Groundwater Depletion in California's Central Valley Accelerates During Megadrought

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Abstract

Groundwater provides nearly half of irrigation water supply, and it enables resilience during drought, but in many regions of the world, it remains poorly, if at all managed. In heavily agricultural regions like California's Central Valley, where groundwater management is being slowly implemented over a 27-year period that began in 2015, groundwater provides two-thirds or more of irrigation water during drought, which has led to falling water tables, drying wells, subsiding land, and its long-term disappearance. Here we use nearly two decades of observations from NASA's GRACE satellite missions and show that the rate of groundwater depletion in the Central Valley has been accelerating since 2003 (1.89 km^3/yr, 1961–2021; 2.41 km^3/yr, 2003–2021; 8.57 km^3/yr, 2019–2021), a period of megadrought in southwestern North America. Results suggest the need for expedited implementation of groundwater management in the Central Valley to ensure its availability during the increasingly intense droughts of the future.

1 Introduction

Groundwater is a critical component of freshwater supplies for human life, for ecosystem and hydrological processes, for agricultural production, and more (1). Groundwater is the major water source for roughly a third of the global population, and it supplies nearly half of the water used for irrigation (2). However, groundwater resources have been under considerable stress around the world (2–6), including in the arid and semi-arid western United States, where groundwater management is in its infancy (7), where groundwater overuse is common (7–8), and where climate change and changing hydrologic extremes are reducing opportunities for aquifer replenishment (9–10).

Among the western states, California is the most populated, as well as the most productive agricultural region, both of which place heavy demands on freshwater resources. During the California droughts of the past two decades, surface water supplies decreased significantly, resulting in an increased reliance on groundwater pumping (11–13). Groundwater supplies roughly two-thirds of California's water supply during droughts, compared to one-third in non-drought conditions (12). Drought-inducing weather patterns have been observed more frequently in recent years (14), while the last two decades correspond to a period of megadrought in southwestern North America (15). These climatic changes have the potential to greatly intensify the stress on groundwater resources in the coming decades.

California's Central Valley is shown in Fig. 1. The region encompasses the Sacramento, San Joaquin, and Tulare basins, the major water sources for which are the mountain snowpack of the Sierra Nevada range. As one of the most important agricultural regions in the U.S., the Central Valley supplies 25% of the food consumed by the nation, with an estimated value of $17 billion per year, or 8% of the U. S. agricultural output by value (11). However, widespread irrigated agriculture and a significant increase in permanent crops, such as vineyards and orchards, make it a region of extremely high groundwater consumption: the Central Valley is the second most-pumped groundwater aquifer system in U.S. (13).

In addition to a shortage of renewable freshwater, overpumping groundwater has led falling to water tables, streamflow depletion, declining water quality and wells running dry (2), as well as to environmental hazards such as land subsidence (16–17), and wastewater intrusion (18). To combat these threats, California enacted its Sustainable Groundwater Management Act (SGMA) in 2014, requiring highly-impacted regions such as the Central Valley and its groundwater basins to develop and implement management plans to achieve sustainable levels of groundwater pumping and recharge by 2042 (19–20). In response to SGMA, or to any groundwater management plan, it is essential to accurately monitor and characterize groundwater dynamics.

Traditional *in situ* water table depth measurements from wells are the most direct approach to monitoring groundwater levels. However, it can be challenging to construct an accurate picture of groundwater levels from well data scattered across a large domain. A high density and fairly uniform distribution of wells are required across the region of interest, which is costly, not typically available, and difficult to compile and standardize if they were (19). Therefore, to characterize groundwater dynamics at the state, groundwater basin, or watershed scales, complementary studies have been conducted using either hydrologic modeling (11, 13, 20–22) or remotely-sensed observations (12, 17, 23–27). Although hydrologic modeling is capable of estimating groundwater variations at high spatial and temporal resolutions, conventional land surface models, e.g., the Noah-MP model (28), omit consideration of human activities such as groundwater pumping, which can dominate the groundwater storage signal in heavily-pumped regions. Hence, groundwater losses in intensively-irrigated agricultural areas such as in the Central Valley are underestimated (29), particularly during droughts. The development of comprehensive groundwater models that include irrigation, farm practices, land subsidence, and other key processes, e.g. the Central Valley Hydrologic Model (CVHM), developed by the U. S. Geological Survey (USGS) (11, 13), is a major advance in modeling aquifer-scale groundwater behavior. However, like most surface and groundwater models, it requires large amounts of monitoring well observations for model calibration and implementation. This is a labor-intensive, expensive and time-consuming process that may be most suitable for detailed applications and investigations at regional scales.

