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Research article

Planning for groundwater sustainability accounting for uncertainty and costs: An application to California's Central Valley

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ABSTRACT

In regions experiencing aquifer depletion, planning for groundwater sustainability requires both accurate accounting of current groundwater budgets and an assessment of future conditions, with changes in recharge and pumping. Hydrologic variability, climate change effects on water flows, changing water infrastructure operations, and inherent uncertainties in modeling, challenge the plans to achieve groundwater sustainability. This paper examines the importance, magnitude, and policy implications of uncertainties in groundwater overdraft estimation for water management in California. We review water balance estimates from two regional-scale groundwater models—C2VSim and CVHM—for sub-regions within California's Central Valley, and examine the variability and uncertainty in historical and future estimates of groundwater overdraft. Assuming reductions in agricultural water use for sub-regions with overdraft, we estimate the probabilities of ending groundwater overdraft for different periods. We also obtain the economic costs associated with these reductions in agricultural production. Results from both groundwater models show significant inter-annual variability in flows affecting groundwater storage, and our model comparison highlights the uncertainty in water budget estimates for Central Valley sub-regions given the differences between models. The analysis of the probabilities of achieving sustainability at the sub-regional scale show that the average overdraft rate is important and that greater variance in annual groundwater storage increases uncertainties in ending overdraft, especially for shorter periods. Greater reductions in annual net water increases the reliability of achieving groundwater sustainability, but rising rapidly agricultural economic losses. Setting management thresholds below groundwater levels can ease meeting sustainability criteria, but also can introduce a false pathway to sustainability. Finally, we discuss policy implications for the design of local groundwater sustainability plans and state assessment and regulation of local plans.

1. Introduction

Groundwater depletion is increasing globally (Wada et al., 2010), driven primarily by agricultural production with insufficient groundwater regulation (Dalin et al., 2017; Moench et al., 2016). In California, groundwater depletion has been a concern since the early 20th century. Land subsidence from overdraft in the San Joaquin Valley began in the mid-1920s, affecting about 13,500 km^2 (~5200 square miles) by 1970 with a maximum subsidence exceeding 8.5 m (28 feet) (Poland et al., 1975). During the 2012-16 drought, lands sank at rates up to ~0.55 m/year (Murray and Lohman, 2018). Groundwater depletion also caused wells to go dry throughout the western US (Perrone and Jasechko, 2017), and in California alone, over 2000 households supplied by groundwater wells reported shortages between 2014 and 2016 (CA.gov, 2018; Pauloo et al., 2020). Groundwater overdraft also causes environmental impacts, as groundwater sustains various aquatic, terrestrial and coastal ecosystems, and their landscapes (Howard and Merrifield, 2010).

In 2014, during the 2012-16 drought, California adopted the Sustainable Groundwater Management Act (SGMA) (Water Code 10727.2). This set of laws requires development and implementation of local groundwater sustainability plans (GSPs), which must include measurable objectives and interim 5-year incremental milestones, to achieve groundwater sustainability in basins defined by the State within 20

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years of plan implementation (2040 for critically overdrafted basins, and 2042 for the remaining high and medium priority basins). A key feature of SGMA is reliance on local governance, rather than direct State implementation. Over 120 groundwater basins have been identified and over 300 local Groundwater Sustainability Agencies (GSAs) have been formed. These agencies are tasked with developing and implementing plans to meet their sustainability goals and avoid six undesirable results: lowering of groundwater levels, reduction of groundwater storage, land subsidence, seawater intrusion, water quality degradation, and adverse impacts to streamflow and groundwater-dependent ecosystems.

Achieving SGMA-mandated groundwater sustainability goals has become pressing for California's water management. However, estimating local overdraft rates and designing plans to meet sustainability criteria over time will often be challenging. Overdraft estimates are inherently uncertain given hydrological variability and errors in estimating aquifer characteristics, groundwater inflows, recharge, pumping, stream depletion, and connections with nearby aquifers. Estimates also vary over time with water demands and water system operations. Estimates of overdraft rates in the Central Valley range from 1.7 km^3/year to 11.2 km^3/year for different periods and assessment methods (Brush et al., 2013; Escriva-Bou and Hanak et al., 2017; Famiglietti et al., 2011; Faunt et al., 2009; Xiao et al., 2017). This raises questions about which methods are most accurate and poses challenges for basin plans and regulations to end groundwater overdraft.

Some characteristics of California's Central Valley make the estimation of overdraft and regional groundwater-balance components especially challenging. California has a highly variable climate with the highest frequency of both droughts and floods in the United States (Dettinger et al., 2011). Precipitation, snowpack, streamflow, surface water availability, groundwater recharge, and water demands are highly variable and require significant annual (and seasonal) flexibility in water operations. Massive surface storage and conveyance infrastructure provide this flexibility in water operations. Yet extended droughts, such as those seen recently, dramatically increase reliance on groundwater to supplement surface water supplies. Increasing climate variability and fundamental changes in policy further complicate estimation of long-term overdraft (Hanson et al., 2012). Water balance calculations and models under such circumstances are therefore subject to significant uncertainties.

Here, as in groundwater-dependent irrigated agricultural regions around the globe (Tuninetti et al., 2019), ending groundwater overdraft will require significant and politically difficult shifts in economic enterprises and management institutions (Hanak et al., 2017; Harou and Lund, 2008). Finding and implementing more desirable and feasible solutions has immense importance for managing droughts and ensuring the long-term profitability of California's agriculture. Improved understanding of uncertainties in groundwater balance estimation will help local water users and local and state governments address groundwater overdraft and improve groundwater sustainability for sustaining rural communities and agricultural prosperity (Howitt et al., 2014).

This paper has three main objectives. First, by reviewing estimates of water balance at the sub-regional, regional, and supra-regional scale from two groundwater models for California's Central Valley, we highlight the uncertainty associated with these estimates. Second, and assuming different reductions in agricultural water use for sub-regions in the Central Valley, we estimate probabilities of ending groundwater overdraft within the time frame mandated by SGMA. Finally, we estimate the economic costs of decreased agricultural production associated with these water use reductions. Note that we assume that these reductions in water use are feasible and socially acceptable—not intending to deal with the social dimensions of groundwater sustainability such as individual or social behavior, or agency representation. However, the analysis allows us to draw policy implications for the quantitative design of local sustainability plans and state assessment and regulation of such plans that are helpful given the many uncertainties of their assumptions.

2. Case study: California's Central Valley

The Central Valley of California covers about 52,000 square km and it is one of the most productive agricultural regions in the world (Faunt et al., 2009). From more than 200 crops and animal products, the valley received in 2017 over $40 billion in agricultural sales—80% of California's agricultural output (CDFA, 2018).

The Central Valley, centrally located in California's geography, is an alluvial basin that is roughly 650 km long and between 30 and 110 km wide. It is bounded by the Cascade Range to the north, the Sierra Nevada to the east, the Tehachapi Mountains to the South, and the Coast Ranges and the San Francisco Bay to the west (Faunt et al., 2009). The valley has a single surface water flow outlet at the Carquinez Strait, which connects to San Francisco Bay and the Pacific Ocean. The Central Valley is generally divided into three large hydrologic regions and two smaller hydrologic regions. The three large regions each comprise approximately a third of the valley: the northern Sacramento River Basin, central San Joaquin River Basin, and the southern Tulare Basin—an endorreic basin (Brush et al., 2013). The two small hydrologic regions, the Eastside Streams and the Delta, are located between the Sacramento River and the San Joaquin River Basins.

For practical reasons, we will use four regions in our analysis: the Sacramento Valley, the Delta & East Side Streams, the San Joaquin River, and the Tulare Lake Basin. Following the California Department of Water Resources (DWR), we have further subdivided the four regions within the Central Valley aquifer system in 21 sub-regions (Fig. 1).

