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Statewide Effects of Ending Long-Term Groundwater Overdraft in California

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Abstract: Groundwater overdraft is a major problem globally and has been a growing problem for California for decades. This overdraft is predominantly driven by the economic value of water for agricultural production and cities. Spurred by the recent drought, California passed legislation requiring the elimination of groundwater overdraft by 2040. This paper employs a statewide hydroeconomic optimization model to explore potential water supply effects of ending long-term groundwater overdraft in California's Central Valley for several general water policies with historical and warmer–drier climates. The model minimizes agricultural, urban scarcity, and operating costs over 82 years of historical hydrologic variability, given today's infrastructure and environmental flow constraints. The model results assess effects of overdraft and Delta policies for different climates on water deliveries, economic costs, environmental flows, water market operations, and the economic value of expanding infrastructure capacities. Prohibiting long-term overdraft leads to reduced agricultural water use and reoperations, and reduced outflows to the sea from the Sacramento-San Joaquin Delta, where water availability policies become important. In combination with a warmer–drier climate, ending overdraft further exacerbates water scarcities, increases environmental and economic costs, and increases the marginal economic value of water exports from the Delta, which are likely to worsen water conflicts and illustrate connections of California's groundwater and surface water problems. Economically useful adaptation actions include more water transfers involving the Delta, water markets, and trades; conjunctive use of surface water and groundwater; and recycled wastewater supplies for coastal urban users. **DOI: 10.1061/(ASCE)WR.1943-5452.0001096.**

Author keywords: Overdraft; Adaptation; Hydroeconomic modeling; Water management.

Introduction

Groundwater overdraft is a common response to surface water scarcity when high economic demands exist for water use in agriculture and cities. In California, supply and demand disparity combines with a great seasonal and geographical imbalance of water supplies and demands, where water is much more available during winter in northern parts of the state, but water demands are mostly in central and southern California in spring and summer. This disparity has led to an unusually interconnected water system that stores and delivers water to users when and where it is most needed (Hanak et al. 2011; Nelson et al. 2016). In California, groundwater overdraft of 1.2–2.5 km^3 per year occurs in the context of a very large diverse network of water supplies, demands, infrastructure, and policies (Hanak et al. 2017).

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The Sacramento-San Joaquin Delta (Delta) is the major hub in California's water system, with environmental and water allocation policies that drive operation, planning, and management decisions. Lund (2016) reviewed the Delta's role in supply reliability and issues related to operations and regulations. Changes in regulations and climatic conditions and increasing water demand make Delta water management complex, requiring adaptive planning and management. This paper explores how ending groundwater overdraft in California potentially affects water management and performance more generally over the state's extensive surface water network.

Conjunctive use of groundwater and surface water is especially important for addressing supply imbalances between years. When surface water is abundant, water is mostly supplied from surface water sources for agricultural and urban uses, and some surface water artificially recharges aquifers. In droughts, when surface water is scarcer, more water is pumped from groundwater. Groundwater adds flexibility to water operations, especially in drier times. Most economic consequences of drought surface water scarcity in California are mitigated with groundwater pumping (Lund et al. 2018; Medellin-Azuara et al. 2015). Groundwater's expanded use in dry years contributes to groundwater overdraft (Harou and Lund 2008; MacEwan et al. 2017).

Groundwater overdraft occurs when groundwater pumping exceeds aquifer recharge over a long period (CDWR 2003). Groundwater is often more accessible or has better water quality than surface water, requiring less treatment cost, and is often less expensive to exploit. On average, groundwater supplies about 30% of California's water use, increasing to 40% or more during dry years, with many small towns and cities in the Central Valley relying entirely on groundwater (CDWR 2003, 2016). California's Central Valley aquifer accounts for approximately 74% of state groundwater extraction (CDWR 2015a). Annual average statewide overdraft is 1.2–2.5 km^3 (1–2 million acre-feet) (CDWR 2003, 2015a). More than 90% of California's groundwater overdraft is in its Central Valley aquifer, with a depletion rate of 2.2 $km^3/year$ (Scanlon et al. 2012). Groundwater overdraft can increase pumping costs; degrade groundwater water quality; increase land subsidence; incur costs for deepening wells; reduce flows for streams, wetlands, and springs that are hydraulically connected to aquifers; and cause seawater intrusion into coastal aquifers (Konikow and Kendy 2005; Harou and Lund 2008; CDWR 2016; MacEwan et al. 2017). Several regions, including San Joaquin Region and Tulare Lake Basin of the Central Valley, Antelope Valley, the Santa Clara Valley, and several coastal aquifers, suffer from overdraft in California (CDWR 2015a). Extensive groundwater use along the Cosumnes River, southeast of Sacramento, has lowered the groundwater table, draining the river's base flow during the dry season. As a result, Chinook salmon find inadequate streamflow as they migrate from the ocean (Zektser et al. 2005). The Tulare Lake Basin, an intensely agricultural region, relies on overdraft for roughly 13% of its net water use (Hanak et al. 2017), despite water imports and groundwater banking (Harou and Lund 2008; Faunt 2009; Scanlon et al. 2012), and sees severe land subsidence. Groundwater use in California has been historically uncontrolled with few regulations.

Signed into law in September 2014, California's Sustainable Groundwater Management Act (SGMA) began widespread regulation of local groundwater basins and established standards for sustainable and effective groundwater management, including eliminating overdraft. SGMA requires local agencies to develop and implement groundwater sustainability plans (Robinson 2014; CDWR 2016; Nishikawa 2016). Nelson et al. (2016) showed that eliminating overdraft would change water management and operations in California and increase water scarcity costs. Expanding surface supplies or reducing groundwater demand can diminish groundwater overdraft and increase groundwater sustainability, with increasing water storage helping to balance supplies and demands (Scanlon et al. 2012).

In addition to groundwater regulations, climate change will alter water availability, management, and operations in California. A warmer climate will have more precipitation as rain rather than snow in the Sierra Nevada Mountains, shifting runoff from spring to winter (Lettenmaier and Sheer 1991; Miller et al. 2003; Zhu et al. 2005; Vicuna et al. 2007; Vicuna and Dracup 2007; Cayan et al. 2008; Vicuna et al. 2010; Hanak and Lund 2012). Because California's water system is substantially snowmelt-driven, many operations and uses can suffer from climate warming and need to adapt water infrastructure, operations, regulations, and demands to changing conditions (Dogan 2015; Buck 2016).

This paper evaluates potential effects of ending long-term groundwater overdraft on the economic operation of California's extensive water supply system within capacity and environmental constraints, using several management scenarios under historical (1921–2003) and warmer–drier climates. Adaptations, such as expanded surface storage and Delta exports, reduced Delta outflow, water transfers, and conjunctive use, are discussed and examined using the CALVIN hydroeconomic optimization model. The next section describes the study area and evaluated scenarios. The CALVIN model is then briefly described. The modeling results are presented to evaluate the effects of ending groundwater overdraft on water deliveries, scarcity costs, and groundwater storage within California's extensive surface and groundwater supply network. Effects of Delta export and outflow policies on water management are explored. These results, of course, are subject to modeling errors and limitations, so relative comparison of results and qualitative lessons are more useful.

