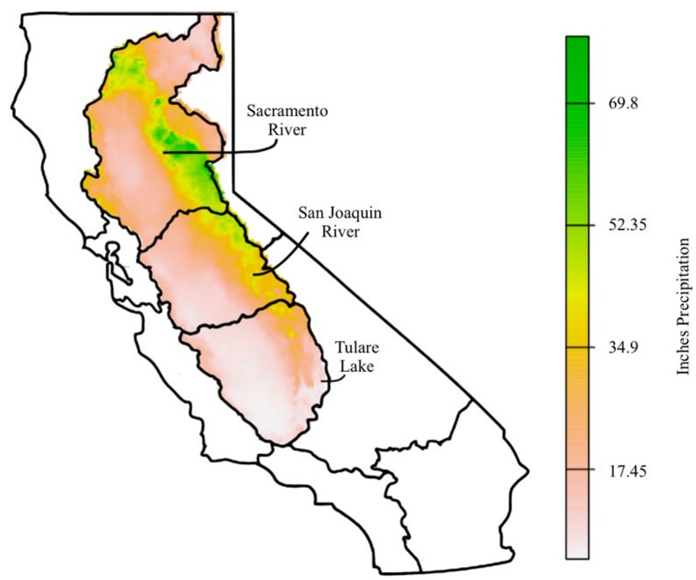

Figure 3: Hydrologic Regions of California. Department of Water Resources reports water budget data for each hydrologic region separately. PRISM precipitation data is visible in color. Most of the Central Valley is arid and receives water imported from the northern regions. Critically overdrafted basins are located in the San Joaquin and Tulare Lake hydrologic regions.

This research used historical data on water budgets from California's Department of Water Resources. The data was available by hydrologic region for 1998-2016.[24] As per the modified Massoud et al methodology described in the previous section, this water budget data was sorted into nine different supply or demand sectors.

A linear model was created correlating the quantity of water supplied or consumed by each sector with the precipitation anomaly for the years of 1998-2016. *m* and *b* values for equation (1) were taken from these correlations. To prevent water budget imbalance, supplies were scaled to meet projected demands.

These correlations were used for a backwards projection of the water budget for these years, shown in *Figure 4* alongside the Department of Water Resources reported water budgets.