Studies using remotely-sensing observations have demonstrated proficiency of satellites for providing complementary information on groundwater dynamics in an efficient manner (30), often over very large areas. For example, Liu et al. (2019) and Neely et al, (2021) (17, 27) observed land surface subsidence using Interferometric Synthetic Aperture Radar (InSAR) in high groundwater demand areas. Earth surface deformation in those regions was attributed and correlated to changes of groundwater storage. The Gravity Recovery and Climate Experiment (GRACE) satellites, and its follow-on (GRACE-FO) mission, accurately and routinely measure earth's time-variable gravity field, which is dominated by the redistribution of water over the globe (31). Since the first GRACE mission was launched in 2002, it has allowed for tracking variations in total water storage (TWS; i.e. all of the snow, surface water, soil moisture and groundwater combined) at monthly and longer timescales, for regions that are 150,000 km^2 or larger (32). The groundwater component of TWS can be isolated using a water storage balance approach (33) by incorporating other hydrological measurements and estimates for snow water equivalent (SWE), and surface water and soil moisture storage. GRACE and GRACE-FO, hereafter referred to GRACE/FO, have been widely used to estimate groundwater storage changes (12, 23–25, 34–35) and to monitor hydrological drought (26, 36–37). While the GRACE/FO satellite-based approach lacks the spatial and temporal detail of hydrological models, it generally corresponds well with model simulations and *in situ* water balance and groundwater observations, and provides a reliable large-scale view of groundwater dynamics that is otherwise difficult to construct.

Famiglietti et al. (2011) (12) integrated TWS anomalies measured from GRACE with estimates of SWE from National Oceanic Atmosphere Administration's Snow Data Assimilation System (SNODAS) (38), soil moisture from NASA's North American Land Data Assimilation System (NLDAS) (39), and *in situ* observations of surface water storage from the California Data Exchange Center (40) to quantify groundwater storage variations in the Central Valley from 2003–2010. The goal of the present study is to use the nearly two decades of GRACE/FO observations to understand the longer-term dynamics of Central Valley groundwater, including their response to changing extremes of wet and dry periods, water management, and to the knowledge that SGMA will be entering its implementation phase within the next few years. Specific objectives of this study are to 1) retrospectively quantify phases of groundwater recharge and loss by integrating GRACE/FO-derived TWS with other terrestrial water components for the past two decades; 2) examine GRACE/FO-derived groundwater storage changes in the context of longer-term decadal trends and observations; 3) better understand the relationship between surface water allocations by the State of California and the U. S. federal government to estimated groundwater storage changes; and 4) to demonstrate the capability of GRACE/FO-derived groundwater storage changes to support regional groundwater management efforts, such as California's SGMA.

2 Results

Groundwater storage variations were calculated using TWS anomalies for the Sacramento, San Joaquin and Tulare basins (Fig. 2(A)) and subtracting the anomalies of soil moisture, surface water, and SWE (Fig. 2(B)) (see Material and Methods). Figure 2(C) shows observations of precipitation (P), evapotranspiration (ET) and stream discharge (Q) for the river basins, while Fig. 2(D) shows a close correspondence between dS/dt derived from GRACE/FO, and that computed using P – ET – Q in Eq. 1. The good agreement between GRACE/FO-derived and observed dS/dt demonstrates that GRACE/FO is capable of accurately monitoring basin-wide water balance changes, and provides further confidence in the groundwater estimates described below (12). Figure 3(A) shows the monthly groundwater storage anomalies derived from GRACE/FO and the datasets shown in Fig. 2(A and B) in the Central Valley between September 2003 and December 2021. Figure 3(A) shows that three notable periods of groundwater recharge and loss were identified in the past 18 years. Recharge periods are from October 2003 to July 2006, March 2011 to July 2011, and October 2018 to August 2019. Groundwater loss phases correspond to the well-known droughts that occurred during that time period, namely August 2006 to February 2011, August 2011 to March 2017, and since September 2019. Estimated rates of groundwater gains and losses are summarized in Table 1.

Table 1

Groundwater change rate and total volume changes in Central Valley. The signs of – and + indicate groundwater losses and gains, respectively.

	Change Rate (mm/yr)	Change Rate (km^3/yr)	Volume Change (km^3)
Oct. 2003 – Jul. 2006	+ 22.8 ± 16.0	+ 3.50 ± 2.46	+ 9.9 ± 4.1
Aug. 2006 – Feb. 2011	-42.9 ± 7.8	-6.59 ± 1.20	-30.2 ± 2.6
Mar. 2011 – Jul. 2011	+ 257.7 ± 20.3	+ 39.60 ± 3.12	+ 16.5 ± 2.0
Aug. 2011 – Mar. 2017	-42.6 ± 5.8	-6.55 ± 0.89	-37.1 ± 2.1
Oct. 2018 – Aug. 2019	+ 189.4 ± 108.2	+ 29.10 ± 16.63	+ 25.8 ± 15.9
Sep. 2019 – Dec. 2021	-55.8 ± 21.8	-8.57 ± 3.35	-20.0 ± 5.1
Sep. 2003 – Aug. 2017 (Lifetime of GRACE)	-19.4 ± 2.1	-2.98 ± 0.32	-41.7 ± 1.2
Sep. 2003 – Dec. 2021	-15.7 ± 1.4	-2.41 ± 0.22	-44.2 ± 0.9
1962–2021	-12.3 ± 0.8	-1.89 ± 0.12	-113.4 ± 0.9

A period of groundwater recharge (22.8 ± 16.0 mm/yr; 3.50 ± 2.6 km^3/yr) in the Central Valley was observed at the beginning of the GRACE mission during 2003–2006, when the precipitation amounts were close to or slightly higher than the 20-year average. The NOAA National Weather Service report (41) reveals that weak to moderate levels of El Niño events during 2004–2006 resulted in nearly normal amounts of precipitation and snow in the study region. A volume of 9.9 ± 4.1 $km^3$of groundwater was replenished during this phase of the analysis.