Study Area and Management Scenarios

The Sacramento and San Joaquin Rivers drain the Central Valley's water into San Francisco Bay through the Sacramento-San Joaquin Delta, the major hub for California's water supply network (Fig. 1). Drainage from the Delta into San Francisco Bay, and eventually the Pacific Ocean, is called Delta outflow. In the CALVIN statewide hydroeconomic model, Delta outflow is divided into required and surplus amounts. Required Delta outflow is a minimum flow regulatory requirement that must be maintained for salinity management and aquatic species protection (CSWRCB 2000). Some localized flow requirements within the Delta are not included in this model, giving the model somewhat more flexibility. Surplus outflow is the difference between total and required Delta outflows, and may be available for water supply. The Central Valley includes the Sacramento Valley in the north, the San Joaquin Valley, and the Tulare Lake Basin in the south. Water exports through the Delta-Mendota Canal (DMC) and California Aqueduct (CAA) transfer water from the Delta to southern regions: San Joaquin, Tulare Lake Basin, and southern California.

Policy cases evaluated here put different restrictions on Delta water operations and eliminate overdraft under 82-year (1921–2003) historical and warmer–drier climates with 2050 water demands (Table 1). Policy 1 allows historical overdraft rates in CALVIN's 82-year modeling horizon. A no-overdraft policy is applied to the Central Valley groundwater aquifer in Policies 2–5, requiring that groundwater storage at the end of each 82-year run cannot be less than groundwater storage at each run's beginning. Policies 3–5 add different Delta export constraints to this no-overdraft policy. Policy 3 maintains historical Delta outflows, by month, in addition to the no-overdraft policy, so reductions in Delta outflows cannot substitute for lost historical supplies from groundwater overdraft. Policy 4 further restricts Delta export operations by constraining water exports to historical quantities, in addition to maintaining a no-overdraft policy. This prevents the optimization model from curtailing water use north of the Delta to supply water south of the Delta to accommodate supplies lost there from the end of groundwater overdraft. Policy 5 reduces Delta exports by 95%, largely eliminating them, in addition to maintaining a no-overdraft policy.

Aquifers outside the Central Valley are much smaller and less connected to the statewide water network, and so have less interregional water management implications. The larger connected ones in southern California also are already managed to prevent overdraft. Focusing on ending overdraft in the Central Valley is by far the most important aspect of overdraft in California, accounting for 90% of the state's overdraft, although local overdraft also occurs elsewhere, such as in Pajaro, Salinas, and other coastal aquifers, as well as fractured rock mountain aquifers. Groundwater and surface water management are closely linked in California. The policy cases described in Table 1 help illustrate the Delta's role in water operations and adaptations to overdraft and groundwater management. The five policy cases are evaluated under historical and warmer–drier climates, so 10 sets of model run results are compared in the results section.

CALVIN Model

Combining hydrology with economics, hydroeconomic models are common in water management, representing water operations and allocations driven by the economic value of water within water availability, infrastructure, policy, and environmental constraints (Cai 2008; Booker et al. 2012; MacEwan et al. 2017). Harou et al. (2009) discussed hydroeconomic modeling in water

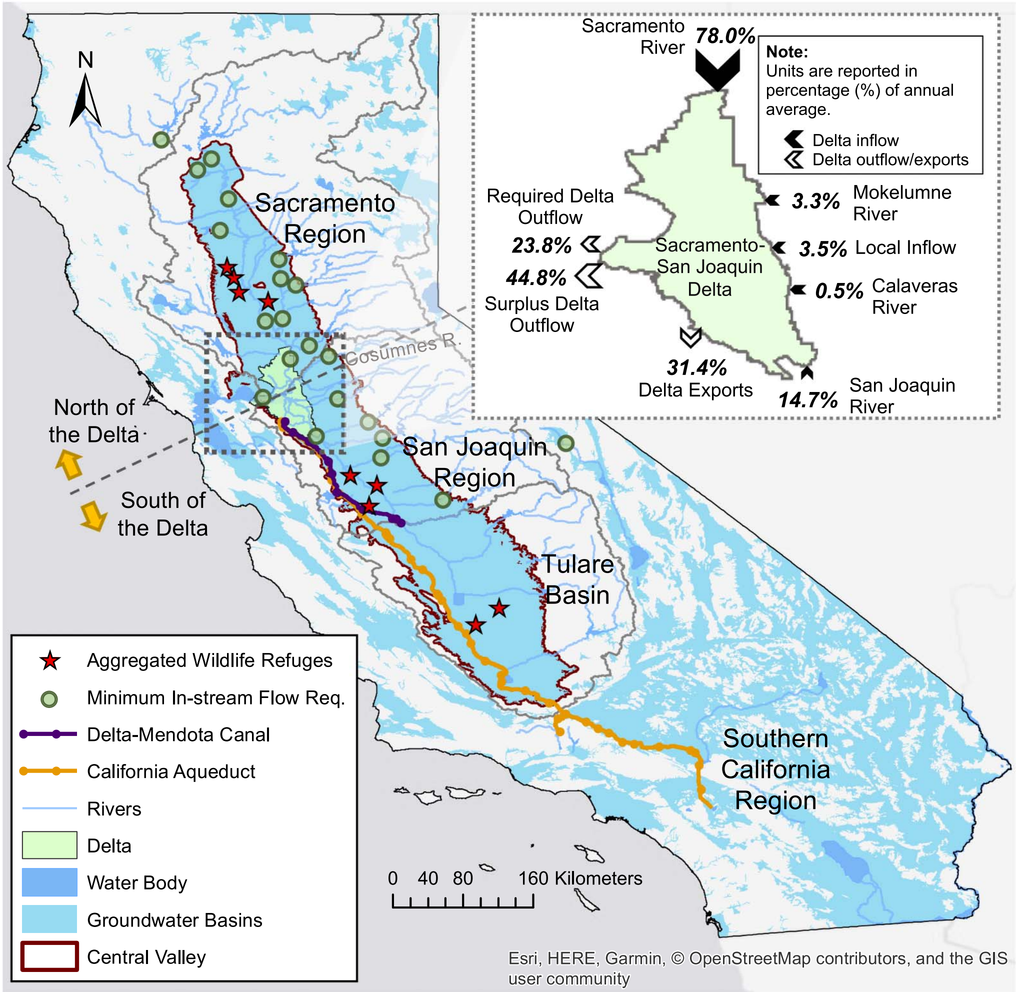

Fig. 1. Study area: California's groundwater basins, aggregated wildlife refuges, and minimum in-stream flow requirements represented in CALVIN, and the Sacramento-San Joaquin Delta: major rivers, exports to south of Delta, and outflow into the San Francisco Bay. Groundwater basins are from *Groundwater Bulletin 118* (CDWR 2016). (Numbers as percentages of total inflow and outflow are from base historical CALVIN results.) (Esri, HERE, Garmin, © OpenStreetMap contributors, and the GIS user community.)