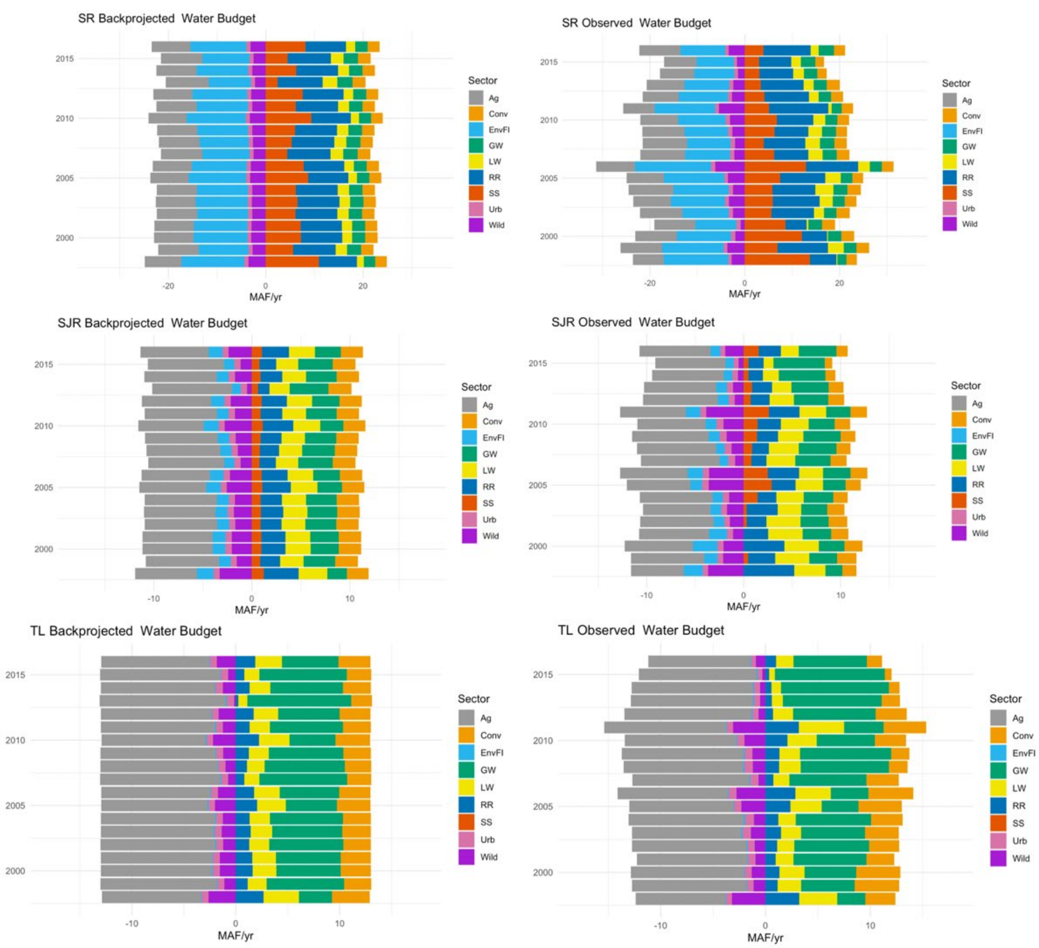

Figure 4: Water budget modeled (left) and as per the DWR measurements (right) for 1998-2016. The proportionally far heavier consumption of groundwater and use of water towards agriculture is evident in both the historical and modeled San Joaquin (SJR) and Tulare Lake (TL) hydrologic region water budgets. Most critically overdrafted basins are located in these hydrologic regions.

The PRISM-based precipitation anomaly data was used to calculate annual recharge using equation (2). Annual recharge and groundwater pumping (taken from the water budget) were used find annual groundwater storage change and cumulative groundwater storage impact over this period with equations (3) and (4).

ii) Verifying the Model

To verify the model, results were compared to GRACE satellite groundwater estimates and the Central Valley Hydrologic Model (CVHM). Both models compare present-day groundwater levels to the groundwater level in 1962, when comprehensive groundwater measurements for the Central Valley began to be recorded. GRACE does this by measuring annual groundwater changes and summing this to create the cumulative groundwater depletion estimates. CVHM is a three-dimensional hydrologic model that tracks how spatially defined water supply and demand across the Central Valley changes water availability.

Using the methodology in part *i)* of this section, Massoud et al found their model for groundwater storage change to accord with CVHM data (1981-2014) with a Root Mean Square Error value of 6.8km^3 and correlation coefficient of 0.9532. Massound 2018 declares this an acceptable error given the measurement error associated with CVHM and GRACE.[25] This thesis uses the same methodology, using updated precipitation and water budget data for 1998-2018.

The results with the updated data verify the accuracy of this methodology. The cumulative groundwater changes were compared to CVHM, GRACE, and the Public Policy Institute of California (PPIC)'s Department of Water Resources-based drawdown estimates (*Figure 5*).

Model results matched with GRACE with an R^2 = 0.89 and an average RMSE of 7.71 MAF. It matched CVHM with R^2 = 0.94 and an RMSE of 6.03 MAF. Given the measurement error associated with DWR data and the random errors associated with cumulative aquifer drawdown as calculated by GRACE, this is accepted as a reasonable average error.

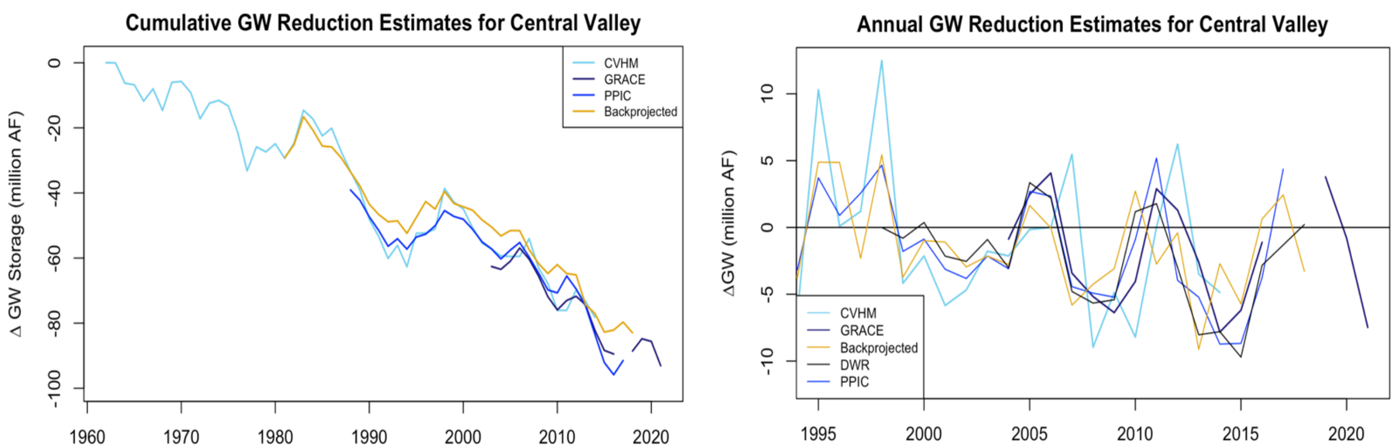

Figure 5: Cumulative aquifer drawdown from 1962, when comprehensive groundwater measurements started being made, and the x-axis year. GRACE measures changes in the gravitational field of the earth by measuring minute distances between two satellites orbiting at the same time. These changes in gravitional field are used to calcuate changes in mass, in this case assumed to be changes in groundwater inside the Central Valley's aquifers. Drought, like the 2014-2016 drought, is evident in the severe drop shown in this groundwater storage model. The back projected model developed here appears to have a more conservative estimate of how much groundwater is consumed in times of drought and acquifer recovery in wet years.