The Central Valley has a pronounced north to south precipitation gradient. Seventy-five percent of California's precipitation occurs north of Sacramento, in the southern border of the Sacramento Valley (Hanak et al., 2011). That makes the Sacramento Valley streams much water-rich that their counterparts in the San Joaquin and Tulare basins. In these regions, the compounded effect of lesser water availability and a larger agricultural footprint—the agricultural demand in these basins is two thirds of the total in the valley—caused more problems of groundwater depletion. Although the pace of groundwater pumping accelerated during the 2012–16 drought, overdraft has been a challenge for many decades (Brush et al., 2013; Faunt et al., 2009). Of the 38 Central Valley basins subject to SGMA, 11 of them are considered to be critically overdrafted—all located in the San Joaquin and Tulare basins (Hanak et al., 2019).

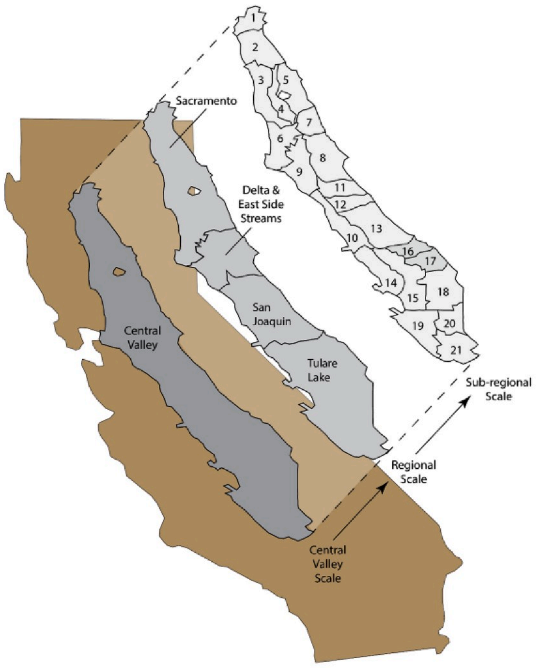
3. Data and methods

To describe the methods for the three related objectives mentioned in the introduction, this section includes three sub-sections. First, the analysis of variability and uncertainty of groundwater overdraft estimates—which includes a basic introduction on methods for estimating groundwater budgets, the estimation of groundwater balance components of California's Central Valley, and the methods to analyze the variability and uncertainty of groundwater overdraft estimates. Second, the assessment of the probabilities to end overdraft over a period—which includes the definition of groundwater sustainability, the assessment of water use reduction needed for sustainability, and the estimation of the probabilities (or uncertainties) to achieve sustainability over a period. Finally, the estimation of the agricultural costs associated with the reductions in water use needed to end groundwater depletion.

3.1. Analyzing variability and uncertainty of groundwater overdraft estimates

3.1.1. Methods for estimating groundwater budgets

Methods for simulating water budgets in agriculturally-dominated groundwater systems typically rely on crop-irrigation accounting methods of varying complexity usually involving an uncoupled or iteratively coupled groundwater model. Uncoupled agricultural water



Basin	Sub-region	General description
Sacramento Valley	1	Sacramento River above Red Bluff
Sacramento Valley	2	Red Bluff to Chico Landing
Sacramento Valley	3	Colusa Trough
Sacramento Valley	4	Chico Landing to Knights Landing
Sacramento Valley	5	Eastern Sacramento Valley foothills near Sutter Buttes
Sacramento Valley	6	Cache-Putah area
Sacramento Valley	7	East of Feather and south of Yuba Rivers
Delta and East Side Streams	8	Valley floor east of the Delta
Delta and East Side Streams	9	Delta
San Joaquin Basin	10	Delta-Mendota Basin
San Joaquin Basin	11	Modesto and southern Eastern San Joaquin Basin
San Joaquin Basin	12	Turlock Basin
San Joaquin Basin	13	Merced, Chowchilla, and Madera Basins
Tulare Basin	14	Westside and Northern Pleasant Valley Basins
Tulare Basin	15	Tulare Lake and Western Kings Basin
Tulare Basin	16	Northern Kings Basin
Tulare Basin	17	Southern Kings Basin
Tulare Basin	18	Kaweah and Tule Basins
Tulare Basin	19	Western Kern County and Southern Pleasant Valley
Tulare Basin	20	Northeastern Kern County Basin
Tulare Basin	21	Southeastern Kern County Basin

Fig. 1. Spatial extent of sub-regional, regional, and Central Valley-wide areas for model analyses and comparison.

balance models are used extensively in semi-arid agricultural basins, with unquantified groundwater pumping and recharge treated as closure terms for the land-surface water budget (Belitz et al., 1993; Ruud et al., 2004). Coupled models, such as the Integrated Water Flow Model (IWFM) (Dogrul, 2012) and MODFLOW Farm Process (MF-FMP2) (Schmid et al., 2006) are common, with iteratively-coupled codes linking a groundwater model with an agricultural water balance model. Coupling agricultural and groundwater components can, in theory, more accurately simulate feedbacks between agricultural, vadose, and groundwater processes and simulate crop processes such as soil-moisture-deficit and direct groundwater uptake. Both uncoupled and coupled approaches require data on crops, weather, and climate to estimate crop water demand, and surface water delivery estimates to calculate demand for groundwater pumping. Fundamentally, agricultural groundwater pumping—lacking measured or reported data—is usually estimated as the residual of combined surface water diversion plus precipitation minus crop water demand and irrigation efficiency.

Typically, the choice of numerical model to simulate groundwater flow is largely inconsequential, in that resulting computed hydraulic heads and water budgets depend little on the choice of the code given the same initial and boundary conditions to the groundwater system. All available codes solve the same governing groundwater flow equations and yield comparable results when discretized and parameterized similarly (Anderson et al., 2015; Wang and Anderson, 1977). However, coupled groundwater/surface-water/landscape models like IWFM and MF-FMP2 not only solve the groundwater flow equation, but also employ varied conceptual and mathematical representations of surface hydrology, vadose zone hydrology, and land and water management, including agricultural processes. Consequently, greater uncertainty relates to differences in representing these processes. Methodological differences between IWFM and MF-FMP2 primarily relate to the partitioning of ET requirements, representation of soil-moisture conditions, and prioritization of water allocation. For instance, MF-FMP2 assumes steady-state soil-moisture conditions, while IWFM simulates transient soil-moisture storage conditions. Several studies highlight these and other differences (Dogrul et al., 2011; Harter and Morel-Seytoux, 2013; Schmid et al., 2011), but none are diagnostic of how model differences affect the assessment of future conditions in applied settings.

3.1.2. *Estimates of groundwater balance components of California's Central Valley*

MF-FMP2 and IWFM models and methods have been separately applied for the Central Valley to estimate historical groundwater budgets (Brush et al., 2013; Faunt et al., 2009). These methods, integrated in CVHM and C2VSim models respectively, provide estimates of historical regional hydrologic budgets in the Central Valley. They simulate coincident domains during an overlapping, multi-decadal period. This spatial and temporal overlap aids in estimating the effects of methodological differences between models on the estimation of regional and sub-regional water budgets, especially how they estimate agricultural groundwater pumping.

We use data outputs from CVHM and C2VSim models that describe groundwater balance components for the 21 sub-regions that comprise the Central Valley during a 29-year period from 1975 to 2003. These outputs include surface diversions, evapotranspiration, pumping, and changes in groundwater storage.

3.1.3. *Variability and uncertainty of groundwater overdraft estimates*

California's Mediterranean climate is highly variable with pronounced seasonality and multi-year wet and dry periods. Historic variability of flows affecting groundwater balances is represented graphically using both models' results, and estimated analytically using basic statistical metrics.

To measure model uncertainty in annual groundwater storage estimates, we employ statistical analyses of C2VSim and CVHM outputs. Specifically, we perform a *paired samples t-test* to analyze if the annual means of the sub-regional changes in groundwater storage from the two models differ significantly. Similarly, we use a *Levene test* to assess if the variances of the annual sub-regional changes in groundwater storage from the two models differ significantly. Because the *t-test* assumes normality in the samples, we also performed a *Shapiro-Wilk test* to assess the normality of the datasets.