Table 1. Policy cases evaluated under historical and perturbed (warmer–drier) climates

Policy	Description	Implementation	Importance
Policy 1	Operations with historical overdraft	Allows continued historical (1921–2003) long-term overdraft rate over 82-year run for all Central Valley groundwater basins. $\text{Storage}_{2003,i} - \text{Storage}_{1921,i} = \Delta S_i$, $\forall$ groundwater basins i.	Base case operations
Policy 2	No overdraft	Ending groundwater storage cannot be less than initial groundwater storage. $\text{Storage}_{2003,i} \geq \text{Storage}_{1921,i}$, $\forall$ groundwater basins i.	Operations without overdraft and with no new Delta restrictions
Policy 3	No overdraft and no reduction in Delta outflow	In addition to a no-overdraft policy, no reduction in monthly Delta outflow is allowed. Historically based outflow is used as a lower bound for model results. $\text{Storage}_{2003,i} \geq \text{Storage}_{1921,i}$, $\forall$ groundwater basins i. $\text{Outflow}_m \geq \text{Outflow}_{\text{historical},m}$, $\forall$ months m.	Forces water use reallocation across basins without reducing Delta outflow
Policy 4	No overdraft and no additional Delta exports	In addition to a no-overdraft policy, no additional Delta exports are allowed. Historically based Delta exports are used as upper bounds for model results. $\text{Storage}_{2003,i} \geq \text{Storage}_{1921,i}$, $\forall$ groundwater basins i. $\text{Exports}_m \leq \text{Exports}_{\text{historical},m}$, $\forall$ months m.	Operations and use changes occur only within basins, cannot adjust statewide
Policy 5	No overdraft and minimal Delta exports	Overdraft is ended without Delta exports. Delta exports are limited to 5% of export capacity due to flow constraints along California Aqueduct and Delta-Mendota canal. $\text{Storage}_{2003,i} \geq \text{Storage}_{1921,i}$, $\forall$ groundwater basins i. $\text{Exports}_m \leq 0.05 \times \text{Export Capacity}_{\text{historical},m}$, $\forall$ months m.	Largely eliminates Delta export water supplies

resources. CALVIN is a hydroeconomic optimization model for water operations planning and allocation in California (Draper et al. 2003; Dogan et al. 2018). CALVIN represents California's extensive intertied water infrastructure and demands, including agricultural, urban, and environmental uses. The model network includes surface and groundwater supplies; reservoirs and aquifers; infrastructure for conveyance, storage, and treatment; and economic costs for water operations and shortages to users. Constraints on operations represent limits for water availability, capacities, and environmental flows. Additional water policies (such as ending overdraft and Delta policies) can be represented as constraints on operations and water allocations. As an optimization model, CALVIN seeks to minimize statewide net economic water scarcity and operating costs (maximize net benefits) within these physical and policy constraints. Conjunctive use of surface water and groundwater occurs to the extent it is economical with water market transfers, artificial recharge, and alternative water-supply options, such as desalinated, potable, and nonpotable recycled water occurring in times and locations that provide the greatest statewide economic benefit. Urban and agricultural water demands estimated for the year 2050 are employed. Environmental constraints represent a simplification of current regulations. The 82-year historical hydrology represents the state's hydrologic variability. CALVIN provides insights into California's water management and the potential effects of new policies. Draper et al. (2003), Tanaka et al. (2006), and Connell-Buck et al. (2011) discussed limitations of the model. The model does not represent dynamic groundwater flows. Instead, it uses fixed recharge and return flow proportions for each groundwater subbasin obtained from the Central Valley Groundwater-Surface Water Simulation Model (C2VSim) (Dogrul et al. 2016). CALVIN also uses fixed-unit pumping costs derived from the Statewide Agricultural Production Model (SWAP) (Howitt et al. 2012).

Mathematically, CALVIN is a network-flow model over a physical network represented by a set of nodes $\boldsymbol{N}$ and links $\boldsymbol{A}$. Links are defined by $(i, j, k) \in \boldsymbol{A}$, where i is the origin node (located in time and space), j is the terminal node, and k is piecewise component used to represent nonlinear penalty (or cost) curves with a convex piecewise delineation. Component k represents multiple links from origin node i to terminal node j with monotone increasing unit costs. Each link has a flow X_{ijk}, which is the decision variable; unit cost c_{ijk}; lower bound l_{ijk}; upper bound u_{ijk}; and amplitude or loss factor a_{ijk}. The objective function and constraints are

$$\min_{X \in \boldsymbol{A}} z = \sum_i \sum_j \sum_k c_{ijk} X_{ijk} \qquad (1)$$

subject to

$$X_{ijk} \geq l_{ijk}, \quad \forall\ (i, j, k) \in \boldsymbol{A} \qquad (2)$$

$$X_{ijk} \leq u_{ijk}, \quad \forall\ (i, j, k) \in \boldsymbol{A} \qquad (3)$$

$$\sum_i \sum_k X_{jik} - \sum_i \sum_k a_{ijk} X_{ijk} = 0, \quad \forall\ j \in \boldsymbol{N} \qquad (4)$$

The objective function [Eq. (1)] sums over all links i, j, k and represents the total cost of flow conveyed in the network over all locations and time steps. Eqs. (2)–(4) represent lower bound, upper bound, and mass balance constraints, respectively.

Warmer–Drier Hydrologic Conditions

Climate change effects vary for different regions. At high latitudes and wet tropics, river runoff and water availability are more likely to increase, whereas arid and semiarid areas are likely to see less runoff (Bates et al. 2008). California's Sierra Nevada runoff, driven largely by snowmelt, is susceptible to changes in temperature and precipitation, which drive snowpack accumulation and snowmelt runoff timing. Higher temperatures will shift and steepen snowmelt runoff and affect reservoir operations that regulate water for spring and summer irrigation and urban supplies and electricity demands (Miller et al. 2003; Vicuna et al. 2007).

A warmer–drier climate scenario, employed here, represents higher air temperatures and reduced precipitation. CALVIN's 82-year (1921–2003) historical hydrology, representing hydrologic variability, is perturbed to reflect a warmer–drier climate as described by Zhu et al. (2005) and Connell-Buck et al. (2011), derived from the Geophysical Fluid Dynamics Laboratory (GFDL) CM2.1 A2 climate scenario that projects a 4.5°C increase in annual temperature by the end of the century and an average decrease of 27% in precipitation for California (Cayan et al. 2008). CDWR (2015c) has identified several climate scenarios likely to occur in California, ranging from wet and cold to warm and dry. The warmer–drier scenario is useful for evaluating California's water system performance and assessing vulnerabilities under extreme conditions (Herman et al. 2018). Table 2 shows mountain rim inflows to surface reservoirs and streams, groundwater recharge (deep percolation to aquifers), and local runoff as remaining inflows to the system. Mountain rim inflows to the Central Valley, the largest component, are the most reduced with a warmer–drier climate.