Table 1: Comparison of error between back projected model results and other methods of estimating groundwater depletion. Differences and RMSE given in million acre-feet. CVHM and GRACE measurements have random error

Comparison Between Measurement Methods	CVHM	GRACE	PPIC (DWR) Estimates
RSQ	0.94	0.89	0.96
Average Difference *(MAF)*	4.79	6.91	5.77
RMSE *(MAF)*	6.03	7.71	6.43

C. Predicting Groundwater Levels with GSP Implementation

The tested model was used to predict possible groundwater future scenarios. These included groundwater quantities in the case without SGMA, the case with all GSP management solutions applied without any restriction, and the case with limited GSP management solution implementation.

Water budgets for 2018-2040 were calculated through equation (1) using slope and intercept values from the linear models created and tested in the last section. Future *PP(t)* values were calculated from Coupled Model Intercomparison Project Phase 5 (CMIP 5) precipitation predictions, publicly available California's Cal-Adapt Dataset. The annual values from these models were normalized by the most recent historical 30-year average to maintain consistency in calculating *PP(t)*. This study utilizes all ten of the precipitation models used in the ensemble. Annual precipitation values for both RCP 4.5 and RCP 8.5 scenarios were used.

Equation (2) was used to estimate groundwater recharge that would come from already existing recharge systems. To "implement" GSP management strategies in the model, equation (3) was modified to be:

$$\Delta GW\ Storage(t) = GW\ Recharge(t) - GW\ pump + GSP(t)$$

With *GSP(t)* as the millions of acre-feet of reduced groundwater demand or increased groundwater supply as per GSP management strategies for critically overdrafted basins.[‡]

This research used the Public Policy Institute of California's "San Joaquin Valley GSP Supply and Demand Projects" database to find each strategy's description, first year of implementation, and average annual benefit at full implementation.[26] The Public Policy Institute of California pulled data directly from the submitted GSPs. Based on the strategy description, strategies for each subbasin were sorted into three categories: immediate implementation, gradual implementation, surface water, and unlikely. These categories dictated how much of the average annual benefit at full implementation would be counted towards groundwater savings and when.

Those in the immediate category would count their full annual benefit towards the yearly groundwater budget upon the first year of their listed implementation. Benefit from gradually implemented plans were logarithmically scaled up beginning in their first listed year of implementation. Surface water and unlikely categories would be immediately implemented in a face-value model but excluded or limited in a capped scenario.

[‡] Subbasins for Hydrologic Region: **San Joaquin River -** Chowchilla, Delta-Mendota, Eastern San Joaquin, Madera, Merced. **Tulare Lake -** Kaweah, Kern, Kings, Tulare Lake, Tule, Westside. There are no critically overdrafted basins in the Sacramento River hydrologic region and therefore no first round GSP management plans for analysis.

Plans were categorized in "immediate implementation" when implementation was associated with no quantifiable obstacle to their implementation. In 2040, these plans make up 1.08 MAF of the annual groundwater replenishment.

Several different types of plans were considered to qualify as "gradual implementation". These included plans that had no listed initial year of implantation and plans that associated some overdraft savings with an education program, pumping fees, or land buyback programs. Those programs were expected to have lower than full groundwater savings in the early years of the program. In 2040, these plans make up 0.35 MAF of the annual groundwater replenishment.

Management plans that relied on increased surface water supplies were listed in the surface water category. Such plans include those for surface water trading, surface water treatment, drawing new supplies from surface storage facilities, and recycled water that ends up as consumptive use rather than flowing downstream to be used as agricultural or recharge water. In a face-value scenario, these are, in effect, no different than immediately implemented GSPs. In 2040, these plans make up 0.75 MAF of the annual groundwater replenishment.

Surface water plans were flagged because they are structurally suspect. Double-counting is made possible by decentralized planning and the lack of water rights associated with GSPs. Given the propensity to balance the water budget by assuming new water supplies rather than managing demand, the availability of water for