3.2. *Assessing the probability of ending overdraft over a period*

3.2.1. *Defining groundwater sustainability*

Under SGMA, GSAs must define a "measurable objective" that reflects a desirable, fixed operating range for groundwater storage. The range must be sufficient to provide resilience to seasonal and long-term climate variability. Over the long term, changes in groundwater storage must generally remain within the targeted range, not to exceed locally defined “minimum thresholds” (DWR, 2017).

Fig. 2 depicts this approach to groundwater sustainability. In the pre-implementation period, sub-regions with overdraft should have a general downward trend in groundwater storage (or elevation). In the implementation period, the downward trend is eliminated, but there are still fluctuations in the groundwater table given hydrologic cycles and demand responses. Then, to operate under sustainable criteria it is essential to assess the annual groundwater overdraft in the pre-implementation period, and then to define a buffer (or minimum threshold below groundwater levels at the beginning of the implementation period) to allow for inter-annual variability. Here, any point over the minimum threshold is considered a “measurable objective” of groundwater sustainability. Although SGMA defines sustainability in terms of groundwater storage as well as water quality, groundwater-dependent ecosystems, and surface water connectivity, this paper focuses exclusively on addressing the chronic lowering of groundwater levels.

3.2.2. *Water use reductions needed for groundwater sustainability*

When groundwater extraction exceeds replenishment over long time scales, groundwater use is considered unsustainable. Under the California law, long-term unsustainable groundwater use must be discontinued. To bring basins into balance and avoid unsustainable groundwater use, GSAs will pursue two non-exclusive approaches: bringing new water supplies (e.g., additional surface flow capture, water imports) and/or reducing consumptive water use. In this paper, we assume that there are no additional supplies available, so the downward trend in groundwater storage must be eliminated by reducing consumptive water use (i.e., evapotranspiration) in an amount greater than or equal to the average annual groundwater deficit.

For both C2VSim and CVHM models, we obtain statistics of simulated surface diversions, pumping, evapotranspiration, and changes in groundwater storage. Assuming both models are equally valid, we obtain combined statistics by using annual results from both models and treating them as correlated samples. The combined surface diversion, pumping, and change in groundwater storage volumes were estimated from the mean of the two models’ annual estimates. The combined variance was obtained from the variance of the two samples accounting for their correlation.

3.2.3. *Uncertainties to achieve sustainability over a period*

Three main sources of uncertainty affect sustainability plans: uncertainty in future inflows due to hydrologic variability, uncertainty about models errors, and uncertainty about the assumption of stationary hydrology and water demands, including climate change. This paper only examines uncertainty from hydrologic variability and modeling estimates, leaving the potential effects of climate change and non-stationarity for future analyses.

Long-term hydrologic variability was estimated probabilistically, where modelled annual changes in groundwater storage are based on historical hydrologic records and groundwater use. Stationary hydrology assumes the future hydrology follows the same probability distribution as the past, so historical hydrologic variability can be used for future forecasts. The assumption provides a lower bound on uncertainty estimates, as non-stationarity adds additional uncertainty not quantified here.

Analytically, groundwater sustainability is achieved during the implementation period while the cumulative change in groundwater storage (Δgs) is within the measurable objective, here defined as groundwater storage exceeding the minimum threshold. The difference between groundwater storage at $t = t_0$ (beginning of the implementation period) and minimum threshold is the maximum allowable buffer, b, for Δgs. We assume overdrafted basins achieve sustainability solely by a fixed net annual water use reduction, wr, beginning at $t = t_0$.

To estimate the likelihood of achieving future groundwater sustainability as a function of wr, we use the historic mean ($\mu_{i,j}$, negative for overdraft) and variance ($\sigma^2_{i,j}$) of annual groundwater storage change for each sub-region i with each set of data from model (j = groundwater storage change in C2VSim, CVHM, or two models combined). Following the Central Limit Theorem, we assume that, starting at $t = t_0$, annual groundwater storage change is normally distributed with a mean shifted from the historical mean ($\mu_{i,j} + wr$), but with the same (historic) variance $\sigma^2_{i,j}$, assumed time-independent and unchanging. So, Δgs, obtained as the cumulative sum of annual changes, is also normally distributed with a time-varying expected value, $MEAN_{i,j}(t, wr)$, and variance, $VAR_{i,j}(t)$, which can be obtained from:

$$MEAN_{i,j}(t, wr) = \left(\mu_{i,j} + wr\right)^{*}t$$

$$VAR_{i,j}(t) = \sigma^2_{i,j}{}^{*}t$$

For an annual net water use reduction wr, sub-region i, and model choice j, the probability that the change in groundwater storage is either positive or - if negative - greater than the value of the allowable buffer b, in any future year t with s:

$$P_{i,j}\left(\Delta gs_{i,j} \geq -b|t, wr\right) = \int_{x=-b}^{\infty} f_{\Delta gs_{i,j}}\left(x|MEAN_{i,j}, VAR_{I,J}\right)dx$$

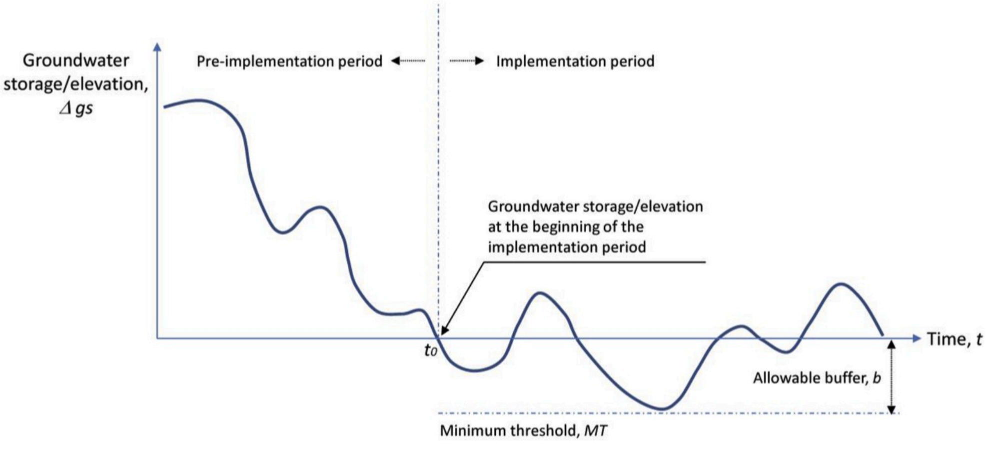


Fig. 2. Hypothetical representation of changes of groundwater storage over time and definition of minimum thresholds to define sustainability.

3.3. Estimating the costs of reduced agricultural production to end overdraft

Water use reductions to achieve sustainability will bring economic losses from reduced agricultural production or due to costs of importing additional surface water. In general, the marginal cost of water shortage and water use reductions increase with shortage. Using marginal cost curves of water shortage in each region, we can estimate the economic cost of any specified annual net water use reduction, *wr*.

