Can Managed Aquifer Recharge Mitigate Drought Impacts on California's Irrigated Agriculture? The Role for Institutions and Policies

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Managed Aquifer Recharge (MAR)—storing water of various qualities in aquifers—is considered a potential strategy to mitigate recurring drought effects in California. We evaluate the performance of specific policies and institutions under a set of climate change scenarios in the Kings Groundwater Basin in California's Central Valley.

California is characterized by growing populations in urban centers along the Pacific coast next to extensive irrigated agricultural areas. Groundwater is a major source for both residential and agricultural uses. It supplies nearly 40% of the water used by these sectors in an average year and significantly more during drought periods. Some agricultural regions are fully supported by groundwater. With the intensification of drought conditions across the state, water users increase groundwater extractions to a level that threatens aquifer sustainability. After consecutive droughts in the last decade, several aquifers in California's Central Valley and around the state were depleted to a critical level. This led to a new regulation on groundwater use—the Sustainable Groundwater Management Act (SGMA), which is designed to recover sustainable groundwater levels in the next 20 years.

MAR is a set of practices and institutions that allows the recharge of water of various types and qualities (surface water, recycled wastewater, and even groundwater from different locations) into a given aquifer. Therefore, it can reduce subsidence (pumping-induced land sinking) damages, prevent saline water intrusion, protect wetland habitat, provide flood protection, and more. In this work, we examine the role of MAR in the Kings Groundwater Basin. Using several climate-change scenarios, we evaluate how MAR applicability is impacted by possible institutional arrangements and regulatory policy interventions.

Features of Our Analytical Framework

We base our methodology on an iterative process between two models: a hydrologic model and a dynamic economic optimization model (EOM). The hydrologic model was developed using the Water Evaluation and Planning (WEAP) software with a detailed representation of the Kings Groundwater Basin and surrounding area (WEAP/CVPAM—Central Valley Planning Area Modified). The EOM uses an integrative approach, that combines partial-equilibrium-optimization models of both the water and agricultural sectors, calibrated and applied to the same region (Figure 1).

The Hydrologic Model

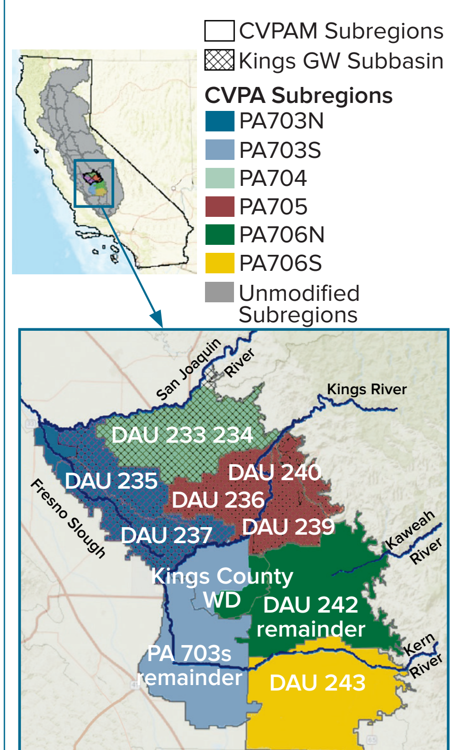
WEAP/CVPAM was used to simulate the hydrology and water management decisions in the region, including rainfall-runoff hydrology, water resources infrastructure, and water consumption, while applying complex operating rules and constraints to the water allocation decisions in the region. WEAP/CVPAM allocates water using a linear programming (LP) framework, defined by user-specified water consumption priorities and supply preferences. Evapotranspiration, applied water, and groundwater volume and height (head) were calibrated against the California Department of Water Resources' land and water use estimates during 1998 to 2010, and data from 2,431 wells in the region.