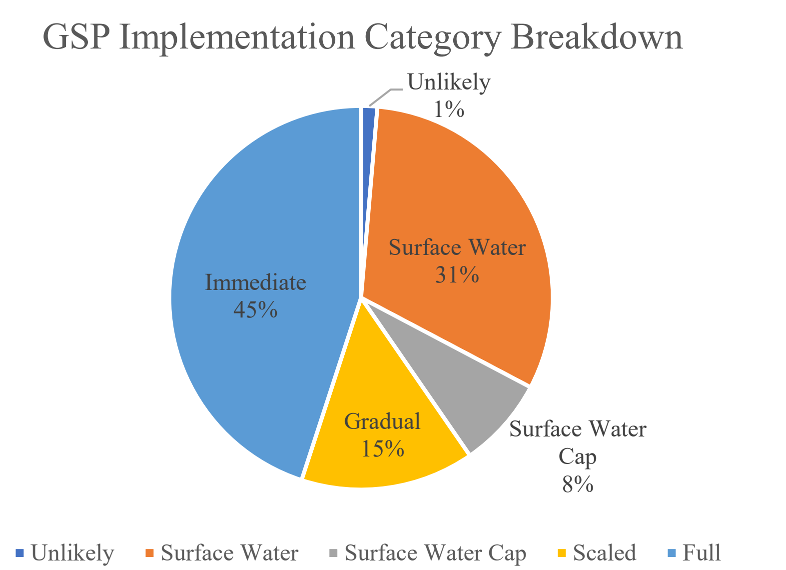

Figure 6: 76% of the groundwater savings came from plans assumed to have the immediate face-value impact at the year of implementation. These were from "full", "surface water", "surface water cap", and "unlikely" categories. 15% of groundwater savings came from plans that were gradually implemented ("scaled"). When analyzing face value implementation, all of these savings are included. When analyzing capped scenarios, "surface water cap" and "unlikely" savings were excluded.

these projects demands more strict scrutiny. Structural critiques also focus on a lack of surface water availability. The Public Policy Institute of California estimated that the amount of surface water available as new supplies for GSA usage likely extends up to a maximum of 0.57 MAF/yr.[27] Central Valley GSPs collectively claim new surface water usage above this value in the implementation for the year 2023.

A new category of capped surface water-dependent GSPs was created to model this limitation. The capped surface water category had the same annual increases as the uncapped surface water category until 2023. From 2023 on, both hydrologic regions were assumed to use surface water-dependent management plans such that the aggregate annual benefit summed to 0.57 MAF, removing the benefit of 0.18 MAF of annual benefit by 2040.

Projects categorized as "unlikely" included those few that referred only to recharge projects that did not list where the recharge would take place or those that implemented "pumping location shifts" rather than decreasing the amount of groundwater to be pumped in the basin.[§] In 2040, these plans make up 0.03 MAF of the annual groundwater replenishment.

The cumulative annual benefit from GSPs were found for years 2018-2040, with benefit from plans first implemented from before 2018 included.

The model would consider three different functions for *GSP(t)*.

No GSP Implementation	Face-value Implementation	Capped Implementation
GSP(t) = 0	GSP(t) = *immediate* + *gradual* + *full surface water plans* + *unlikely plans*	GSP(t) = *immediate* + *gradual* + *capped surface water*

Each case was calculated for precipitation projections for both RCP 4.5 and RCP 8.5.

[§] These projects are included in the GSPs as management solutions not to balance the subbasin's groundwater budget but rather aim to prevent further drawing down groundwater in one particular area in order to prevent adverse effects such as seawater intrusion. Such plans are expected to be groundwater neutral regionally.

Also in question with SGMA's implementation was the viability of recharge to provide the reported annual increase of groundwater supplies by 0.96 MAF in 2040. Given that the recharge parameter comes from skepticism about the capacity to build enough recharge infrastructure rather than from a physical natural resource limitation, it was necessary to consider multiple scenarios of implementation. For the sake of this research, 0%, 50%, 70% and 90% recharge success were considered.

For the capped implementation scenario only, equation (3) became:

$$\Delta GW\ Storage(t) = GW\ Recharge(t) - GW\ pump + GSP(t) - Recharge(t) * Scale$$

Where *Recharge(t)* is the annual groundwater savings for year *t* provided by recharge according to the Public Policy Institute of California's categorization of groundwater sustainability plans. Scale is 0, 0.5, 0.7, or 0.9 depending on the scenario.

After the modified equation (3) was used to find net annual groundwater flows, or $\Delta GW\ Storage(t)$, equation (4) was used to find the long-term impact of these net flows, $GW\ Storage(t)$. Equation (4) started by assuming that in 2018 the groundwater storage was equal to the amount predicted by the historical model developed earlier in section B, and was calculated out until the year 2040.

RESULTS

This model predicts significant decrease in groundwater storage if there is no GSP implementation. Between 2018 and 2040, it finds a loss of 40.26 MAF in an RCP 4.5 scenario and of 34.12 MAF in an RCP 8.5 scenario. In contrast, if GSPs are taken at face-value and each management plan is assumed to be capable of providing its full expected groundwater savings, then groundwater levels are expected to increase by 0.55 in an RCP 4.5 scenario and of 3.32 MAF in an RCP 8.5 scenario in the same time frame. Groundwater levels in 2040 under different scenarios can be seen in *Figure 7* and *Table 2*.