Agriculture is the predominant water use in the Central Valley and development of additional water is limited. Therefore, we here assume that water use reductions needed to achieve sustainability will come from reducing water use in farms. The State-Wide Agricultural Production model (SWAP) (Howitt et al., 2012) provides marginal values of agricultural water use in each Central Valley sub-region that are used as an input in our model. These marginal values are obtained by reducing

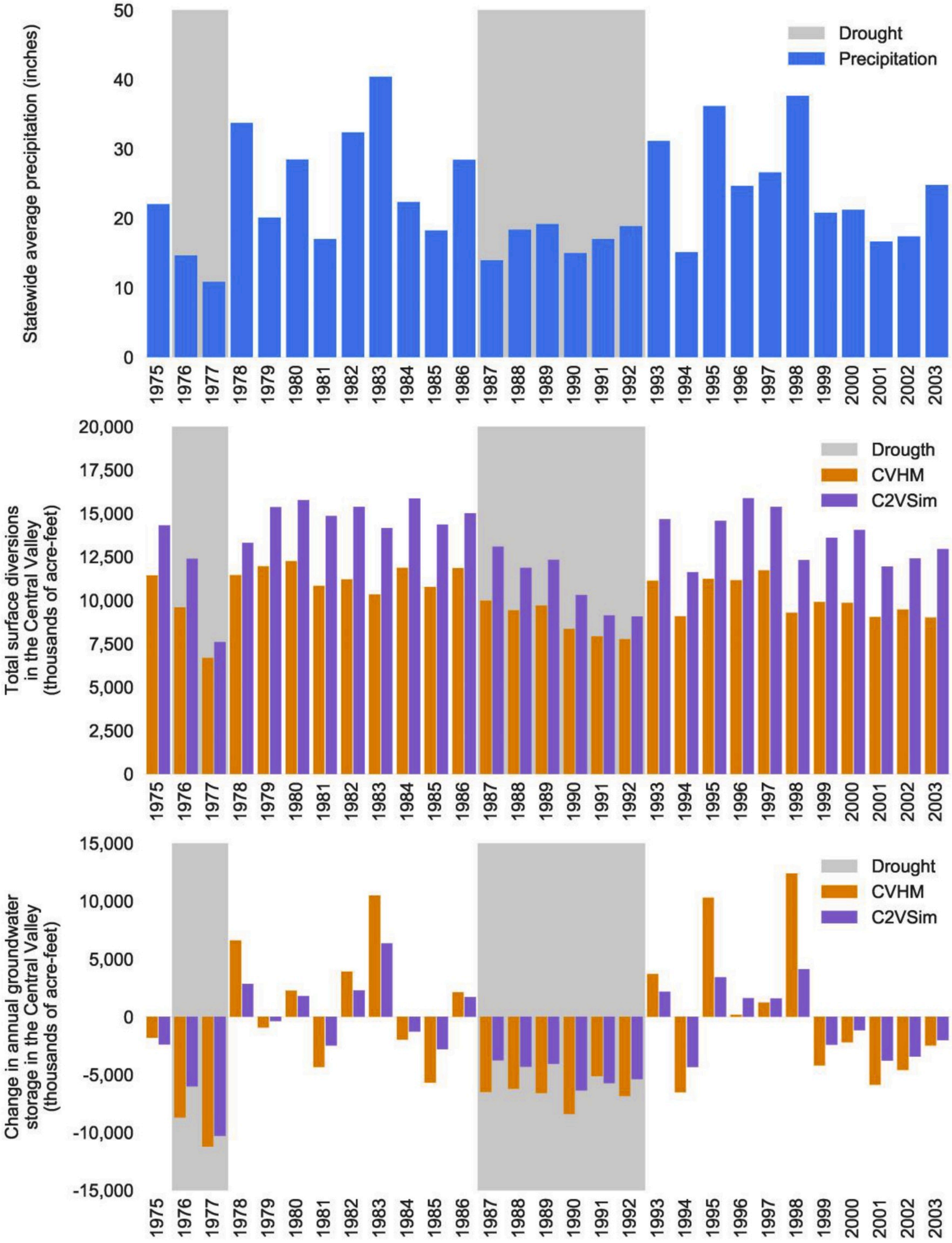


Fig. 3. Inter-annual precipitation variability and human-induced management responses to water availability. The upper panel shows statewide precipitation (NOAA, 2019), the central panel Central Valley surface water diversions, and lower panel change in annual groundwater storage in the Central Valley, both using data from C2VSim and CVHM models (Brush et al., 2013; Faunt et al., 2009).

water deliveries to an agricultural production model calibrated to a base of observed inputs, including land use for crops, water, agricultural supplies, and farm labor. From the marginal cost, the scarcity cost is assessed as the area under the curve between the target demand and the actual water delivered to achieve sustainability (Escriva-Bou et al., 2017). In the Supporting Information, we show the economic cost associated for reductions in water use for each sub-region.

4. Results

To present the results for the three related objectives of this research, this section includes three sub-sections. First, it shows the results related with the analysis of variability and uncertainty of groundwater overdraft estimates. Second, the outcomes to estimate the probabilities of ending overdraft over a period. Finally, the agricultural costs associated to the water use reductions needed to achieve groundwater sustainability.