The Economic Optimization Modeling Framework (EOM)

The EOM framework includes variables for both land-use decisions and farm management practices. The model also factors in water allocations from different sources such as surface water, groundwater, and treated wastewater. Additionally, it accounts for groundwater dynamics, infrastructural development, deep percolation, lateral flows, and, most importantly, in our context, MAR.

We modeled 20 different land categories, including land fallowing, and

Figure 1. Decision Analysis Units (DAUs) and Subdistrict Division in the Model for the Kings Groundwater Basin



matched production functions to main crops grown in the region. We calibrated the EOM to actual water prices, land allocations, and local conditions in the region. The EOM produces an optimal set of water uses, land uses, and quantities to be pumped from and recharged to the aquifer, and derives net benefits by subdistrict.

Set of Policy Scenarios

We used the analytical framework described above to evaluate three alternative policy scenarios regarding MAR in the region. The first, which sets the benchmark for the other two, is the social planner solution (Social), and corresponds to the solution that maximizes the present value of net gains of the entire region, ignoring income distribution implications.

The second, termed Sustainable, is constructed in the spirit of SGMA. In this scenario, we require that each subdistrict groundwater head at the end of the 20-year planning horizon will be greater or equal to its initial level at the onset of the planning horizon. We adopt the criteria from the groundwater sustainability plans (GSP) of the two largest (in terms of land area) groundwater sustainability agencies (GSA) in the region—Central Kings GSA and North Kings GSA.

The third policy scenario, termed Credit, uses the well known principles of "capacity sharing" of an aquifer system. According to this policy, each decision analysis unit (DAU) holds a credit account, based on the storage capacity of the aquifer, which limits the annual amount that can be extracted from the storage/aquifer. An initial endowment of annual credit is assigned to each DAU, which increases with MAR (through infiltration basins) and decreases with pumping throughout the planning horizon. The limitation on groundwater extraction is unique to the Credit scenario. In the other two scenarios, groundwater extraction is limited only by hydrogeologic feasibility constraints, that prevent groundwater levels from falling below some minimal threshold.

For each of the policy scenarios described, we simulate three climate scenarios in terms of regional rainfall and surface water availability from the Kings River, the San Joaquin River, and the Friant-Kern Canal. Under the first simulation, termed Average, we assume constant values of climate conditions throughout the entire planning horizon, set at the long-term annual averages of rainfall and surface water availability in the region. The second, termed Hist1, assumes regional climate conditions similar to those in the period 1975–1996. The third, termed Hist2, refers to the climate conditions in the region during the period 1983–2004.

Compared to long-term climate indicators in the region, under Hist1, the annual average rainfall is higher by 2%, the San Joaquin River flow by 10%, the Kings River flow by 1%, and the flow of the Friant-Kern Canal is lower by 3%. Under Hist2, the San Joaquin River average flow is higher by 7%, whereas average annual rainfall, Kings River, and Friant-Kern Canal average flows are lower by 2%, 3%, and 7%, respectively. Annual variation in rainfall and river flows is higher under Hist1 relative to long-term values. For Hist2, annual variation in Kings River flow is similar to historical values; it is higher by 10% for the San Joaquin River flow, and lower by 5% and 7%, for rainfall and Friant-Kern Canal flow, respectively.

Results

Results for land allocation to crops using the Social scenario under Average conditions suggest that in most subregions, an increase in area of field crops and vegetables takes place at the expense of fallowed land, compared to baseline conditions. Land devoted to permanent crops is similar to observed levels. The exception is DAU 235, in which land fallowing and field crop shares increase, and land allocated to fruit crops and grapes shrinks, compared to observed levels. Interestingly, these land allocation results remain robust in most policy scenarios and climate simulations analyzed.