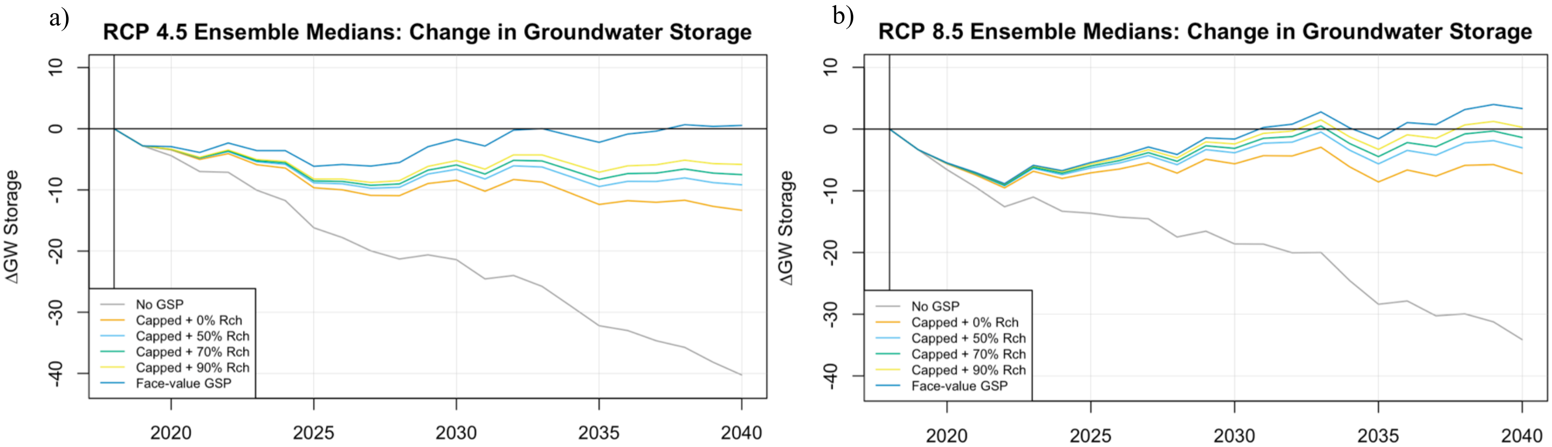

Figure 7: Median values for cumulative change in Central Valley aquifer level from 2018-2040 for RCP 4.5 (a) and RCP 8.5 (b).

Table 2: Total depletion compares 1962 and 2040 aquifer levels. Depletion under SGMA compares 2018 and 2040 storage. Median model results of ten different precipitation projections under different GSP implementation scenarios are presented.

Aquifer Storage Levels (MAF)				
	RCP 4.5		RCP 8.5	
	Total depletion	Depletion under GSP implementation	Total depletion	Depletion under GSP implementation
No GSP	-123.2	-40.26	-117.07	-34.12
Capped + 70% Recharge	-90.45	-7.50	-84.31	-1.37
Face Value Implementation	-82.40	0.55	-79.62	3.32

In the no-GSP, face-value GSP, and capped with limited recharge scenarios, climate scenario did not affect the long term trend. The ensemble model for RCP 4.5 had a lower degree of agreement than RCP 8.5 as the standard deviation of the various groundwater level predictions in 2040 for RCP 4.5 was 22.17 while RCP 8.5 had a standard deviation of 12.89. The trends and discrepancy are displayed in *Figure 8*. Model predictions that are based on CNRM-CM5 precipitation projection data skew the data right. As the median represents the central tendency of a skewed dataset, this is the value considered for the results.

Only in the face-value implementation scenario does any RCP 4.5 scenario achieve recovery. All other scenarios result in between 5 MAF and 15 MAF groundwater storage loss. When surface water is capped and recharge implementation ranges from 0% - 90%, GSPs result in a groundwater level between 26.92 and 34.42 MAF higher than the no-GSP scenario. The 26.92 MAF groundwater savings in the 0% recharge scenario is the savings from non-recharge management plans, and recharge accounts for over 7.50 MAF of groundwater savings.

Two implementation scenarios achieve groundwater sustainable yield with RCP 8.5: face-value implementation and capped surface water + 90% recharge. In 2040, the capped surface water + 0% recharge scenario predicts a 7.20 MAF groundwater loss. This is the lowest predicted groundwater depletion amount outside of the no GSP scenario, and it is higher than the no GSP scenario by 26.93 MAF. Again, this value reflects the impact of non-recharge management plans. Groundwater losses for each RCP 8.5 scenario are less severe than the RCP 4.5 scenario.

While average annual groundwater depletion from 1962-2014 was -1.5 MAF/year,[28] the median for every GSP implementation scenario cut this rate by at least half for the 2018-2040 period (*Table 3*).

Table 3: Average rates consider the rate at which groundwater levels must have depleted each year to achieve the modeled 2040 aquifer levels for each implementation scenario.

	Average Annual Depletion (MAF/year)					
	No GSP	Capped + 0% Recharge	Capped + 50% Recharge	Capped + 70% Recharge	Capped + 90% Recharge	Full GSP
RCP 4.5	-1.83	-0.61	-0.42	-0.34	-0.27	0.02
RCP 8.5	-1.55	-0.33	-0.14	-0.06	0.01	0.15

In RCP 4.5, the groundwater model based on CRNM-CM5 precipitation indicated significant aquifer recovery even in the no GSP implementation scenario (*Figure 8*). There are two major differences with regard to CNRM-CM5 precipitation projections and the other projections: 1) net precipitation was higher than in other projections, and 2) CNRM alone exhibit a significant positive correlation between year and annual precipitation.