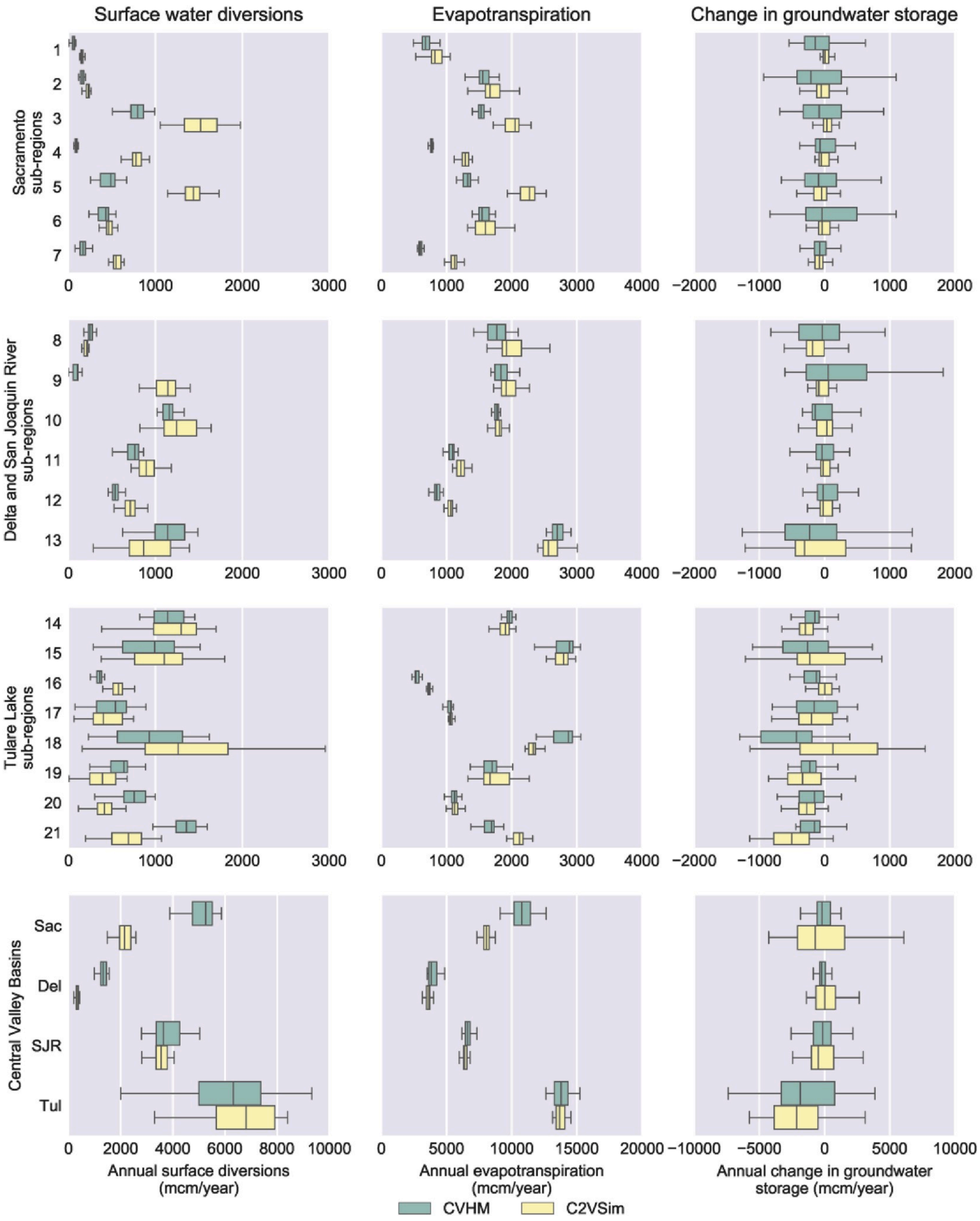


Fig. 4. Variability of annual surface water diversions, evapotranspiration, and change in groundwater storage at sub-regional and basin scales for CVHM and C2VSim in California's Central Valley. The sub-regions in the Sacramento Valley are 1. Sacramento River above Red Bluff, 2. Red Bluff to Chico Landing, 3. Colusa Trough, 4. Chico Landing to Knights Landing, 5. Eastern Sacramento Valley foothills near Sutter Buttes, 6. Cache-Putah area, and 7. East of Feather and south of Yuba Rivers. Sub-regions in the Delta and East Side Streams are 8. Valley floor east of the Delta, and 9. Delta. Sub-regions in the San Joaquin River Basin are 10. Delta-Mendota Basin, 11. Modesto and southern Eastern San Joaquin Basin, 12. Turlock Basin, and 13. Merced, Chowchilla, and Madera Basins. Sub-regions in the Tulare Basin are 14. Westside and Northern Pleasant Valley Basins, 15. Tulare Lake and Western Kings Basin, 16. Northern Kings Basin, 17. Southern Kings Basin, 18. Kaweah and Tule Basins, 19. Western Kern County and Southern Pleasant Valley, 20. Northeastern Kern County Basin, and 21. Southeastern Kern County Basin. For the Central Valley Basins, "Sac" means Sacramento Valley, "Del" denotes Delta and East Side Streams, "SJR" means San Joaquin River basin, and "Tul" Tulare Lake Basin. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

4.1. Variability and uncertainty in groundwater overdraft estimates

As Fig. 3 shows, precipitation in the headwaters is the main driver of water availability, but California's storage and conveyance infrastructure dampens surface diversion reductions significantly in the first years of a drought (see for instance 1987). Farmers replace reductions in surface deliveries by pumping more groundwater, as seen in the latter years of a drought (such as in 1990–1992). The figure also shows that while long-term trends and response to drought are similar between CVHM and C2VSIM, sizable differences exist between the models in annual estimates for surface diversions and change in groundwater storage when evaluated over the Central Valley.

This inter-annual hydrologic variability in California's Mediterranean climate affects groundwater budgets, and becomes another source of uncertainty when planning for future groundwater sustainability.

In planning for groundwater sustainability, estimates of average annual change in groundwater storage and its annual variability at the sub-regional scale are critical. Sub-regional disagreements across models affect the annual average estimates of overdraft and their long-term variability. Annual variability of estimates in changes of groundwater storage for CVHM is significantly greater than those for C2VSim (Fig. 4). In addition, estimates for average annual change in groundwater storage show large disagreements in some regions (e.g., regions 16, 18, and 21).

When adding up these results at the basin scale (lower charts in Fig. 4) that the median change in groundwater storage are similar, but still the inter-annual distributions show some discrepancies. The distributions of surface diversions and evapotranpiration show also sizable differences, especially for the Sacramento and Delta-East Side Streams regions.

Several statistical tests show the relative significance of the conceptual uncertainties reflected in the different modeling approaches (Table 1). The results of the *t*-test for correlated samples—which assesses if the annual means are significantly different between models—show significant discrepancies (p-value <0.01) in sub-regions 14, 15, 18 and 20, and sub-regions 8, 9, 15 and 21 are also in disagreement (p-value < 0.1). The *t*-test assumes normal distributions of the samples, so according to the Shapiro test the results for the t-tests are not guaranteed for regions 9, 14, 15 and 21.

Table 1
Results of the statistical tests for differences in annual mean change in groundwater storage between C2VSim and CVHM estimates. *** denotes a p-value < 0.01; ** a p-value < 0.05; and * a p-value < 0.1.

Sub-region	Equal means *t-test* (p-value)	Equal variances *Levene test* p-value	C2VSim Normality *Shapiro test* p-value	CVHM Normality *Shapiro test* p-value
1	0.105	0.000***	0.112	0.068*
2	0.709	0.001***	0.847	0.023**
3	0.653	0.000***	0.968	0.074*
4	0.424	0.006***	0.009***	0.015**
5	0.523	0.005***	0.296	0.028**
6	0.368	0.000***	0.327	0.072**
7	0.147	0.006***	0.272	0.040**
8	0.029**	0.001***	0.795	0.354
9	0.023**	0.000***	0.136	0.003***
10	0.813	0.323	0.529	0.001***
11	0.637	0.321	0.003***	0.256
12	0.146	0.117	0.072*	0.148
13	0.289	0.272	0.313	0.655
14	0.000***	0.792	0.004***	0.003***
15	0.020**	0.708	0.302	0.046**
16	0.000***	0.430	0.364	0.665
17	0.229	0.284	0.315	0.355
18	0.000***	0.013**	0.117	0.121
19	0.694	0.030**	0.003***	0.324
20	0.000***	0.080*	0.913	0.166
21	0.055*	0.654	0.721	0.000***

The Levene test, which assesses if the model result variances differ significantly, shows all sub-regions in the Sacramento Valley (sub-regions 1 through 7), and Delta regions (sub-regions 8 and 9) have significant discrepancies (p-value < 0.01) between the models and sub-regions 18, 19 and 20 show also discrepancies (p-values < 0.1).

4.2. Probability of ending overdraft over a period

Average annual results for surface diversions, pumping, and change in groundwater storage from C2VSim, CVHM and the combined results, which assume both models are equally valid, are obtained for each sub-regions (detailed results included in the Supporting Information document). Assuming a normal distribution, the estimated mean μ and variance σ^2 of annual groundwater storage change are used to compute the probability of achieving groundwater sustainability, as defined in Section 3.2, over a period T.

Probabilistic changes in groundwater storage are obtained for various net water use reductions, wr, and accounting for a buffer b between the minimum threshold (MT) and groundwater storage levels at the beginning of the implementation period (see Fig. 2 for a detailed explanation of the parameters). Hydrologic and human-induced variability of annual changes in groundwater storage is embedded in the variances obtained for each of the three model results, with the combined model results also reflecting model uncertainty (see Table SI.1, in the Supporting Information document).

Fig. 5 shows the probabilities of ending groundwater overdraft for $b = 0$ in sub-regions in the Delta, East Side Streams and San Joaquin River basins at various reductions in annual net water use, wr, after $T = 20$, 100, or 200 years (similar results for all sub-regions are included in the Supporting Information document). A net water use reduction that equals to the unsustainable use of groundwater (rate of overdraft, $wr_{i,j} = -\mu_{i,j}$) theoretically has a 50 percent chance of achieving sustainability in any temporal period. As $wr_{i,j}$ increases, the probability of ending groundwater overdraft rises for each sub-region, although at different rates depending on the sub-regional variance of annual groundwater storage change.

In Fig. 5 we can see three similar cases with two sub-regions each:

- Sub-regions 9 (Delta) and 12 (Turlock Basin) are sustainable on average, as their average change in annual groundwater storage is positive. Without any water reduction, their chances of maintaining groundwater levels in 20 years is over 70%, however that also means that under unfavorable hydrologic conditions over the next 20 years, they would have to reduce water use to ensure sustainability even that they are sustainable on average.
- Sub-regions 10 (Delta-Mendota Basin) and 11 (Modesto and Southern Eastern San Joaquin Basin) have low values of average annual overdraft (5 and 10 mcm/year respectively). Given that, without any water reduction, they would have almost 50% chances of being sustainable over the next 20 years. To ensure sustainability under any potential hydroclimatic future, they would have to reduce water use by a much larger amount (approximately 100 mcm/year).
- Sub-regions 8 (Valley floor east of the Delta) and 13 (Merced, Chowchilla, and Madera Basins) have larger values of average annual overdraft (68 and 143 mcm/year respectively). Their larger variances also make the curves flatter. It is surprising to see that these regions with significant historic groundwater depletion have about a 20% chance of being sustainable even without any reduction in water use. Conversely, to ensure sustainability under any hydroclimatic future, the water reductions should be at least 3 times the average amount of current depletion.