This period of groundwater storage increase was followed by the 4.5 year long drought that began in August 2006. During the 2006–2011 drought, a groundwater loss rate of 42.9 ± 7.8 mm/yr (6.59 ± 1.20 km^3/yr) was estimated, resulting in 30.2 ± 2.6 km^3 of groundwater loss during that period. Compared with the earlier analysis in (12), an additional year of data was included here, and represented the complete drought phase through 2011, rather than through 2010, as in (12). Although the groundwater loss rate is slightly higher than the 38.9 ± 9.5 mm/yr reported in (12), the difference falls within the 95% confidence interval, confirming the consistency between the two analyses. The analysis was also conducted in each of the three basins in Fig. 1, as shown in Fig. S1 and Table S1 in Supplementary Materials. It shows that the Sacramento, San Joaquin, and Tulare basins all experienced similar groundwater loss rates of ~ 42 mm/yr (40–44 mm/yr).

Prior to the second drought, a short, rapid recharge phase (March - July 2011) replenished 16.5 ± 2.0 km^3 of groundwater (257.7 ± 20.3 mm/yr; 39.60 ± 3.12 km^3/yr), as a result of the strong El Niño in 2010 that brought abundant precipitation in early 2011 (42).

The groundwater loss rate for the second phase of drought in the GRACE/FO record (2011–2017) was –42.6 ± 5.8 mm/yr (6.55 ± 0.89 km^3). Although a similar groundwater loss rate was estimated for the drought of 2006–2011, the second drought lasted a year longer, resulting in roughly 7 km^3 more groundwater loss (-37.1 ± 2.1 km^3 total), equivalent to about 23% of surface water storage in the Central Valley, and greater than the volume of Lake Mead (35 km^3) at full capacity. The GRACE/FO-based groundwater storage changes estimated in this study reached an 18-year low by late 2016. This phase of drought was notable for widespread water conservation efforts across California, and for the passage of SGMA in 2014. The drought ended with atmospheric river events that brought heavy precipitation to California in early 2017 (43). Table S1 shows that during this period, the Tulare basin suffered more severe groundwater losses than the other basins, with a loss rate of 62.6 ± 4.4 mm/yr (-2.66 ± 0.18 km^3/yr). The total groundwater loss in the Tulare basin was 15.1 ± 0.4 km^3, which was nearly 40% of the total loss in Central Valley, yet the area of the Tulare basin only occupies about one quarter of the study region.

The original GRACE mission was decommissioned in late 2017 and transitioned to GRACE-FO after its launch in May 2018. Hence there is year-long data gap in the combined GRACE/FO record from August 2017 – September. 2018. Studies of that time period (19, 27) suggest that groundwater recharge occurred during this data gap. We estimate that during the lifetime of original GRACE mission (2003–2017), 41.7 ± 1.2 km^3 of groundwater were lost (Table 1).

We assume that the groundwater depletion followed the 18-year historical trend (2003–2021), but made no assumption about its seasonal dynamics during the data gap between the GRACE and GRACE-FO missions. From October 2018 to August 2019 we estimated that groundwater storage increased by 25.8 ± 15.9 km^3 (189.4 ± 108.2 mm/yr; 29.10 ± 16.63 km^3/yr).

The third phase of drought in the GRACE/FO record began in September 2019. After the recharge event in the winter of 2018, the major water inputs in the region, including SWE and precipitation, significantly decreased in winters of 2019 and 2020 (Fig. 2 (B and C)). These two winters rank the years 2019 and 2020 as fourth driest consecutive 2-year period on record (44). In particular, precipitation reached an 18 year low in the winter of 2020 (Fig. 2(C)), and TWS shows this same time period as the driest wet season in the GRACE/FO record. Between September 2019 and December 2021, total groundwater losses in the Central Valley were 20.0 ± 5.1 km^3 (55.8 ± 21.8 mm/yr; 8.57 ± 3.35 km^3/yr), which is roughly31 % faster than the previous two droughts.

Overall (2003–2021), groundwater storage changes observed from GRACE/FO in the Central Valley show a trend of groundwater depletion of 15.7 ± 1.4 mm/yr (2.41 ± 0.22 km^3/yr), resulting in a total groundwater loss of 44.2 ± 0.9 km^3, an amount that is greater than 1.25 times the capacity of Lake Mead. Figure S1 and Table S1 show that the depletion rates in the Sacramento, San Joaquin, and Tulare basins, were 12.9 ± 1.8, 16.2 ± 2.0, and 20.6 ± 1.5 mm/yr (0.89 ± 0.13, 0.67 ± 0.09, and 0.85 ± 0.07 km^3/yr), respectively, indicating that the southern Central Valley (combined San Joaquin and Tulare) lost more groundwater than the north, similar to the findings of earlier studies (12, 23). However, the situation was reversed in the drought that began in September 2019, during which we found higher groundwater loss rates of 76.1 ± 28.1 mm/yr (5.48 ± 2.02 km^3/yr) in the Sacramento basin compared to those of 38.1 ± 25.2 and 60.1 ±14.0 mm/yr (1.55 ± 1.03 and 2.57 ± 0.60 km^3/yr) for the San Joaquin and Tulare basins, respectively.