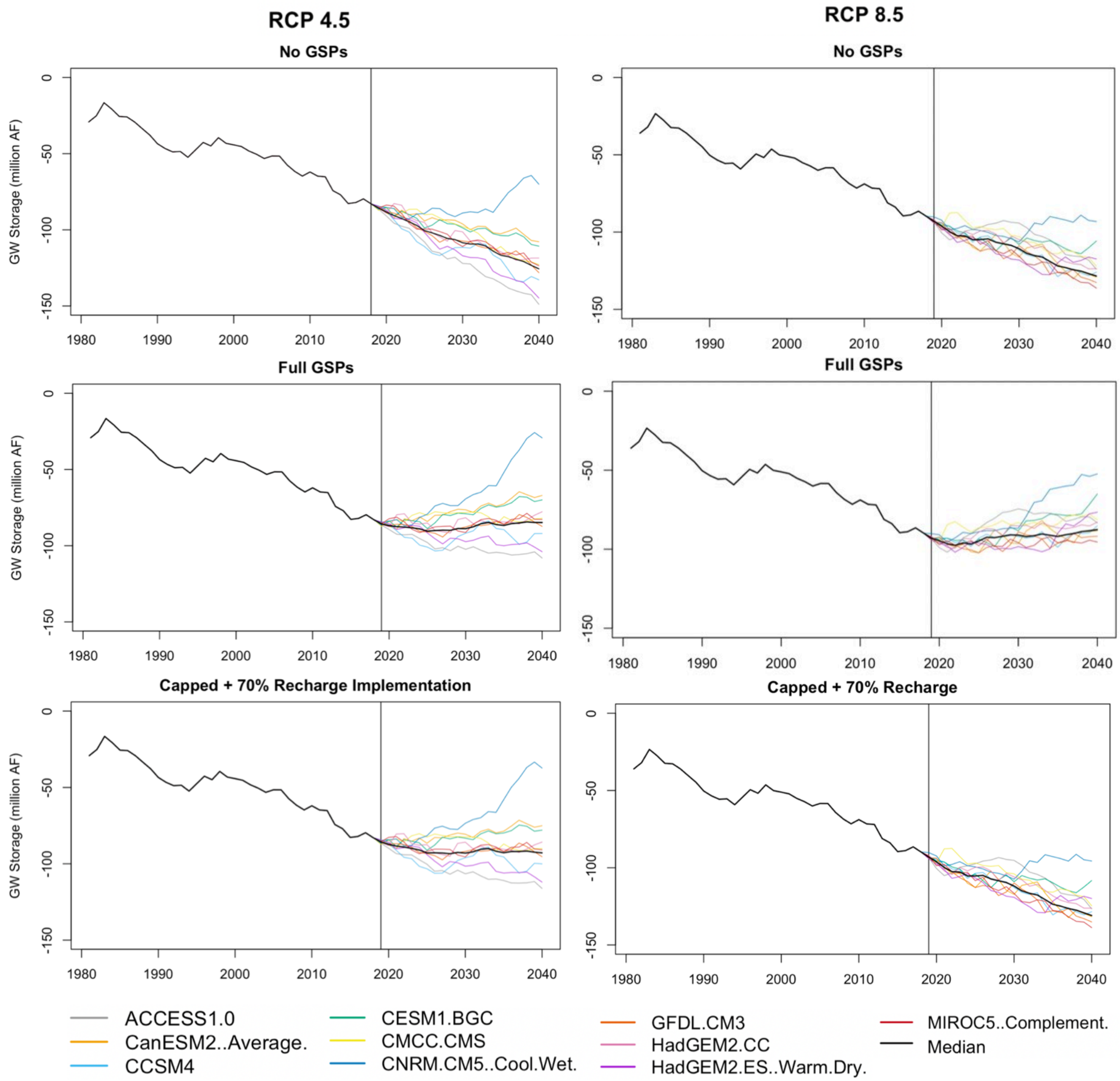

Figure 8: Historical Central Valley overdraft from 1960-2018 and projected aquifer response to anthropogenic uses and various levels of mitigation efforts for 2018-2040. All preciptiation models are taken from CMIP5 projections for California, available from the Cal-Adapt database. Average overdraft is calculated by averaging the results of the ensemble model.

The difference in total annual recharge 2018-2040 for CNRM-CM5 and the next highest precipitation prediction is 159.0 inches. The maximum difference in annual rainfall between precipitation predictions that are associated with declining aquifer levels was 147.5 inches. Comparisons between total precipitation are shown in *Figure 9*.