As the management horizon for water use reductions increases from 20 years to 100 years and to 200 years, probability curves become narrower owing to the decreasing chances of continuously favorable or continuously unfavorable hydrology over longer periods. As T increases,

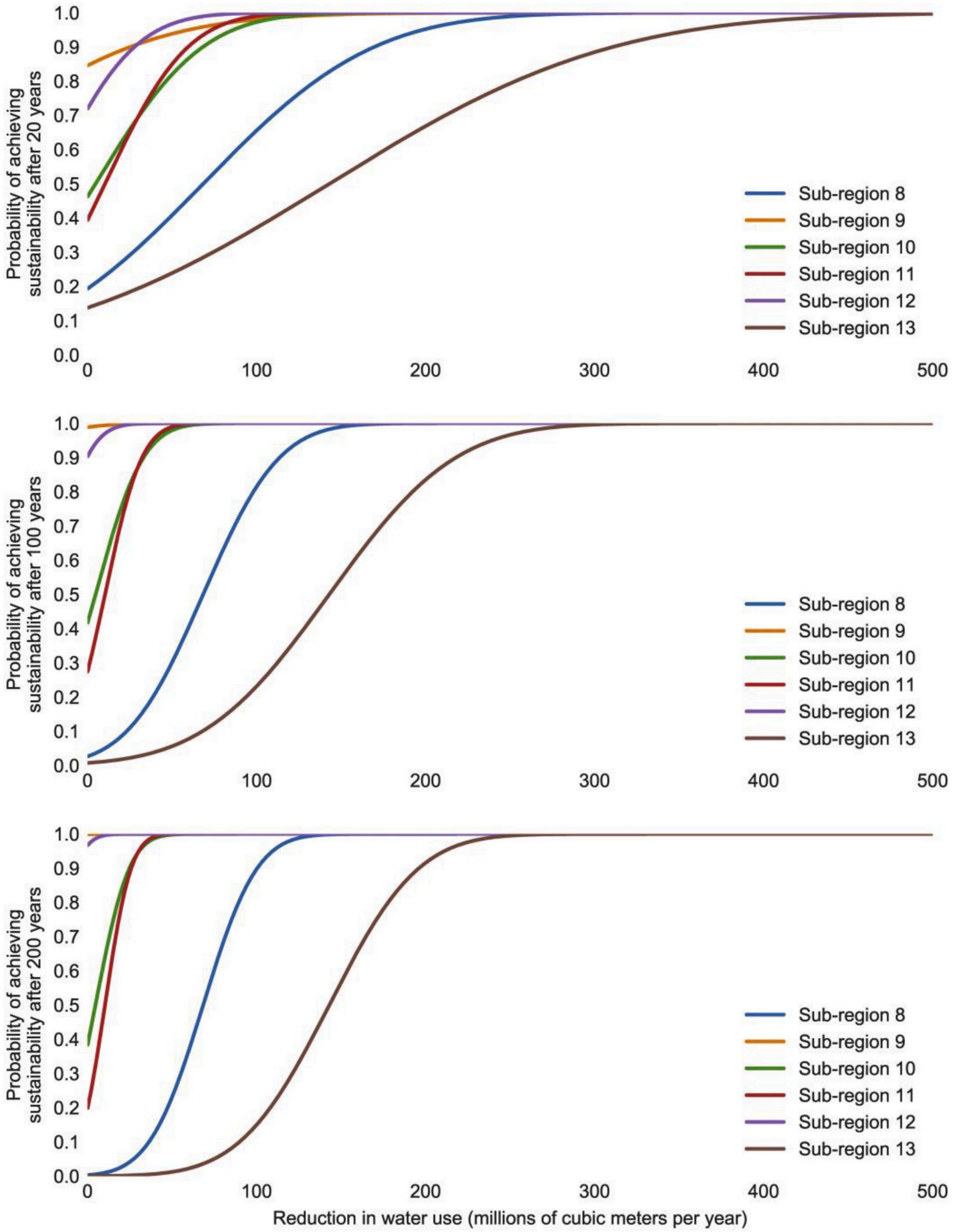


Fig. 5. Probability of achieving sustainability for sub-regions in the Delta, East Side Streams and San Joaquin River Basins, with varying annual water use reduction, in 20yr (upper), 100yr (middle) and 200yr (lower). In this scenario, $b = 0$, that is, the minimum threshold is equal to groundwater storage at $t = 0$. Sub-regions in the Delta and East Side Streams are 8. Valley floor east of the Delta, and 9. Delta. Sub-regions in the San Joaquin River Basin are 10. Delta-Mendota Basin, 11. Modesto and southern Eastern San Joaquin Basin, 12. Turlock Basin, and 13. Merced, Chowchilla, and Madera Basins.

the probabilities decrease of both ending groundwater overdraft with $wr_{i,j} < -\mu_{i,j}$, but also of continuing to be unsustainable with any $wr_{i,j} > -\mu_{i,j}$.

A key point of these results is the importance of the annual variance of the groundwater storage change. Higher variances, due to higher inter-annual variability in water availability and use of groundwater resources, mean more uncertainty in the likelihood of achieving sustainability. Further increases in future variability (and inter-annual variance) that are not considered here, but may occur with climate change and when considering temporal autocorrelation of wet and dry years would further draw out these estimated probabilities of ending overdraft from the simpler independent historical variances employed here.

When introducing a minimum threshold below the groundwater levels at the beginning of the implementation period, chances of overdraft increase substantially. As an example, Fig. 6 shows the probability of achieving sustainability for sub-region 21 (Southeastern Kern County Basin) after $T = 20$ years, for various net water use reductions and with buffer $b = 0$, 3, and 6 m. To convert b, expressed in terms of water level elevation [m], to groundwater storage change, we use the value of

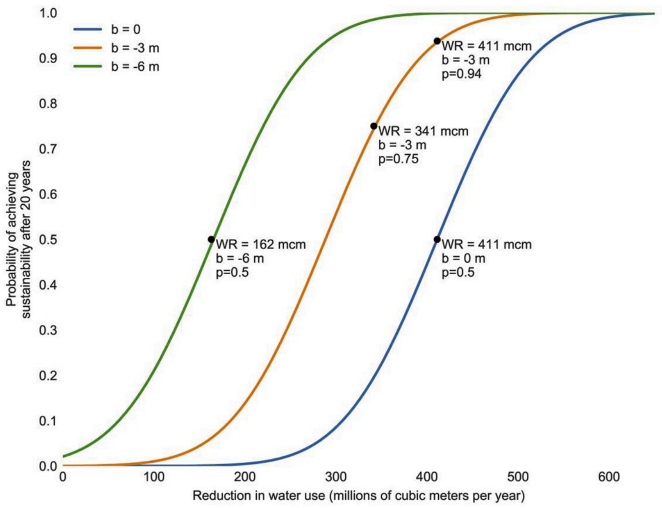


Fig. 6. Probability of achieving sustainability in sub-region 21 (Southeastern Kern County Basin) for various reductions in net-water use and different minimum thresholds below groundwater levels at the beginning of the implementation period (b is the allowable buffer as defined in Fig. 2).

specific yield and the area of the sub-region.

Fig. 6 shows a trade-off between reductions in water use and the choice of buffer b to the minimum threshold. The long-term average overdraft of the sub-region 21 is 411 mcm/year. At $b = 0$, a net water use reduction of the same amount has 50 percent chance of being sustainable. With $b = 3$ m, the chances of being sustainable at that same *wr* increases to 94%, and for $b = 6$ mt, the risk of sustainability failure is near zero. But this trade-off may also be employed to allow *unsustainable* practices that may meet sustainability criteria for short *T* (20 years), but not for long *T*. For instance, for $b = 6$ m, sub-region 21 would have 50% chance of being sustainable after 20 years with a net water use reduction of ~162 mcm/year. With a reduction of ~341 mcm/year and $b = 3$ m, the region has a 75% chance of meeting groundwater storage sustainability after $T = 20$ years. Both reductions are less than the average measured overdraft, $-\mu_{i,j}$, of ~411 taf. Over longer periods, the likelihood that the region remains sustainable at those smaller *wr*, however, will decrease (compare to Fig. 5).