The total annual agricultural water use in the region declines from about 1.4 million acre-feet (MAF) to about 1.2 MAF over the planning horizon. Examining crop levels and water use trends at the subregion indicates that field crops are excessively irrigated in DAU 237 and Kings County Water District (WD) at the beginning of the planning horizon, with a decreasing trend. The time paths of water application levels averaged for each DAU suggest that deficit irrigation is optimal across most of the region and throughout most of the planning horizon. These lower water application levels are attributed to a decrease in regional groundwater extractions, compared to observed values, which according to model results, is increasing from 150 thousand acre-feet (TAF) per year to nearly 200 TAF per year throughout the planning horizon.

Extraction of groundwater is concentrated primarily in DAU 235—a subregion with very little access to the regional surface water sources. On average, groundwater head in the region increases by 10%. We observed an increasing trend in groundwater levels in four DAUs, and a decreasing trend in two others. This generates a cone of depression towards DAU 235, in which groundwater head remains constant through time. Recharge of groundwater is achieved through excess irrigation of field crops and from percolation of treated wastewater.

Negatively correlated with water application levels, the value of water in production presents increasing trends for DAU 235, DAU 237, and Kings County WD. Interestingly, water value in DAU 235 is lower than for the other DAUs mentioned, due to the considerably higher water salinity level in this subregion. Overall, the optimal plan suggested by the model predicts an annual regional profit of about $2.2 billion, distributed roughly according to DAU size.

Policy and Climate Scenarios

Comparing land allocation results across policy scenarios and under Average climate conditions, we find that the results of the Sustainable scenario are similar to the results of the Social scenario. However, the results of the Credit scenario suggest a dramatic decrease in groundwater extraction and total water use, and consequently an increase in land fallowing. This is mostly at the expense of tree crops, and to a smaller extent on field crops in DAU 235. For the rest of the region, land allocation differences compared to the other policy scenarios are far less significant.

Under the Sustainable scenario, total water use in agriculture is higher than in the Social scenario. Similar to the Social scenario, some subregions demonstrate a decreasing trend in water use. However, towards the end of the planning horizon, water use increases again. This translates into excess irrigation, mainly at the beginning and the end of the planning horizon, which manifests in significantly higher recharged quantities to groundwater than under the Social scenario. This recharge strategy results in higher regional groundwater levels, on average, compared to the Social scenario. As in the Social scenario, MAR through infiltration basins is not warranted.

Results of the Credit scenario suggest substantially lower use of water in agriculture, compared to the Social scenario. Groundwater pumping is profoundly lower, and reused quantities of treated wastewater are higher under this scenario compared to the results of the Social scenario. Due to lower water use in agriculture, recharged quantities are also smaller for this scenario compared to the others. However, as mentioned, pumping is also considerably less. Therefore, average groundwater levels increase more overtime in the Credit than the Social scenario. Different from the other scenarios, MAR through infiltration basins is found to be optimal under the Credit scenario. This is because some subdistricts in DAU 235 and Kings County WD rely solely on groundwater, which forces recharge as a means to accumulate credit to enable groundwater extraction throughout the planning horizon.

Comparing results between climate simulations and under the Social scenario, we find that treated wastewater and groundwater storage are used as sources for stabilizing supply and smoothing consumption. This is when significant reductions in surface water supply occur under the Hist1 and Hist2 climate simulations. A second interesting result from the analysis of climate simulations emerges when we compare land allocation across all scenarios. For the most part, land allocation to crops in the region remains similar regardless of the assumed policy scenario or climate simulation used. The exception to this rule is the Credit scenario, in which land allocation results are sensitive to the assumed climate conditions.

Table 1 presents total regional economic welfare differences compared to the Social scenario in annual terms, across scenarios and simulations. The institutional arrangement under the Credit scenario inflicts significant welfare reductions on the region, and specifically on DAU 235, relative to the benchmark. The economic cost of the Sustainable scenario is in the range of $8 to $10 million USD annually, which is relatively mild. By comparison, revenues from agricultural commodities in the Kings Groundwater Basin are estimated at $6 to $8 billion USD annually.