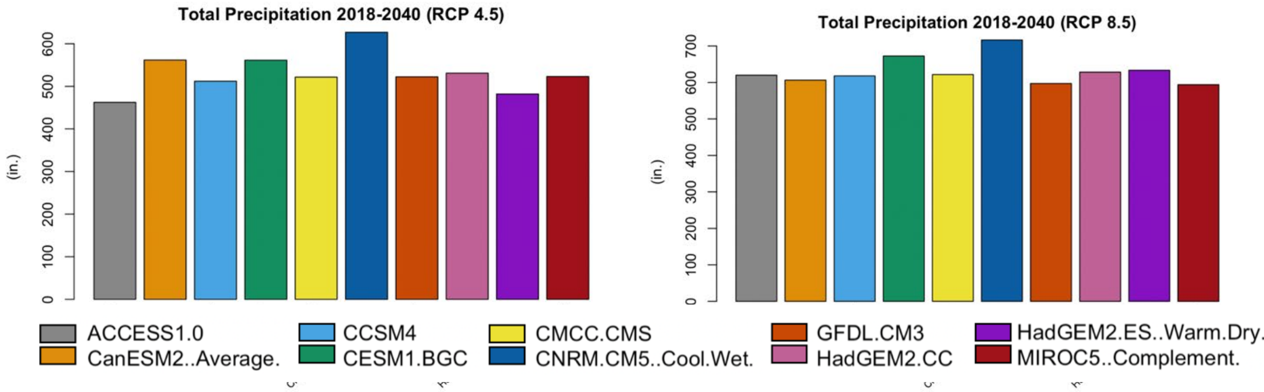

***Figure 9*:** total precipitation for the Central Valley region for years 2018-2040.

CNRM-CM5 and year were correlated with an average slope 0.124 in precipitation increase per year with a p-value of 0.0008. No other precipitation projection had a correlation between precipitation and year with a p-value lower than 0.05 (next lowest p-value was 0.22, associated with CMC-CMS). To test the importance of this correlation, a trial was run where the precipitation values for 2019-2040 were randomized. The test results in an RCP 4.5 climate scenario with no GSP implementation are compared in *Figure 10.*

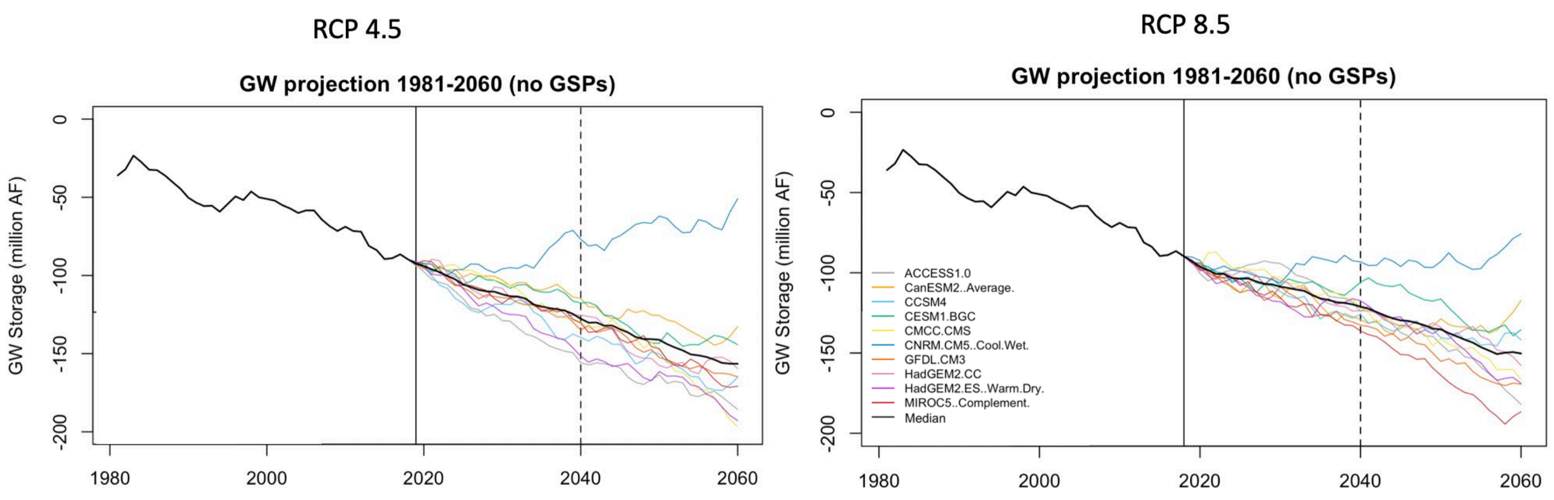

***Figure 10*:** Comparison between the model results with the original CNRM-CM5 data (left) and with CNRM-CM5 precipitation data randomly assigned to years within the 2018-2040 range (right).

The uniqueness of CNRM-CM5 was not affected by randomization. In the non-randomized scenario, the model using $PP(t)_{CNRM\text{-}CM5}$ predicted groundwater storage would be 29.51 MAF higher than it was in 2018. With the randomized $PP(t)_{CNRM\text{-}CM5}$ values, the model predicted groundwater storage would recover by 12.85 MAF.

DISCUSSION

California's long history of agricultural water use and recent megadrought underscores the importance of successful groundwater management. SGMA served as a milestone in California's political capacity to create a framework to try to manage groundwater, but the actual implementation of this will be a long and arduous process that requires continuous monitoring to establish the success of the management strategy along the way. This research serves this function.

This research uses Massoud's empirical method for estimating groundwater change by using updated data and generates estimates of historic groundwater consumption that remain within CVHM and GRACE measurement errors. By combining multiple different sets of water-related data, it is possible to conduct a Central Valley basin-wide audit of regional groundwater.