Longer-term trends and comparison to observations. The dynamics of GRACE/FO groundwater estimates were compared with water table depth anomalies observed from groundwater wells, as shown in Fig. 3(B). We removed seasonal variations using climatology to avoid seasonal inconsistencies and to examine long term trends. Overall, the dynamics of the two measurements demonstrate similar trends from 2003 to 2021. While there is a greater difference between the well and GRACE/FO estimates following 2017, Fig. 3 (B) shows that the groundwater estimates using GRACE/FO are capable of capturing the periods of loss and recovery observed on the ground, and in particular, the greater rate of groundwater loss since 2019, which appears even stronger in the observations than in the GRACE/FO estimates.

Figure 3(C) shows cumulative groundwater losses from 1962–2021 using the CVHM (13) and GRACE/FO. From 2003 to 2014 when both CVHM and GRACE data were available, the groundwater depletion rate for the CVHM was 17.3 ± 6.2 mm/yr (2.66 ± 0.95 km^3), matching that from GRACE, 16.8 ± 5.9 mm/yr (2.58 ± 0.90 km^3), indicating that the two methods are compatible and may be combined for the further analysis. The combined CVHM-GRACE/FO groundwater depletion rate from 1962 to 2021 was 12.3 ± 0.8 mm/yr (1.89 ± 0.12 km^3/yr), resulting in a total groundwater loss of 113.4 ± 0.9 km^3. In addition, Fig. 3(C) shows that the periods for groundwater recovery were shorter, and mostly driven by extreme weather events (42–43, 45) in the nearly two decades of the GRACE/FO record. Although groundwater was recharged, these extreme wet events typically generated flooding, and had significant negative social, environmental and economic consequences. This sequence of extreme hydrological events - long-term extremely dry conditions with considerable groundwater losses, punctuated by short-term extremely wet conditions with short bursts of groundwater recharge - underscores the challenge of sustainable groundwater management under changing climate.

Figure 3(A) and Table 1 show that the rate of groundwater loss is accelerating in the Central Valley. Groundwater loss rates observed from GRACE/FO (15.7 ± 1.4 mm/yr; 2.41 ± 0.22 km^3/yr) between 2003 and 2021 are 28% faster than the longer-term (1962–2021) depletion rate of the combined CVHM-GRACE/FO record (12.3 ± 0.8 mm/yr; 1.89 ± 0.12 km^3/yr). The most recent phase of groundwater loss, between September 2019 and August 2021 (55.8 ± 21.8 mm/yr; 8.57 ± 3.35 km^3/yr), is nearly 31% faster than GRACE/FO estimated losses the previous two drought phases during the GRACE/FO record, and nearly 5 times faster than the long-term depletion rate.

Surface water allocations and groundwater use. Figure 4 compares GRACE/FO estimated groundwater storage changes to annual surface water allocations via the two primary aqueducts in the Central Valley, the California State Water Project (SWP) (46) and the federal Central Valley Water Project (CVP) (47). The two aqueducts transport surface water from northern California to the south. When surface water is abundant, greater allocations are made to farmers, relieving stress on groundwater and allowing for recovery, and vice versa. Between 2003 and 2007, surface water storage was increasing (Fig. 2(B)), allowing for larger allocations (> 60%) from both aqueducts, less reliance on groundwater, and hence increasing groundwater storage. Surface water storage and then allocations decreased between 2007 and 2009, resulting in significant groundwater storage decline.

The second drought in the GRACE/FO record began in August 2011, triggering decreasing surface water allocations that resulted in heavy groundwater demand. During this period, CVP cut its allocation to 0% in 2014 and 2015, while the SWP reached its historic low allocation of 5% in 2015 and 2016. These led to intensified groundwater pumping through 2016.

Groundwater storage variations continued to reflect surface water allocations, increasing in 2017 and 2019 with above-average surface water storage, followed by major losses in both surface water allocations, and groundwater storage, through the end of 2021. For example, in 2020, aqueduct allocations decreased to 20% for both projects, and to 0% and 10% in 2021 for the CVP and SWP, explaining in part the increased rate of groundwater loss during this time period.

3 Discussion

The GRACE/FO missions have been operating during a period of megadrought in California and southwestern North America. The years 2000–2021 represent the driest 22-year period since at least 800, which may be a harbinger of more global warming-fueled extreme megadrought in the future (15). Stress on groundwater resources under these drying conditions will likely increase in the coming decades (6), and will be exacerbated by the need to provide more water and produce more food for a growing population.

The results reported here have important implications for the future of water management in California, especially since shortage conditions have been declared for the first time in history on the Colorado River (48), which will ultimately limit the allocation of surface water to California should these conditions persist or worsen. The key findings are 1) that groundwater loss rates measured by the CVHM and GRACE/FO are accelerating relative to the long-term depletion rate, 2) that TWS showed the driest wet season in the winter of 2020; 3) that recharge periods during the last two decades were short and infrequent, and 4) that even the normally wetter, northern half of the Central Valley is now suffering from groundwater losses. Taken together, these results underscore the importance of SGMA for groundwater management and of the GRACE/FO missions for providing basin- and valley-wide ‘big picture’ (49) assessments of the state of groundwater storage variations.

The current trajectory of groundwater storage in the Central Valley, shown in Fig. 3(A) since 2003, and over the last 6 decades in Fig. 3(C), shows a clear pattern of brief groundwater recovery events during shorter wet periods, followed by longer periods of groundwater loss during drought, and an overall trend of long-term groundwater depletion. This well-established pattern is largely driven by irrigation needs for agricultural production (11–13, 23). When annual surface water allocations delivered to farmers by the State Water Project and the Central Valley Project aqueducts are reduced, farmers have little choice but to use more groundwater.