With higher temperatures and less precipitation, the warmer–drier climate has less water availability than average historical (1921–2003) conditions in all months, except January (Fig. 2). Warmer–drier conditions significantly shift runoff timing and quantity of water, especially in spring. Peak flows occur in winter rather

Table 2. Annual average surface inflows and groundwater recharge and changes with warmer–drier conditions

Hydrologic component	Historical (km^3/year)	Warmer–drier (km^3/year)	Difference (km^3/year)	Change (%)
Mountain rim inflow	38.1	27.5	−10.6	−28
Groundwater recharge	7.5	7.1	−0.5	−6
Local runoff	2.1	0.7	−1.4	−68
Total	47.7	35.2	−12.5	−26

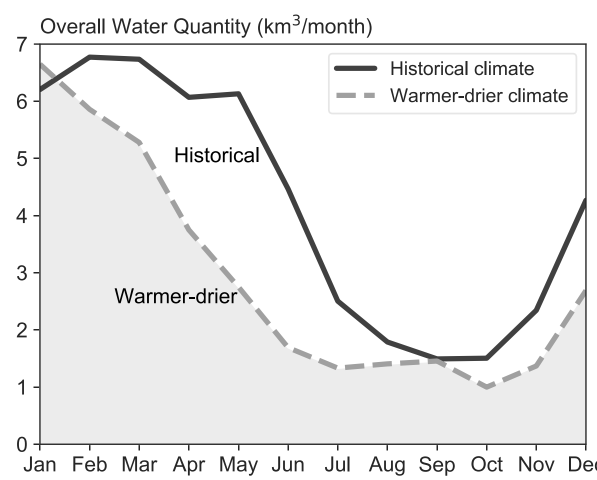

Fig. 2. Statewide overall monthly surface water availability under historical (1921–2003) and warmer–drier hydrologic conditions.

than spring with climate warming, potentially increasing winter floods. Large streamflow reductions are expected in spring.

Results

Results presented in the following sections show the interaction of groundwater overdraft and Delta surface water management policies on agricultural and urban water deliveries and water scarcity costs. The implications of these operations for groundwater and surface reservoir storage behavior, as well as the likely economic value of expanded water storage capacity, additional Delta exports, and reduced Delta outflow, are evaluated. These results are compared for the historical climate and a warmer–drier climate. Economically, the most useful adaptations to ending groundwater overdraft and a drier climate are to increase Delta exports and reduce Delta outflow. Restrictions on outflow and exports increase economic impact, and a warmer–drier climate greatly worsens water scarcities and economic losses. The environmental and water supply policy trade-offs for groundwater and Sacramento-San Joaquin Delta policy are tightly linked.

Water Scarcity and Economic Costs

A policy with no long-term overdraft reduces groundwater withdrawals available to agricultural and urban water users, resulting in greater water scarcities, mostly to agricultural users (Table 3). Water scarcity is defined here as the difference between a user's total demand and all water delivered. When a user's total economic demand for water is not met, scarcity and corresponding economic costs occur from reduced agricultural production or lost urban economic well-being (Howitt et al. 2012). With historical hydrologic conditions, ending overdraft has little effect on urban water deliveries, even though many urban areas depend solely on groundwater, because urban water suppliers can purchase water from agricultural users, which are 80% of human water use in California. This concentrates water scarcity with agricultural users. The warmer–drier climate greatly increases water scarcity and its costs.

Statewide annual average cost increases with the end of overdraft for both historical and warmer–drier climates (Table 3). However, ending overdraft is less costly when more adaptation is allowed in a policy (Policy 2). More flexible policies increase Delta diversions and reduce environmental outflows. When Delta outflows are restricted in addition to a no-overdraft policy, water scarcities increase greatly, despite water trades from north to south of the Delta. The warmer–drier climate increases scarcities for the no-overdraft and no Delta outflow reduction case more than for the no-overdraft and no Delta export scenario with the historical hydrology. Preventing reductions in Delta outflow when the climate is drier forces a reduction in agricultural and urban water use (and Delta exports).

When exports to south of the Delta are not made, some additional demand north of the Delta can be met, but additional deliveries north of the Delta are for much less economically valuable agricultural uses than would have been supplied south of the Delta with this water, increasing total water scarcity cost even with lower water scarcity volumes. Policy 3, where overdraft is ended without reducing Delta outflow, and Policy 5, where only minimal Delta exports are allowed in addition to a no-overdraft policy, result in the greatest total economic costs with the warmer–drier climate. However, net increases between historical and warmer–drier climates are higher in Policy 3, showing the importance of Delta outflow in a warmer–drier climate.

Conjunctive Use and Water Supply Portfolios

Annual average surface water and groundwater deliveries to agricultural and urban users from surface and groundwater under historical and warmer–drier conditions are shown in Fig. 3. CALVIN's surface deliveries decrease and groundwater deliveries increase during drought years, 1924, 1929–1934, 1947–1950, 1959–1961, 1976–1977, and 1987–1992 (CDWR 2015b) with historical hydrology (Fig. 3). However, warmer–drier conditions significantly reduce surface deliveries, whereas average groundwater deliveries are less affected and variability in groundwater pumping is much diminished.

The no-overdraft policy with the historical climate, despite its additional scarcity and costs, does not fundamentally alter agricultural and urban water supply portfolios, except where south-of-Delta exports are eliminated (Table 4). With a warmer–drier climate, agricultural scarcities increase remarkably, and urban users increase their use of more expensive recycled wastewater.

Environmental Deliveries

Located on the Pacific Flyway, California's wildlife refuges and wetlands are especially important for migratory birds (Fig. 1). Minimum flow requirements are vital to support downstream ecosystems. CALVIN represents wildlife refuge deliveries and

Table 3. Statewide annual average agricultural and urban demand and water scarcity volumes as percentages of total water demand for no-overdraft policy and warmer–drier climate, and statewide annual average water scarcity costs (in million dollars per year)

Water scarcity and cost	Climate	User group	Total statewide demand[a]	With overdraft (Policy 1)	No overdraft (Policy 2)	No OD + no delta outflow reduction (Policy 3)	No OD + no additional delta export (Policy 4)	No OD + no Delta export (Policy 5)
Water scarcity volume (% of total demand)	Historical	Agricultural	31.2	2%	3%	4%	3%	24%
		Urban	14.8	1%	1%	1%	1%	5%
	Warmer–drier	Agricultural	31.2	29%	34%	55%	37%	46%
		Urban	14.8	5%	5%	9%	5%	10%
Water scarcity cost ($million per year)	Historical	Agricultural	—	49	69	94	85	2,707
		Urban	—	93	97	126	126	697
		Total	—	141	166	221	211	3,404
	Warmer–drier	Agricultural	—	2,359	3,084	6,226	3,571	7,625
		Urban	—	599	621	1,203	633	1,613
		Total	—	2,958	3,705	7,429	4,204	9,238
	Increase in total scarcity cost			2,817	3,539	7,208	3,993	5,834

[a]2050 annual average (km^3/year) agricultural and urban water demand estimates.