The similarity between an RCP 4.5 and RCP 8.5 scenarios indicates that when taken on an annual basis the climate scenario does not significantly change what management strategies are necessary to control long-term groundwater levels. The time granularity of this is essential. The interannual variability associated with precipitation and water availability mandates that groundwater management strategies are evaluated on a long-term basis.

In both RCP 4.5 and RCP 8.5, GSP implementation in all scenarios exhibits great success in slowing groundwater consumption. This in and of itself would be a historic achievement considering the long-term continued trend of groundwater depletion even when new surface water infrastructure began to carry new water to the Central Valley. Further, despite critiques about GSPs not accounting for surface water quantity limitations or considering the viability of building new recharge infrastructure, this model predicts that these limitations only limit the impact of GSPs by about 20-30% within each climate scenario.

Without GSPs, groundwater levels decline faster than the historic average. In the face-value implementation scenario, groundwater levels stabilize around 2018 groundwater levels. If GSPs are able to bring this about, California could avoid the major drinking water and infrastructure risks that plagued it in the 2012-2016 drought. By maintaining a regionally higher groundwater level, fewer management plans would have to focus on maintaining groundwater levels in a particular area – for example, fewer mitigation efforts would have to be made to contain sea water intrusion or to prevent streamflow depletion.

Groundwater planners, however, ought to consider their risk tolerance as this study has evaluated the effect of the central tendency of the ensemble model. Differences between precipitation models and the median value are at times higher than the difference between GSP implementation scenarios.

The anomalous scenario of CNRM-CM5 in RCP 4.5 is also instructive with regards to how and why precipitation is important. This scenario alone led to an increase in aquifer levels with no GSP management plans implemented, which seems improbable. Importantly, this increase in aquifer levels was reflected even when CNRM-CM5's correlation between year and precipitation projection was removed. The unique model result depended on the higher net amount of precipitation. With higher precipitation, more surface water is available for use and groundwater stores do not need to be drawn upon. Simultaneously, more water is diverted to recharge.

Given that the same no-GSP scenario yields both negative and a positive trend results in long-term storage, there may be a tipping point where enough precipitation, or enough groundwater mitigation efforts, can bring about aquifer recovery beyond even the point of deep drought California faced in 2018. Further research ought to explore more about where this tipping point is situated and why, as well as whether or not it's possible to determine if we are in a CNRM-CM5 type scenario or are on the other side of the tipping point. Given that only CNRM-CM5 exhibited this trend, it seems unlikely that California will find itself in this type of scenario.

Because net precipitation over some period was more important the distribution of precipitation within those years, the CNRM-CM5 case reiterates that change in groundwater storage at a certain date is mostly path-independent. This model indicates that water budgets under SGMA will not encounter structural issues as a result of California's predicted increase in "whiplash" precipitation years. Whiplash precipitation occurs when years that have 90th percentile drought are immediately followed by years with 90th percentile precipitation.[29] Subbasins will have to maintain their groundwater protection measures during these years in order to see the predicted long-term recovery.

This study does not consider the timing of precipitation within the course of a year. This factor could have significant impacts on the practical implementation of GSPs. Flooding threats and recharge basin limitations, in particular, could challenge this model's assumption of linear relationships between precipitation and water budget sectors. When water is released from surface water storage to prepare for an influx of new water from precipitation events or snowpack melt, this water is no longer available to be used according to GSP management plans. This empirical model accounts for this behavior, but there will be an increased gap between the results of this model and actual future groundwater levels if managers must increase the frequency of this behavior due to changing intra-annual precipitation patterns.

Similarly, timing of water availability may change the precipitation recharge component of equation (2), $\alpha + PP(t)$. If precipitation events become more extreme, the ratio between precipitation recharge and total annual precipitation may decrease due to soil saturation during precipitation events. A higher ratio of the water is likely to travel immediately into streams and rivers instead of percolating into the soil. Once again, more extreme precipitation events would lead to a gap between model results and effective recharge. This issue can be helped by building infrastructure to capture this runoff in surface storage infrastructure or stormwater injection wells. This builds up the β part of equation (2). If the β component can increase at the same rate that the α value decreases, equation (2) results will remain the same and this model's predictions will remain accurate. This requires a high degree of coordination in conjunctive surface and groundwater management. If management needs require that water is not used for recharge, the recharge limited scenarios in this research provide information on the expected results on aquifer levels.

While this methodology is limited in its capacity to do analysis on a finer spatial resolution, it has been able to quantify the long-term impact of some structural weak points in SGMA. Limiting surface water to 0.57 MAF/yr does not have a significant long-term impact on the success or failure of groundwater sustainability plans, and limiting recharge only has moderate impact. This research, then, supports SGMA as an effective piece of legislation for the purposes of protecting aquifer health. Groundwater Sustainability Agencies ought to determine their risk tolerance, identify the amount of recharge infrastructure they can afford to build out, and manage their subbasin accordingly.

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