Implications for groundwater management. The impact of this behavior on groundwater storage is shown very clearly in Fig. 4. When SWP and CVP surface water allocations increase, groundwater storage recovers, and vice versa. Since groundwater supplies are limited, and continued depletion is resulting in several negative consequences (falling water tables, drying wells, increasing pumping and well-drilling costs, decreasing groundwater access, land subsidence, declining groundwater quality, streamflow depletion (2)) continued overdrafting of groundwater supplies during drought is clearly unsustainable in the long term, in particular in the face of their increasing frequency and severity. This underscores the importance of SGMA, as well as of conjunctive management of surface and groundwater resources. Furthermore, since groundwater losses are accelerating rather than decelerating ahead of SGMA implementation, which may well be in anticipation of impending restrictions, results suggest the need for expedited implementation of groundwater management in the Central Valley to ensure its availability during the increasingly intense droughts of the future.

4 Methods

Total water storage from GRACE and GRACE-FO. Monthly estimates of total water storage (TWS) are taken from the JPL RL06M Version 2 GRACE/FO mascon solution (50–51). Two post-processing algorithms are applied: the Coastal Resolution Improvement (CRI) filter to reduce land/ocean leakage errors, as well as gridded gain factors which act to redistribute mass (in a mass conserving fashion) at 0.5^{o} resolution within each 3^{o} mascon element (52). The application of both algorithms allows for an exact averaging kernel to be applied when estimating mass over the study region. The TWS time series for the study region is shown in Fig. 2(A). Uncertainty of the TWS estimates was computed by accounting for both measurement and leakage errors, as described in (52). This study used the data from September 2003, coincident with the starting date of the Snow Water Equivalent data, to December 2021.

Total terrestrial water storage consists of groundwater (GW), soil moisture (SM), surface water (SW), and snow water equivalent (SWE), as shown in Fig. 2(B). SM in the 0-200 cm layer was obtained from the NLDAS phase 2 product (NLDAS-2) over the study region (39). The NLDAS-2 provides monthly SM estimates from three land surface models, including Noah (53), Mosaic (54), and Variable Infiltration Capacity (VIC) (55), at a spatial resolution of 0.125^{o}. The mean SM of three models was used for the groundwater calculation. The uncertainty in the mean SM was estimated from the standard deviation of the three models. The NLDAS-2 product has been fully assessed for its applicability (56–57).

The monthly SW storage was obtained from 92 in situ gauges of dams and reservoirs (40), managed by California's Department of Water Resources (DWR), in the study region (Fig. 1). Measurements from these active gauges were compiled to estimate the majority of the surface water variations in the study region, and were converted into units of equivalent water height (mm). Uncertainty of SW was set at 15% of the SW storage since no published error estimates for these gauges are available (12).

The SWE was obtained from the SNODAS data product (38), which was estimated by fusing the remotely sensed estimates and *in situ* observations assimilated into a Snow Thermal Model (SNTHERM.89) by the National Operational Hydrologic Remote Sensing Center. SNODAS provides daily SWE estimates at a spatial resolution of 1 km. The accuracy of SNODAS SWE has been reported from ~ 10–20% of the SWE values at the basin scale for different regions (58–60). Therefore, we assume an uncertainty of 15% for SWE. These terrestrial water storage components were aggregated into the Central Valley domain for groundwater calculations (Fig. 2(b)).

A water balance approach was used to compare GRACE/FO derived TWS to observations, given as:

$dS/dt = P - ET - Q$ (1)

where dS/dt is the change of total water storage in a given time t, P is precipitation from the monthly PRISM 4-km product (61–62), ET is monthly evapotranspiration derived from MODIS observations and MERRA-2 meteorological data using the Priestley Tylor – Jet Propulsion Laboratory (PT-JPL) model (63), and Q is stream discharge compiled from the two gauging stations of Verona and Vernalis which are operated and maintained by U.S. Geological Survey (USGS) (64), as shown in Fig. 1. All are given as integrated monthly totals and are expressed as basin-averaged depths. Thus, dS/dt represents the change of total water storage in a month. Figure 2(C) shows P, ET and Q for the study period and Fig. 2(D) shows the comparison of dS/dt from GRACE/FO and from the observed water balance approach. The Root Mean Squared Difference between the two is 26.4 mm, and is within the range of the mean uncertainty using GRACE/FO measurements (43.6 mm).

Auxiliary datasets. *In situ* well measurements were used to compare observed groundwater dynamics with those estimated here. The well data were compiled and processed using original datasets from groundwater monitoring networks managed by California’s DWR and the USGS (19). More than 1000 wells across the study region were compiled in order to best represent groundwater dynamics across the area. Water table depths below the surface were calculated for comparison. Although the spatial and temporal distribution of available wells across the Central Valley is highly variable over time, the well data provide valuable information to support use of GRACE/FO signal to understand groundwater storage changes.

Historical (1962–2014) cumulative groundwater loses were obtained from USGS Central Valley Hydrology model (CVHM) (11, 13). The CVHM is a comprehensively calibrated hydrology model using *in situ* monitoring wells and is developed to provide water resource information to decision makers who are engaged in managing the Central Valley aquifer system. In this study, annually-averaged data from the CVHM were used and combined with GRACE/FO-derived groundwater storage for comparison, and to place the GRACE/FO-derived cumulative changes into historical context.