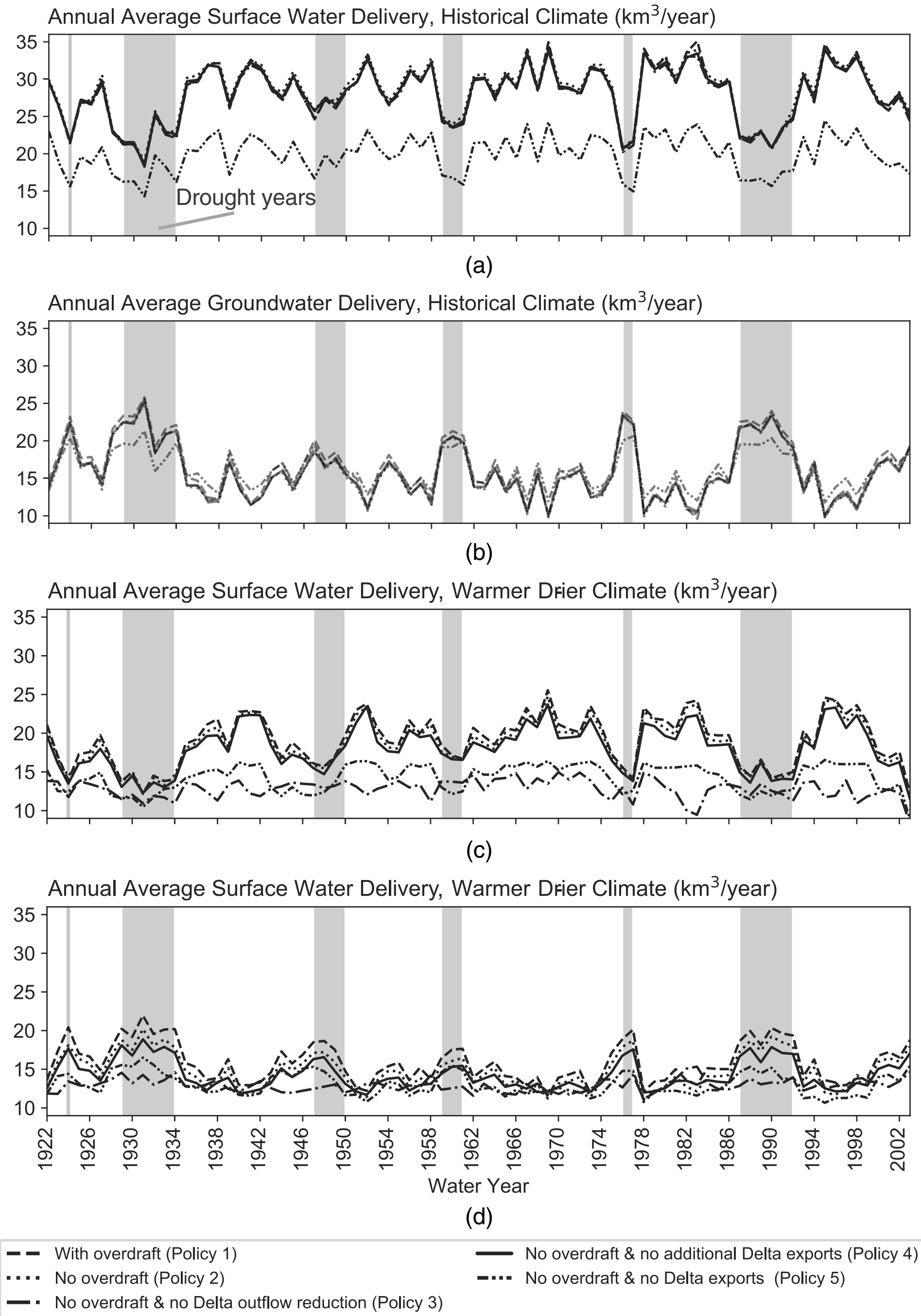

Fig. 3. Annual average water deliveries to agricultural and urban users from (a and c) surface water; and (b and d) groundwater under no-overdraft cases with (a and b) historical and (c and d) warmer–drier climates.

minimum in-stream flow requirements as constrained (fixed or lower-bound) flows, meaning these environmental deliveries are made before any agricultural or urban uses. Table 5 compares average opportunity costs (Lagrange multipliers or shadow prices) to economic (agricultural and urban) water users of environmental deliveries under no-overdraft policies and warmer–drier conditions. Coming from the linear programming nature of the CALVIN model, shadow prices represent the economic benefit ($) to economic uses from one unit (m^3) change in required environmental deliveries. These prices also indicate overall economic water scarcity and the marginal user willingness to pay for water as environmental water requirements increase. Shadow prices are higher south of the Delta, where water is scarcer and more economically valuable (Table 5). Environmental flows have greater opportunity costs as water becomes less available with the no-overdraft policy. The warmer–drier climate significantly raises water scarcity and the opportunity costs of environmental flows, with higher percent increases north of the Delta. Wildlife refuge deliveries and required Delta outflow have higher opportunity costs than minimum in-stream flows because they are consumptive use with smaller return flow fractions. Although current environmental uses can be mostly met with the no-overdraft policy and the warmer–drier climate, maintaining existing environmental flows becomes more challenging.

Table 4. Agricultural and urban water supply portfolios with percent deliveries from groundwater, surface water, and reuse

Climate	Scenarios	Agricultural supply portfolio (%)				Urban supply portfolio (%)			
		GW[a]	SW[b]	On-site reuse	Scarcity	GW[a]	SW[b]	Wastewater reuse	Scarcity
Historical	Base historical with overdraft[c] (Policy 1)	29	68	2	2	51	46	2	1
	No overdraft (Policy 2)	27	68	2	3	50	47	2	1
	No overdraft + no Delta outflow reduction (Policy 3)	27	67	2	4	50	47	2	1
	No overdraft + no additional Delta export[c] (Policy 4)	28	67	2	3	49	47	2	1
	No overdraft + no Delta export[c] (Policy 5)	30	45	2	24	45	37	12	5
Warmer–drier	Warmer–drier hydrology with overdraft[c] (Policy 1)	29	41	1	28	45	42	8	5
	No overdraft (Policy 2)	26	39	1	34	44	43	8	5
	No overdraft + no Delta outflow reduction (Policy 3)	21	24	1	54	43	35	13	9
	No overdraft + no additional Delta export (Policy 4)	25	37	1	37	44	43	8	5
	No overdraft + no Delta export[c] (Policy 5)	21	31	1	46	43	30	17	10

[a]Groundwater.
[b]Surface water.
[c]Values do not add up to 100% due to rounding.

Table 5. Average opportunity costs (dollars per thousand m^3) of wildlife refuge deliveries, minimum in-stream flow requirements, and required Delta outflow

Environmental user	Climate	Region[a]	With overdraft (Policy 1)	No overdraft (Policy 2)	No overdraft + no Delta outflow reduction (Policy 3)	No overdraft + no additional Delta export (Policy 4)	No overdraft + no Delta export (Policy 5)
Wildlife refuge[b]	Historical	NOD	6	9	49	7	2
		SOD	55	66	104	105	847
	Warmer–drier	NOD	347	390	933	384	97
		SOD	549	585	917	612	1,363
Minimum in-stream flow requirement	Historical	NOD	7	8	10	9	12
		SOD	8	12	9	15	73
	Warmer–drier	NOD	101	113	82	134	109
		SOD	173	149	83	152	290
Required Delta outflow	Historical	—	5	6	52	5	0.3
	Warmer–drier	—	301	337	944	317	17

[a]NOD = North of the Delta; and SOD = South of the Delta.
[b]Represented wildlife refuge (wetland) demands: Sacramento Valley (North of Delta): Sacramento, Delevan, Colusa, Sutter National Wildlife Refuges (NWR), and Gray Lodge Wildlife Area (WA); San Joaquin Valley (South of Delta): Volta, Los Baños, Grasslands, Mendota WA, and San Luis and Merced NWR; Tulare Lake Basin (South of Delta): Pixley and Kern NWR.

Groundwater Storage

The Central Valley has a modeled cumulative groundwater overdraft of 104 km^3 (84 MAF) over the 82-year operating period at historical overdraft rates (Nelson et al. 2016). Groundwater storage was modeled for various water management policies over the 82-year hydrologic period. Fig. 4 shows the cumulative change in groundwater storage of the Central Valley aquifer with filling and drawdown periods. Total storage generally increases in wet years when recharge from surface water is highest and decreases with additional pumping in drought years. Total storages are lower when overdraft is allowed. There is less change in groundwater storage under the warmer–drier climate due to less water availability in all cases. Overall, there are two large drawdown and refill periods for the no-overdraft with climate change cases, 1924 to 1986 (62 years) and 1986 to 1998 (12 years). These durations demonstrate the likelihood of multidecade drawdown cycles for the aquifer, which poses practical problems for assessing aquifer sustainability.