4.3. Agricultural costs of ending overdraft by reducing water use

Using the probabilities obtained for ending overdraft over a specified period *T*, and the economic costs of water use reductions from Section 3.3, we estimate the economic costs of achieving sustainability over a period with a given reliability and for different thresholds. Here we assume no additional water supplies, and the regions achieve sustainability only by reducing agricultural water use.

Trade-off curves of the reliability of achieving sustainability versus economic costs of water use reductions follow an S curve (see Fig. 7 for an example with 3 sub-regions, and the Supporting Information document for detailed results of all sub-regions). Small water use reductions have low probability of achieving sustainability but incur smaller economic costs. Achieving sustainable water levels with high likelihood requires an exponential increase in economic costs, because larger and more expensive reductions in water use are needed, especially to guarantee sustainability after shorter periods. For instance, at $b = 0$, the economic cost to achieve sustainability in region 15 is $10 million per year for a reduction in water use of the same amount than the groundwater overdraft (a 50 percent chance of achieving sustainability). To ensure sustainability, the cost would be roughly 6 times higher. Greater annual net water use reduction increases the reliability of groundwater sustainability, but at rapidly increasing economic costs.

Allowing for minimum thresholds below the groundwater levels at the beginning of the implementation period ($b > 0$) significantly reduces the economic costs to guarantee sustainable management over the shorter 20 year period. But longer compliance periods, reduce the economic effects of the thresholds. This confirms that the introduction of thresholds can imply a false pathway to sustainability, if a GSA chooses a $wr < -\mu_{i,j}$ and thus taking the explicit, significant risk in failing the sustainability criteria after 20 years for the benefit of having some significant chance of succeeding. However, over longer management periods, the risk of failure, at $wr < -\mu_{i,j}$, will only increase, at potentially higher economic costs to implement corrections in *wr*. The trade-off between economic losses and groundwater management sustainability therefore needs significant consideration when designing the measurable objectives, the minimum threshold, and, hence the operating buffer *b*, as these significant affect risk of failure and water use reduction decisions.

5. Policy implications

Ending groundwater overdraft in the Central Valley will not be a clean or easy process. There will be continuous challenges and uncertainties, politically and technically, requiring adaptive adjustments to both water-budget estimates and management actions over time. The original treatise on adaptive environmental management (Holling, 1978) suggested the use of field data and frequently updated models to assess past and current actions and inform and suggest changes in management, which in turn can also be tested with data and updated models. This section discusses some aspects of adaptive management likely to be needed for SGMA implementation to be successful.

5.1. Initial estimates will be wrong

Substantial mis-estimation of overdraft will likely occur during the first years of California's Groundwater Sustainability Plan (GSP) implementation. Errors in overdraft estimation can arise from many sources, including mis-estimation of water budget components like groundwater pumping, recharge of applied water, streamflow, and precipitation, evaporation and evapotranspiration, groundwater flows to and from neighboring regions. Errors can also stem from inaccurate future projections of water use and hydrologic conditions over the planning period, as well as from model uncertainties. Newer estimates of overdraft will improve with time, but uncertainties will unavoidably remain.

To improve the estimates it will be essential to consider local knowledge, better data, and models with sufficient resolution. Both C2VSim and CVHM were developed by governmental agencies at the Central Valley scale, sometimes with difficulties to obtain local data, and their objectives were not to develop local groundwater plans. Models that consider local knowledge are likely to have less uncertainties that those shown in this paper.

Many future scenarios must be considered and prepared for groundwater sustainability. Plans, planners, and stakeholders should be prepared for droughts imposing more difficult sustainability vs. economic trade-offs, luckier cases where overdraft rates are lowered faster than expected, and mis-estimations where overdraft rates fall more slowly than expected. Responses to these conditions will be unique to each GSA, but the consequences will be expensive and should be carefully considered using data-informed models.

The methods employed in this paper can help estimate the probabilities of outcomes and show the range of outcomes that groundwater plans, planners and regulators should prepare for. The presence of unavoidable uncertainties in overdraft estimates and forecasts will make decision-making harder and more controversial, and imply risks and expenses for local water users, GSAs, and state regulators.

5.2. How can groundwater plans include uncertainty?

Effective groundwater plans should include procedures for tracking

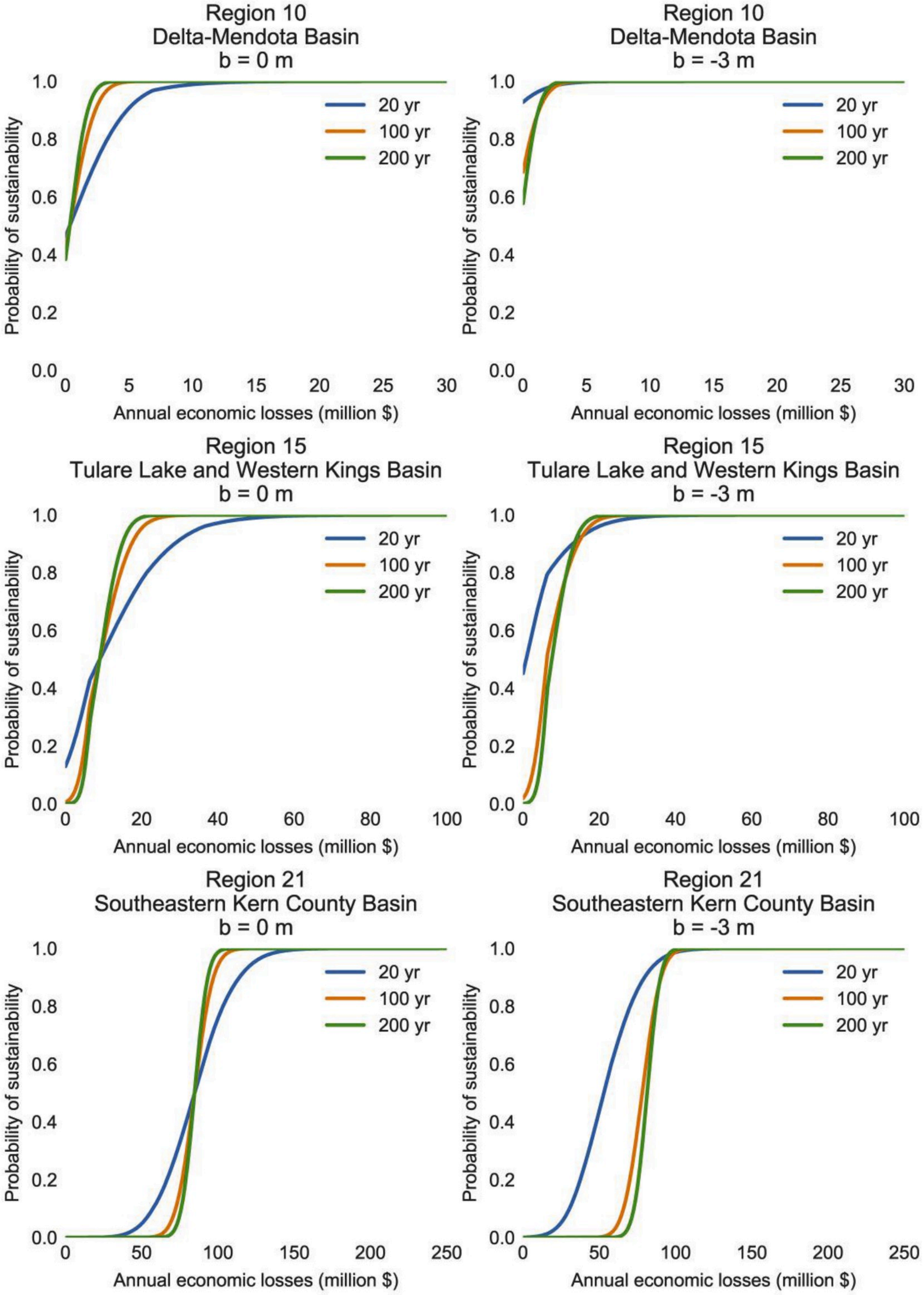


Fig. 7. Trade-offs between economic cost and probability of achieving groundwater sustainability after 20, 100 and 200 years and economic losses for sub-regions 10, 15 and 21.

divergence from planned sustainability milestones and adapting management actions, particularly during droughts. Management adaptation at certain pre-agreed trigger points in measured groundwater storage also will be desirable with improved modeling and data, as well as with changes in external water availability.