Finally, the surface water allocation amounts, determined by the federal CVP and the California SWP (46–47), and distributed in their aqueducts, were used to understand how the variations in surface water availability drive farmers' groundwater usage patterns.

Estimating groundwater storage variations. Groundwater storage variations, computed as anomalies, were obtained by subtracting the water mass anomalies in soil moisture, snow water equivalent and surface water storage from the total water storage anomalies measured from GRACE:

GW = TWS-SM-SWE-SW (2).

In this study, we assumed that the mountains surrounding the basins contain limited capacity for groundwater storage (12), though Argus et al. (2017) (65) present evidence for some mountain storage. Following Famiglietti et al., (2011) (12), we attribute the groundwater variations derived from GRACE/FO as having occurred in the Central Valley.

We identified three phases of groundwater recharge, from October 2003 to July 2006, from March 2011 to July 2011, and October 2018 to July 2019. We also identified groundwater loss phases during two notable California droughts of August 2006 to February 2011 and August 2011 to March 2017, and the ongoing drought since 2019. Trends for recharge and loss phases were calculated by linear regression, and a student's-t test was applied with a confidence interval of 95% to estimate trend uncertainty. Groundwater losses during the GRACE/FO missions, 2003–2021, were summarized and compared with those observed from wells and CVHM estimates when the data were available. Combining the GRACE/FO and CVHM data, we quantified cumulative groundwater loss between1962 to 2021.

Declarations

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Authors declare that they have no competing interests.

Supplementary Materials

Supplementary Text

Figs. S1-S2

Table S1

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Figures

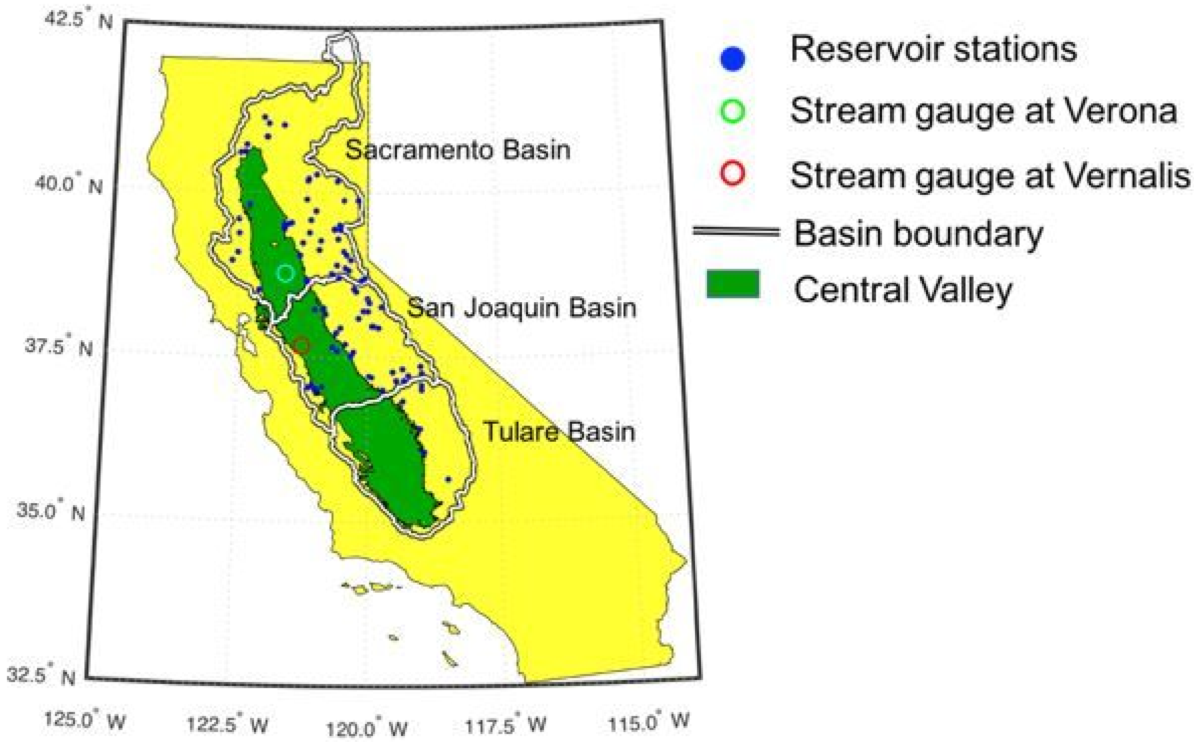

Figure 1

California's Central Valley. The study region encompasses the Sacramento, San Joaquin, and Tulare Basins.