We use the difference in regional economic welfare divided by total recharged quantities as an upper limit of the dollar value for recharged quantities in the region. Table 2 presents the differences compared to the Average climate simulation of total recharged

Table 1. Reductions in Economic Welfare Compared to the Social Scenario (1,000 USD)

	Average	Hist1	Hist2
Social (benchmark)	—	—	—
Sustainable	7,893	9,921	9,879
Credit	1,756,849	2,283,592	1,732,795

Note: The regional economic welfare achieved under the Social scenario is the highest. Therefore, values presented in the table are all negative.

Table 2. Differences in Total Recharged Quantity and Economic Welfare per Unit of Water Recharged Compared to the Average Climate Simulation Across Policy Scenarios

		Differences in Total Quantity Recharged (TAF*)	Differences in Economic Welfare per Unit of Water Recharged ($/AF*)
Hist1	Social	667	1,556
	Sustainable	447	421
	Credit	713	38
	Average	**609**	**671**
Hist2	Social	316	682
	Sustainable	323	294
	Credit	116	332
	Average	**251**	**436**

* Note: TAF=thousand acre-feet; AF= acre-feet.

quantities in the region over the entire planning horizon, as well as the differences in economic welfare per unit of water recharged across policy scenarios for the climate simulation Hist1 and Hist2.

Total quantities recharged in the region are lower for both climate simulations compared to Average conditions. The value of an acre-foot (AF) recharged in the region is in the range of $38 to $1,556 per AF. Excluding the Credit scenario under Hist1 climate conditions, the value of a unit of water recharged exceeds the value of water in production, which is in the range from $50 to $250 per AF. This suggests that the indirect benefits associated with recharged water quantities are substantial and surpass their direct benefits in most cases.

Conclusions and Policy Implications

In a first-best scenario, our analysis suggests that a significant reduction in groundwater, complemented by deficit irrigation, is possible without inflicting significant changes to crop-yield levels and land-use decisions. We find that excess irrigation of field crops and some flooding of fallowed land at the beginning of the planning horizon is the preferred method for recharging groundwater stocks, regardless of the assumed climate conditions. This strategy is amplified when minimal threshold levels of groundwater head at the end of the planning horizon are imposed, as part of our Sustainable scenario, suggesting that this institution incentivizes MAR and increases its value to the region. Diverting water to infiltration basins and away from the irrigation of crops is only warranted under the Credit scenario, and at a high economic cost, suggesting there are substantial tradeoffs associated with this recharge method for the region.

Total recharged quantities in the region over the entire planning horizon across policy scenarios and climate simulations are substantial, ranging between 4.88 MAF to 9.54 MAF. In most cases, the calculated value of a unit of water recharged is high compared to the direct value of water in production, supporting MAR.

Our analysis suggests that institutional arrangements are meaningful. This is demonstrated through the changes in regional land allocation and water-use decisions under the Credit scenario, causing detrimental economic impacts compared to the Social benchmark.

Results from the analysis also suggest that the impact of future climate uncertainty on the region is highly dependent on the prevailing institutions, and provides an estimated $500 million annually as an upper limit for the regional economic damage associated with uncertainty in water availability.

The Sustainable scenario presents a good compromise for the region between the ideal benchmark (Social) and the more stringent institutional arrangement (Credit). In the Sustainable scenario, groundwater levels increase the most, economic losses are small, and the simulated climate conditions appear to have a minor impact on the optimal strategy. This, in turn, implies that this institution is likely feasible and relatively easy to implement, monitor, and enforce.

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For additional information, the authors recommend:

Reznik, A., A. Dinar, S. Bresney, L. Forni, B. Joyce, S. Wallander, D. Bigelow, and I. Kan. 2020. "Managed Aquifer Recharge as a Strategy to Mitigate Drought Impacts in Irrigated Agriculture: Role of Institutions and Policies with Application to California." UCR SPP Working Paper Series, March, 2020 WP# 20-04. https://bit.ly/3ndWXEt.

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