One adaptive management approach is to let annual pumping quantities vary with hydrologic conditions. Economically, pumping should decrease in wet years to increase in-lieu groundwater recharge, and be allowed to increase in dry years (Tsur, 1990). However, long-term pumping rates must also adapt to long-term storage limitations and risks of undesirable results. Pumping should decrease if groundwater elevations fall over extended droughts. Having pumping rules adapt to hydrologic conditions, using trigger storage levels, can help preserve groundwater for drier years, provide time to prepare for greater shortages under prolonged drought conditions, and allow adjustments to groundwater use as conditions and understanding develop.

Local variability in water supplies also should be considered when planning for sustainability. Here, higher variances in surface supplies, even with lower average overdraft, might increase variability in groundwater levels, with potentially tougher groundwater cuts if sustainability thresholds are achieved. GSAs should account for variability in surface water supplies.

5.3. Adjusting groundwater pumping shares across years

As an example of flexible rules to allow more groundwater use in drier years and discourage groundwater use in wetter years, shares of pumping could be set by a formula based on precipitation and surface water availability for the basin. For example, in the Tulare basin water supplies are mostly local, with some supplemental San Joaquin basin and Sacramento Valley imports. During wet years, groundwater use would be reduced and natural as well as some form of active agricultural managed aquifer recharge (Ghasemizade et al., 2019) would supplement groundwater availability for drier years. As groundwater is drawn down, pumping shares would be reduced to reflect growing water scarcity.

Implementing such rules in real time is tricky, because runoff and water import quantities typically are not accurately known until after the wet season has ended. So a forecast of allowable pumping must be made early in the calendar year, before the growing season, with credits and penalties for going over or under the final allocations affecting allowable pumping in future years.

5.4. Adjusting average groundwater pumping over time

Drought lengths and intensities are largely unpredictable, particularly with climate change. While snowpack, soil moisture storage, and existing California surface water storage can be replenished within a single wet winter (i.e., during 2006, 2011, and 2017), groundwater storage recovery occurs on multi-year to multi-decadal periods. A four-year drought can require decades of above average to wet precipitation years to recover water levels. From 2001 to 2017, California has had only 3 very wet years (2006, 2011, 2017) and another 3 average to above average years (2005, 2010, 2016)—resulting in nearly two decades of net "groundwater drought" in some areas. Even under sustainable conditions, the Central Valley's large inter-annual hydrologic variability can produce aquifer drawdown and refill cycles over decades. Adaptive management will be needed to adjust groundwater pumping to longer term water availability.

An approach to adjusting long-term pumping to long-term groundwater levels would be to have a fee for groundwater pumping which increases with lower groundwater levels. Funds from this fee would be used to recharge additional water or purchase land to fallow and reduce net basin water use. Such a fee might increase with greater depth to groundwater, and decrease as groundwater levels recover.

Having adjustments built into local groundwater plans should make it easier to implement plans, easier for water users to anticipate changes in their groundwater availability, and easier for state agencies to evaluate plans. In California, GSAs will likely need to adjust such rule and fee formulae, but adjustments should be less abrupt and controversial than changing fixed pumping rates or allowable pumping volumes.

While long-term withdrawal from groundwater must be less than in the past for currently overdrafted basins, the large storage capacity of the Central Valley aquifer system and other alluvial aquifer systems in California provides opportunities for long-term water availability planning unlike any available with California's surface water storage. Groundwater storage capacity gives agencies multi-year planning horizons to adjust to drought conditions as they evolve, while addressing sustainability requirements.

5.5. How can state agencies regulate responsibly with uncertainty?

Uncertainty in overdraft rates and local groundwater plan effectiveness also challenge state regulators, such as California's Department of Water Resources (DWR) and State Water Resources Control Board (SWRCB). Groundwater basins will often deviate from the groundwater and overdraft targets specified in groundwater sustainability plans. Does this mean that the plan is unsustainable, or that the basin is merely unlucky in the short term and future wetter periods will likely improve conditions? In making these judgements and regulatory responses, California's state agencies involved in local plan regulation should have similar and compatible procedures and rules. Especially important would be to overview the tradeoff between reductions in net water use and thresholds below groundwater levels at the beginning of the implementation period.

One approach would be for state regulatory agencies to set clear expectations for the range of uncertainty that local planning efforts must account for in setting local decision-making processes, triggers, and actions as part of an adaptive water management process for a local groundwater plan. If recent conditions have been dry, expectations of progress in eliminating overdraft might be explicitly reduced for a time. If recent conditions are wet, expectations for overdraft reduction would be tightened.

State regulators also should support reducing uncertainties in modeling estimates and basin response to hydrologic variability and basin management over time. The 5-year review included in California's regulations might be used to assess improvements of plans and modeling.

Local plans not designed to account for variability and uncertainty in future surface water availability will make it more difficult for local groundwater and state agencies to find, enforce, and adjust criteria and policies. Regulatory assessment should correspond to physical reality, given the large variability and uncertainty in estimates of overdraft and long-term sustainability. Drier than planned conditions that force much higher than anticipated pumping reductions, economic or legal disruptions might merit regional and state assistance to help local governments and water users comply with groundwater regulations.

6. Conclusions

We have reviewed water balance estimates from two regional-scale groundwater models for sub-regions within California's Central Valley. The results show significant annual variability of water-budget estimates. This variability is influenced by different climatic and hydrologic regimes within each sub-region, and varied human-related water management.

The models' results are generally comparable at the regional scale, but agreement between the two models decreases at the sub-region scale. Statistical analysis of the results of both models at the sub-regional scale suggests significant modeling uncertainty. These uncertainties and variabilities pose significant challenges for planning and regulating groundwater sustainability.

Using combined model result statistics, we obtained probabilities of achieving groundwater sustainability by net water use reductions for each sub-region in the Central Valley for different planning horizons. The variance of the annual groundwater storage change significantly increases uncertainty of achieving sustainability, especially for shorter periods.

Greater annual net water use reduction increases the reliability of groundwater sustainability, but at increasing economic costs. Setting minimum thresholds at levels of 10 ft or 20 ft below current levels would significantly increase the probability of achieving sustainable outcomes within 20 years and buffer against the risk of unfavorable hydrologic conditions. But it may incur other costs due to land subsidence, canal infrastructure damage, and well outages. The trade-off between economic losses and groundwater sustainability probability should be considered in regulation and planning for sustainability. It will be also key to assess the trade-off between net water use reductions to achieve sustainability and thresholds below groundwater levels at the beginning of the implementation period, which may lead to false sustainability pathways.

Eliminating groundwater overdraft is essential for sustaining prosperity in agriculture and rural communities through future droughts and to sustain desirable environmental conditions in California. Accounting methods that consider hydrologic variability and model uncertainty will be central in understanding groundwater sustainability and providing a consistent and transparent basis for local and state groundwater policy and management.

Data availability

The data and code to replicate all the analyses included in this paper are available at https://github.com/alesbou/GWSustainabilityUncertainty-Costs.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

A. Escriva-Bou: Conceptualization, Methodology, Data curation, Writing - original draft, Writing - review & editing. **R. Hui:** Conceptualization, Methodology, Data curation, Writing - original draft, Writing - review & editing. **S. Maples:** Conceptualization, Data curation, Writing - original draft, Writing - review & editing. **J. Medellín-Azuara:** Conceptualization, Writing - review & editing. **T. Harter:** Conceptualization, Methodology, Writing - review & editing. **J.R. Lund:** Conceptualization, Methodology, Writing - original draft, Writing - review & editing.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2020.110426.

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