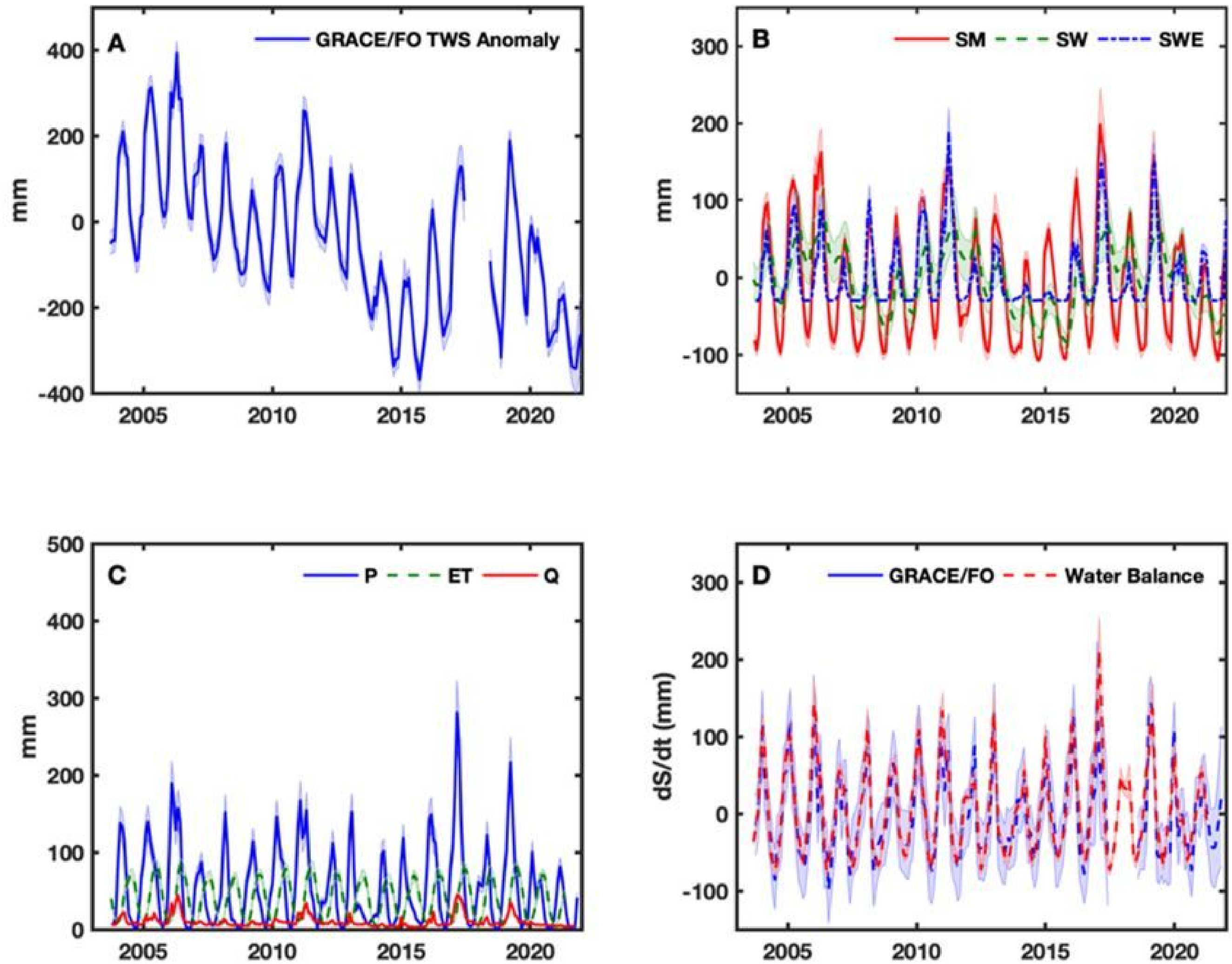

Figure 2

Datasets used for groundwater calculation. (A) GRACE/FO observed monthly total water storage anomalies. (B) anomalies of three terrestrial water storage components of soil moisture (SM), surface water (SW), and snow water equivalent (SWE). (C) three water balance fluxes of precipitation (P), evapotranspiration (ET), and streamflow (Q). (D) comparison of monthly change in water storage (dS/dt) between that derived from GRACE/FO and from an observed water balance, and. All variables are represented in equivalent water height in millimeters for the study region.