Surface Storage Expansion

California has roughly 50 km^3 of surface storage capacity, with the largest reservoirs in the northern and eastern parts of the state (Hanak et al. 2011). Reservoirs in California store winter runoff and spring snowmelt for irrigation, urban, ecosystem, and hydropower uses during the dry season, and to manage floods (Lund 2016). Table 6 shows the average marginal value of expanding current surface storage capacity north and south of the Delta. It shows statewide economic benefits ($/year) per 1,000 m^3 of storage capacity expansion. This marginal benefit is mostly from agricultural, urban, and hydropower economic values. A warmer–drier climate increases the marginal value of expanding storage capacity north of the Delta (NOD), but reduces its value south of the Delta (SOD). Because a warmer–drier climate affects timing, magnitude, and variability of surface runoff, more economically valuable water can be captured NOD, but SOD reservoirs more rarely refill with the drier hydrology. Although water becomes more valuable in a warmer–drier climate, making capacity expansion more economically valuable NOD, ending overdraft without reducing Delta outflow reduces storage capacity benefits, mostly because little water is available to fill additional reservoir capacity (Table 6). Capacity expansion also has less benefit when overdraft ends without Delta exports with the warmer–drier climate because any stored water cannot be delivered to higher-valued water demands SOD. For expanded storage capacity to be economically valuable, there must be both economic water demand and availability of water to store.

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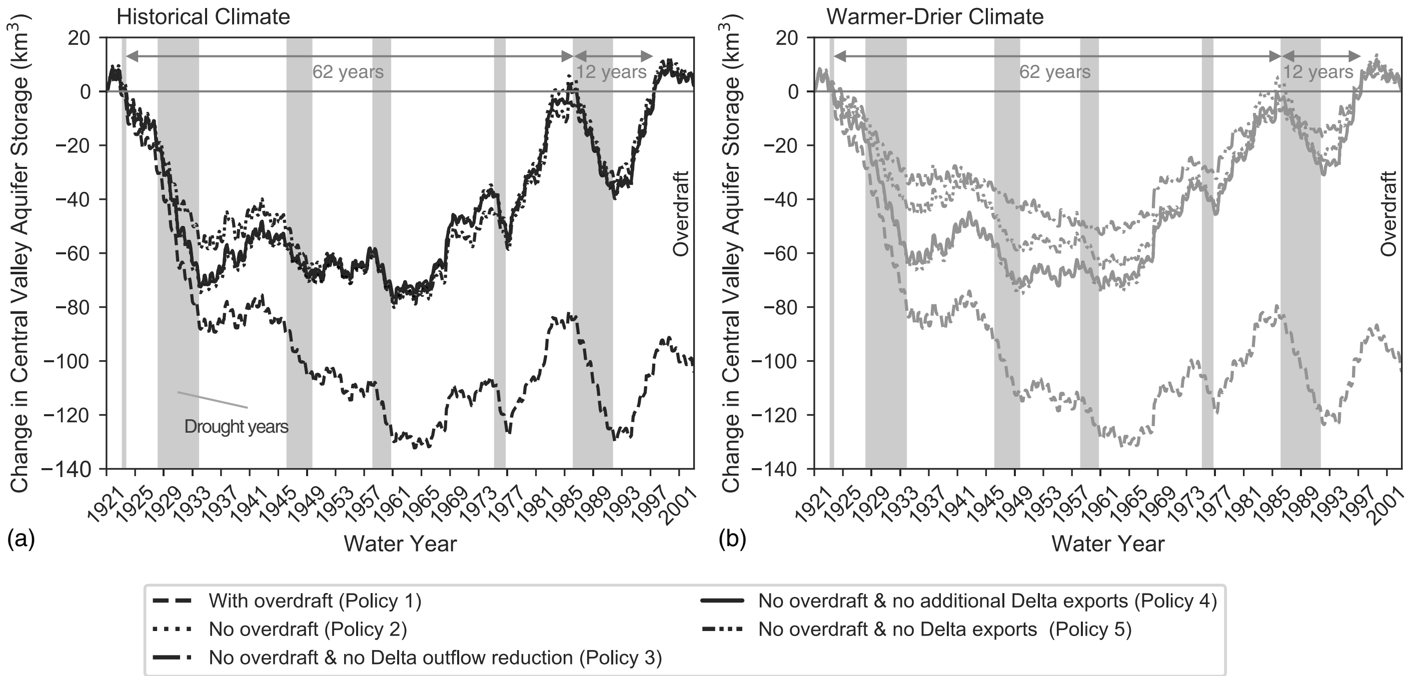

Fig. 4. Cumulative monthly change in Central Valley aquifer modeled storage between September 1921 and 2003 under (a) historical; and (b) warmer–drier hydrologic conditions. Historical droughts are shaded in gray (km^3).

Table 6. Average marginal economic value of expanding surface water storage capacity (dollars per thousand m^3 per year)

Climate	Scenario	Average marginal value of storage expansion ($/thousand m^3/year) NOD[a]	SOD[b]
Historical	With overdraft (Policy 1)	7	7
	No overdraft (Policy 2)	8	7
	No overdraft + no Delta outflow reduction (Policy 3)	6	6
	No overdraft + no additional Delta export (Policy 4)	8	6
	No overdraft + no Delta export (Policy 5)	5	1
Warmer–drier	With overdraft (Policy 1)	141	1
	No overdraft (Policy 2)	149	1
	No overdraft + no Delta outflow reduction (Policy 3)	41	1
	No overdraft + no additional Delta export (Policy 4)	159	1
	No overdraft + no Delta export (Policy 5)	78	1

[a]North of the Delta.
[b]South of the Delta.

Table 7. Annual average water exports from the Delta via California Aqueduct and Delta-Mendota Canal and average marginal economic values of additional Delta exports

Climate	Scenario	Annual average export (km^3/year)	Marginal value of additional export ($/thousand m^3)
Historical	With overdraft (Policy 1)	8.1	9
	No overdraft (Policy 2)	8.9	12
	No overdraft + no Delta outflow reduction (Policy 3)	8.2	9
	No overdraft + no additional Delta export (Policy 4)	8.1	50
	No overdraft + no Delta export[a] (Policy 5)	0.5	1,426
Warmer–drier	With overdraft (Policy 1)	7.6	296
	No overdraft (Policy 2)	7.9	321
	No overdraft + no Delta outflow reduction (Policy 3)	4.1	220
	No overdraft + no additional Delta export (Policy 4)	7.4	274
	No overdraft + no Delta export[a] (Policy 5)	0.5	1,688

[a]Exports are reduced to 5% of allowable capacity.

In addition, expanding storage is much less economically valuable without export capacity to south-of-the-Delta water users, showing the importance of Delta operations for storage capacity expansion.

Delta Water Exports

The economically driven model seeks to increase water exports from the Delta when long-term groundwater overdraft ends in the Central Valley. Base case exports are about 8.1 km^3 per year from the Delta (Table 7). With historical climate conditions, prohibiting groundwater overdraft increases water exported from the Delta by an average of 0.8 km^3/year to reduce water scarcity south of the Delta. When reduction in Delta outflow is not allowed, Delta exports increase only 0.1 km^3/year, the amount that south-of-Delta users buy from northern Central Valley users. Ending overdraft with the most flexible adaptation yields the greatest average Delta exports, 8.9 and 7.9 km^3/year, respectively, under historical and

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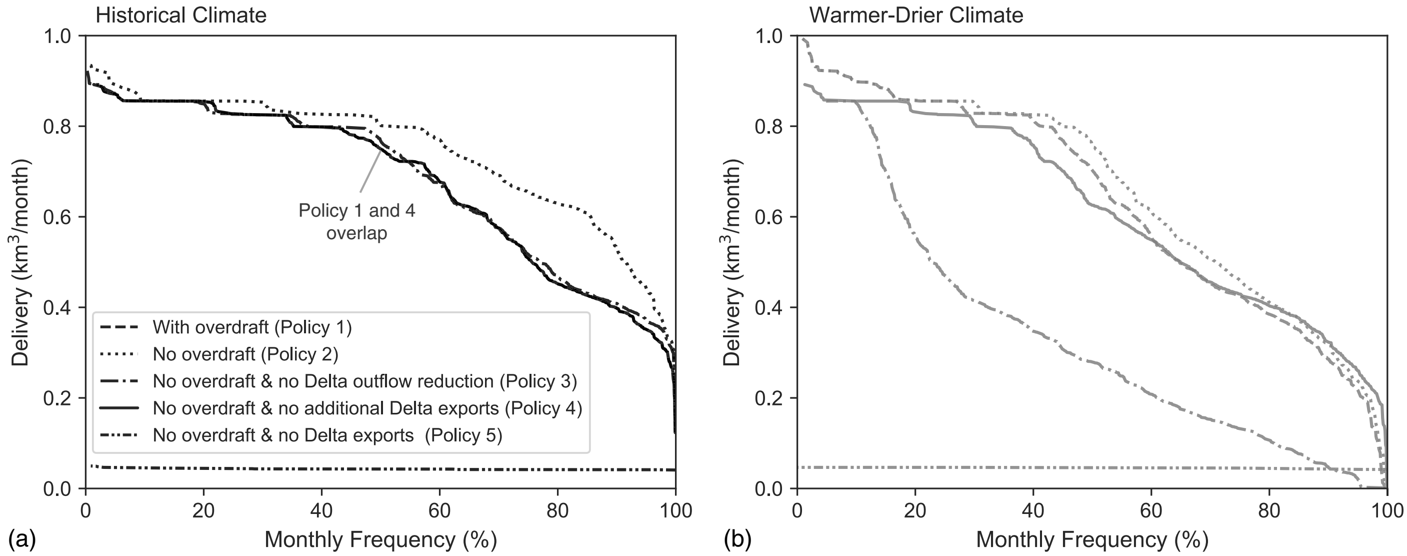

Fig. 5. Delivery reliabilities of monthly water exports from the Delta via California Aqueduct and Delta-Mendota Canal for 10 evaluated scenarios with (a) historical; and (b) warmer–drier climates (km^3/month).

warmer–drier climates. The largest water export decline occurs in the no-overdraft case that prohibits Delta outflow reduction. The no export case limits exports to 5% of current allowable capacity and allows about 0.5 km^3/year of water to be exported for some wetland uses with almost no delivery to agricultural and urban users. Reductions in supplies that cannot be replaced with additional water imports increase water scarcity volumes and costs. Export pumping becomes more valuable with warmer–drier conditions (Table 7).

Exported water comes from either the valley's rivers and Delta outflows or water trades from north-of-Delta users. Water exports are close to the allowed capacity in about 50% of months (Fig. 5). The allowed export capacity (monthly varying, averaging about 320 m^3/s) is less than physical capacity due to environmental regulations (obtained from the State of California's CALSIM II model) (Draper et al. 2004). Under historical hydrology and without overdraft, Delta exports have higher deliveries at any probability level, and differences increase after 50% frequency (Fig. 5). The warmer–drier climate reduces the reliability of Delta exports. The largest decrease occurs when overdraft is ended without allowing reduced Delta outflow (Policy 3). In this case, most water available in the Delta supplies this outflow restriction. Unless constrained by Delta policies, ending overdraft increases Delta exports under both climate conditions.

Delta Outflow

Delta outflow is regulated by the State Water Resources Control Board (CSWRCB 2000) and is vital to the estuary ecosystem and salinity control. This outflow is mostly not used directly and reduces salinity for local uses and exported water. CALVIN represents Delta outflow in two parts: required and surplus. Surplus outflow is the difference between total and required outflow. Higher water demands in summer and early fall reduce Delta outflow to the required levels (Fig. 6). Monthly average Delta outflow peaks in February in all cases under historical climate, and peaks shift to January with warmer–drier climate due to runoff timing shifts. In every month, the no Delta export policy increases Delta outflows. Flow fluctuations are higher in the November to April wet season. When overdraft is ended, Delta outflow is exported mostly in the late fall and winter, when outflow is more abundant. Delta outflow decreases with the warmer–drier climate, especially in winter and spring through December to June.

Discussion

Water scarcities and economic costs increase with a warmer–drier climate, beyond the additional scarcity when overdraft is prohibited. Agricultural water users are disproportionately affected by greater water scarcity (Table 3), potentially reducing irrigated area statewide. Urban water users have higher user willingness to pay for water and so purchase additional available supplies from agricultural users.

Ending groundwater overdraft in the Central Valley increases economic demands for Delta exports. The Delta will continue to be central to the state's water issues, and maintaining existing levels of outflow likely becomes more economically expensive. With climate warming, exports increase during winter and almost all pumping capacity is used in January to capture surplus Delta outflow (Fig. 6), whereas exports decrease during spring and summer from the base case. Increasing Delta exports helps reduce water supply impacts of ending groundwater overdraft, but Delta regulatory constraints will likely limit this option. Historically, Delta outflow averages about 17.8 km^3/year, of which only 6.2 km^3/year is currently required (Fig. 6). Additional Delta exports using some surplus Delta outflows help compensate for climate change and ending overdraft. Water trading also helps reduce scarcity costs to SOD water users from willing NOD sellers. Delta pumping capacity and NOD storage could be expanded to capture more Delta outflows, which often exceed required outflows during winter, but this becomes unavailable if all existing Delta outflows become required.

The model eliminates overdraft over the long 82-year modeled period. This is the longest-term overdraft CALVIN can represent with current data availability. Therefore, scarcity and economic cost here are a lower bound because eliminating short-term overdrafts, such as for 5, 10, or 20 years, would increase water scarcities and overall costs. The 82-year hydrologic period has two large groundwater drawdown and refill periods for all no-overdraft cases, lasting 62 and 12 years, respectively (Fig. 4). These long periods demonstrate the need for a multidecade perspective on groundwater management and sustainability regulations.