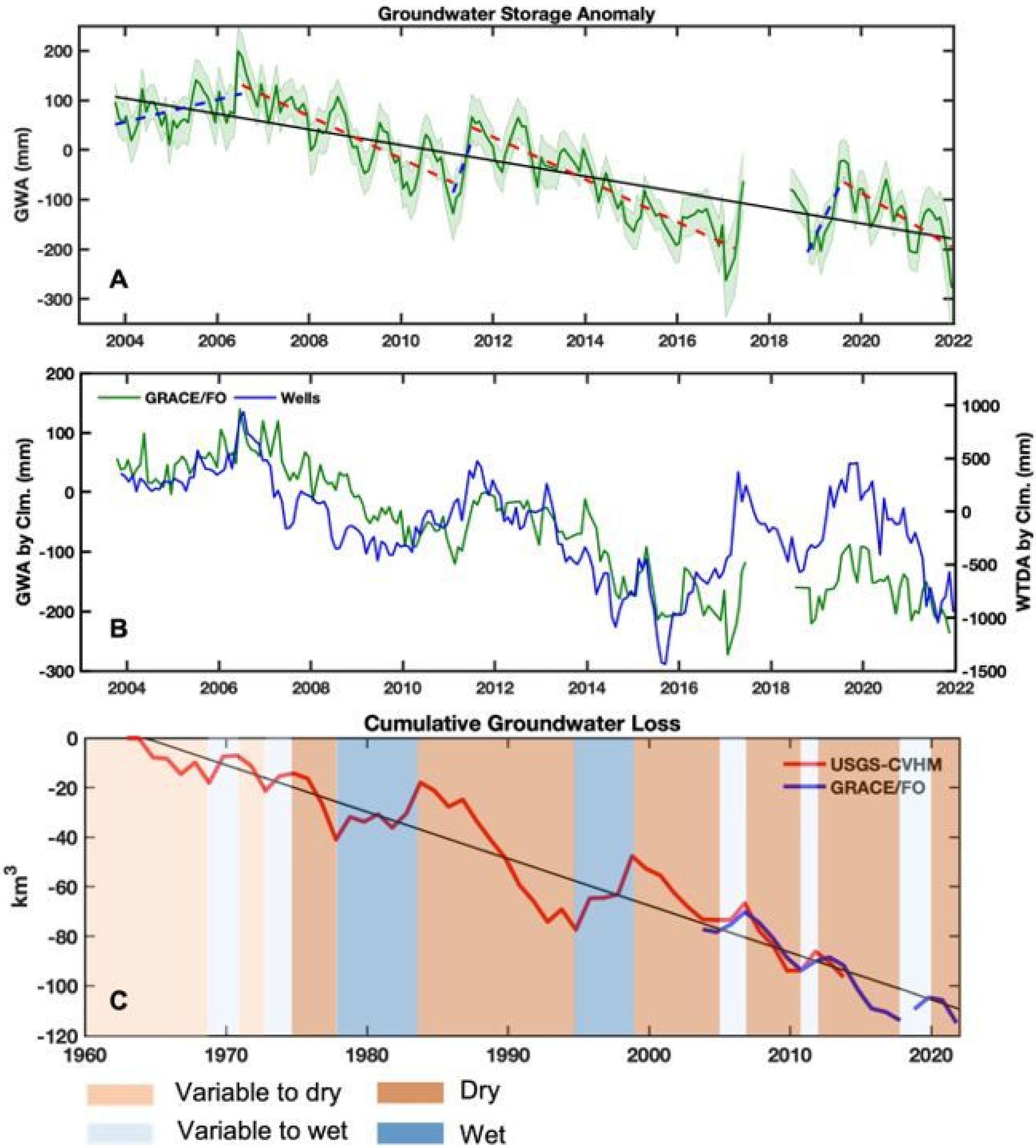

Figure 3

Groundwater dynamics in California's Central Valley. (A) GRACE/FO-derived groundwater dynamics during September 2003 to December 2021 in the Central Valley, CA. Red dashed lines represent groundwater loss trends during the droughts of 2006-2011, 2011-2017, and since 2019. Blue dashed lines represent three short recharge periods. The black line shows the groundwater depletion trend from 2003-2021. (B) Anomalies of GRACE/FO derived groundwater storage and water table depth from monitoring wells. (C) Yearly cumulative groundwater losses combining of USGS-CVHM (Faunt et al., 2016) and the

GRACE/FO estimates since 1962, where the black line represents the groundwater depletion from 1962 to 2021.

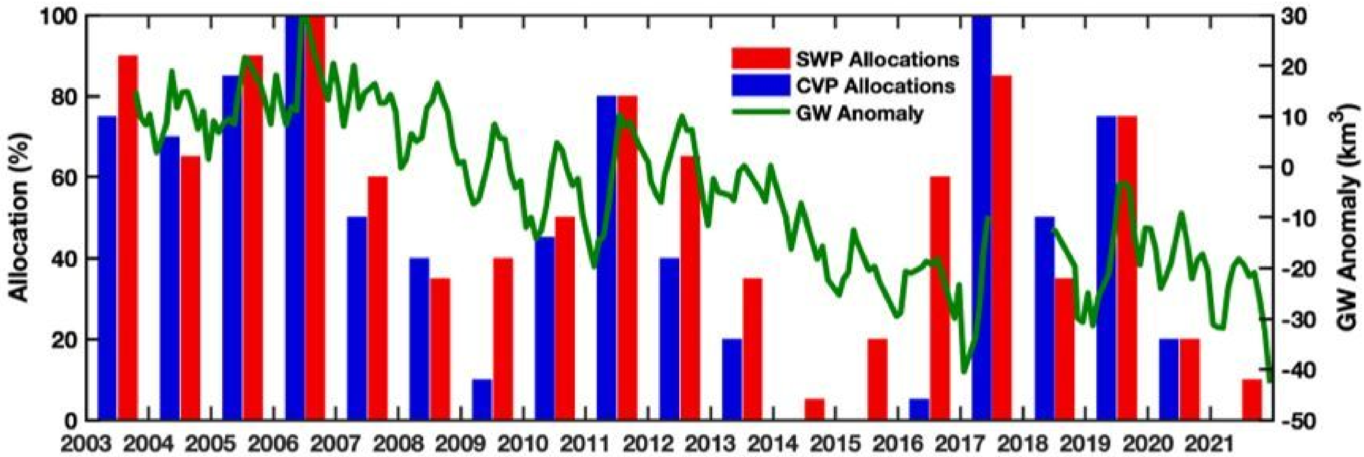

Figure 4

Groundwater and surface water management in Central Valley. Comparison between annual surface water allocations in the aqueducts of the California State Water Project (SWP) and the federal Central Valley Water Project (CVP) and GRACE/FO-derived groundwater storage anomalies.

Supplementary Files

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