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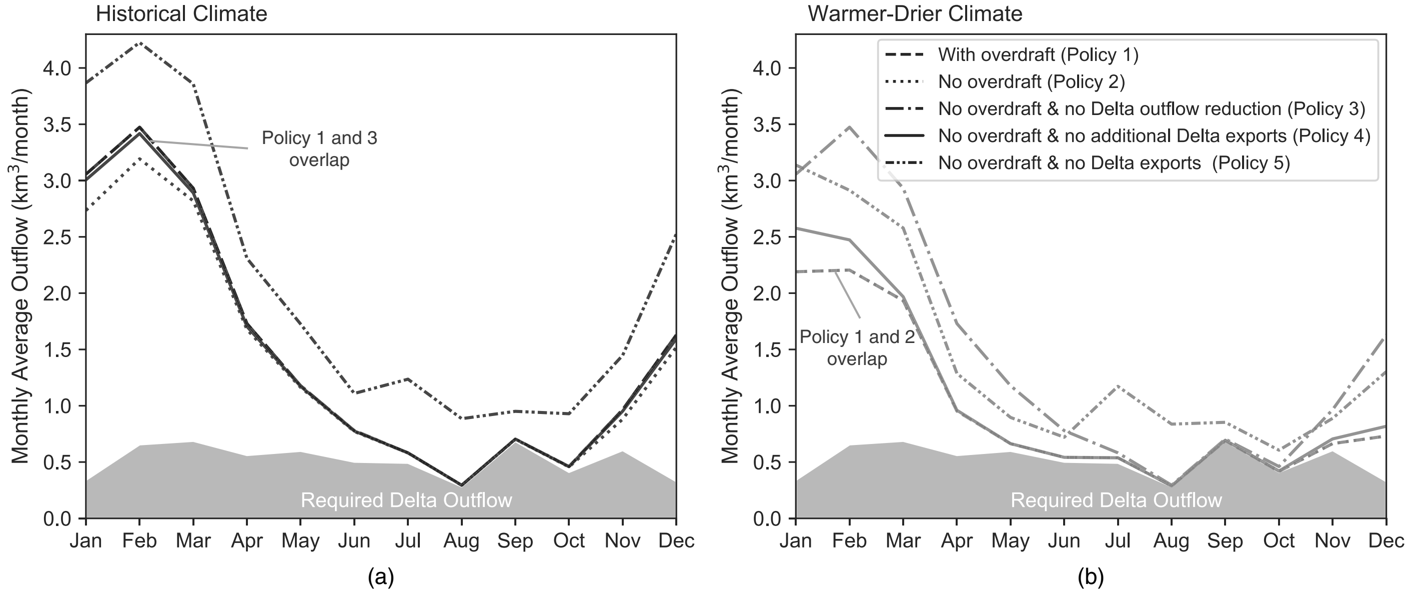

Fig. 6. Monthly average and required minimum Delta outflows from the Central Valley to San Francisco Bay with (a) historical; and (b) warmer–drier climates (km^3/month).

Table 8. Comparison of three recent hydroeconomic modeling studies

Comparison	This study	Medellin-Azuara et al. (2015)	MacEwan et al. (2017)
Model	CALVIN	Coupled SWAP-C2VSim	Coupled SWAP-C2VSim
Coverage	Statewide (1921–2003)	Central Valley (2014)	Southern Central Valley subregion 15, 16, and 17 (1921–2009)
Reduction in surface water availability	30% (warmer–drier hydrology)	36%	—
Water scarcity (% of total demand)	29% (Policy 1, warmer–drier hydrology)	25%[a]	—
Average agricultural economic costs ($) per reduction ($m^3$)	$0.28	$0.68	—
Additional cost of no-overdraft policy ($/year)	$20 million (Policy 2–Policy 1, historical hydrology)	—	$12 million[b]

[a]Decreases to 6% after increased groundwater pumping.
[b]$3 million per year gain after considering avoided capital costs and stabilization value.

Table 8 compares this study with two other hydroeconomic model results. Medellin-Azuara et al. (2015) modeled 2014 drought hydrology conditions (36% less surface water) for the Central Valley, which is comparable to the warmer–drier conditions evaluated in this study (Policy 1, 30% less surface water). Medellin-Azuara et al. (2015) estimated average agricultural economic costs for the 2014 drought as $0.68 per unit reduction (m^3), whereas the long-term average of agricultural costs from CALVIN is about $0.28 per unit reduction (m^3). This is partly because CALVIN optimizes water allocation with perfect hydrologic foresight, giving somewhat optimistic water scarcity costs. MacEwan et al. (2017) modeled sustainable groundwater management, including ending overdraft, for a small subregion in the southern Central Valley. They estimated the additional cost of a no-overdraft policy as $20 million, whereas CALVIN's statewide average is roughly $12 million. These studies show the order of magnitude of results.

Conclusions

This study shows close ties between California's two largest water problems, groundwater sustainability and the Sacramento-San Joaquin Delta, and explores how California's water system might respond to ending groundwater overdraft with historical and warmer–drier climate conditions and various Delta policies using a hydroeconomic model. California's new Sustainable Groundwater Management Act will force many areas of the state to manage and reduce groundwater use and seek additional surface water.

The various no-overdraft cases evaluated here provide insights for water management, planning, and policy decisions for California. Although temporary drought drawdown is useful, all long-term groundwater overdraft must end under the new state law. Ending overdraft should eliminate or reduce adverse effects, such as land subsidence, increased pumping cost, and water quality degradation. However, ending overdraft also increases water scarcity and costs, especially for agriculture. Urban deliveries are largely unchanged due to urban water purchases that increase agricultural water scarcity. Delta exports are critical for water supplies south of the Delta. Ending both Delta exports and overdraft greatly increases agricultural and urban water scarcity costs. Water trading reduces scarcity costs in the San Joaquin Valley and Tulare Lake Basin. If Delta outflow cannot be decreased for environmental and operational reasons, Sacramento Valley users would sell some water to south-of-Delta users. With new or improved infrastructure, some surplus

Delta outflow might be captured to reduce water scarcities, if it is permitted environmentally.

A warmer–drier climate significantly reduces surface water availability, water deliveries to all agricultural and urban users, and the reliability of Delta water exports. The greater water scarcity of ending overdraft and a warmer–drier climate increases the economic opportunity costs of environmental flows and deliveries. Environmental water opportunity costs to cities and farming increase south of the Delta, with higher percent increases north of the Delta. Surface reservoir capacity expansion becomes more economically valuable north of the Delta with a warmer–drier climate. However, without enough water availability or Delta export capacity, storage capacity expansion south of the Delta often becomes less valuable. A warmer–drier climate in combination with ending groundwater overdraft and incompatible water policies further exacerbates water scarcities and increases environmental and economic costs.

The Delta's role in California's water operations will become more important with the end of overdraft and a warmer–drier climate. Delta outflow requirements, allowable export capacity, and environmental policies all have large impacts on surface water adaptations and costs for ending overdraft and climate change. Economically useful adaptations to a no-overdraft policy and climate warming include more diversions from surplus Delta outflow, increased water transfers involving the Delta, water markets and trades to economically reallocate available water, conjunctive use of surface and groundwater, and recycled wastewater supply for coastal urban users. Reconciliations with environmental consequences will be fundamental in shaping these adaptations.

Data Availability Statement

The CALVIN model's source code is available in a GitHub repository (Dogan et al. 2017). The CALVIN model's network data also are available in a GitHub repository (Hart et al. 2015). Data generated or analyzed during the study are available from the corresponding author by request.

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