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RESEARCH

Economic and Water Supply Effects of Ending Groundwater Overdraft in California's Central Valley

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ABSTRACT

Surface water and groundwater management are often tightly linked, even when linkage is not intended or expected. This link is especially common in semi-arid regions, such as California. This paper summarizes a modeling study on the effects of ending long-term overdraft in California's Central Valley, the state's largest aquifer system. The study focuses on economic and operational aspects, such as surface water pumping and diversions, groundwater recharge, water scarcity, and the associated operating and water scarcity costs. This analysis uses CALVIN, a hydro-economic optimization model for California's water resource system that suggests operational changes to minimize net system costs for a given set of conditions, such as ending long-term overdraft. Based on model results, ending overdraft might induce some major statewide operational changes, including large increases to Delta exports, more intensive conjunctive-use operations with increasing artificial and in-lieu recharge, and greater water scarcity for Central Valley agriculture. The statewide costs of ending roughly 1.2 maf yr^{-1} of groundwater overdraft are at least $50 million per year from additional direct water shortage and additional operating costs. At its worst, the costs of ending Central Valley overdraft could be much higher, perhaps comparable to the recent economic effects of drought. Driven by recent state legislation to improve groundwater sustainability, ending groundwater overdraft has important implications statewide for water use and management, particularly in the Sacramento–San Joaquin Delta. Ending Central Valley overdraft will amplify economic pressure to increase Delta water exports rather than reduce them, tying together two of California's largest water management problems.

KEY WORDS

groundwater overdraft, Sacramento–San Joaquin Delta, California's Central Valley, economic costs, CALVIN.

INTRODUCTION

California is a semi-arid state, with difficult water-resource challenges arising from large agricultural, urban, and environmental water demands; a dry and variable climate; and a seasonal and geographical separation between water supplies and water demands. Managing available water supplies involves a vast network of water infrastructure and numerous water-management institutions, which must be able to adapt to changing conditions. Since management is costly, water managers must efficiently allocate existing supplies and operate the system to maximize beneficial uses. The system also must operate cost-effectively to prevent and alleviate flooding, safeguard water quality, protect ecosystems, and maintain water-delivery reliability over a range of hydrologic conditions.

California has a Mediterranean climate with wet winters and dry summers. It averages about 200 million acre-feet (maf) of annual precipitation, of which only 75 maf yr^{-1} of runoff is available for management and use (Hanak et al. 2011). Geographically, most of California's precipitation falls during the winter in mountainous northern areas, while the southern half is much drier. Water demands are highest in the summer (the primary irrigation season for agriculture), and occur mostly in drier central and southern regions. In addition, precipitation varies greatly from year to year. In wet years, flooding is a major concern in the Sacramento basin and Sacramento–San Joaquin Delta. During severe droughts, water shortages can threaten economic and environmental well-being statewide. Managing these water-related challenges involves a large system of reservoirs, aquifers, canals, aqueducts, and pipelines to collect, store, and distribute water.

With limited surface-water sources, much of California's water supply comes from groundwater, especially in drier areas and during drought years. Roughly 15 maf of groundwater is pumped in an average year, providing about 30% of the state's annual water use (Faunt et al. 2009; CDWR 2003). Across the state, hundreds of thousands of wells tap into aquifers, providing water to local farmers and urban areas. About 85% of Californians depend on groundwater for some portion of their drinking water (CSWRCB 2012; Lund and Harter 2013). The Central Coast and other less-populated regions rely almost completely on groundwater, because of a lack of local surface-water supplies and delivery infrastructure. During droughts, groundwater provides up to 65% of the state's annual water use (RMC 2014) and is California's largest water-supply buffer when surface-water supplies are scarce. Water districts often conjunctively manage surface and groundwater, increasing groundwater use during droughts and surface-water use in wetter years (Vaux 1986). The water-storage capacity of aquifers is also much larger than the capacity of surface reservoirs, making groundwater useful as long-term drought storage. However, groundwater availability is limited, and over-use, or overdraft, leads to serious consequences.

Groundwater overdraft occurs when groundwater extraction exceeds recharge over several decades. As of 2009, roughly 2 maf yr^{-1} of groundwater overdraft occurred throughout California, mostly in the San Joaquin and Tulare basins (CDWR 2009). During wet years, some areas augment natural recharge through recharge basins and injection wells to mitigate the effects of overdraft, but this often diverts water from other economically valuable uses. Continued overdraft of groundwater basins gradually lowers groundwater tables, which makes pumping more energy-intensive and costly, and can lead to environmental consequences such as land subsidence, decreased streamflow, increased nitrate migration to well intakes, and water-quality degradation. Despite these negative effects, some areas continue pumping groundwater at high rates since they lack other economically viable water supplies. Historically, groundwater use in California has been largely unregulated with only a few basins (mostly in urban areas) governed by groundwater adjudications or groundwater-replenishment districts (Blomquist 1992; Bachman et al. 2005). In 2014, new state legislation, the Sustainable Groundwater Management Act (SGMA), was adopted to help manage groundwater. SGMA mandates that local groundwater-sustainability agencies be formed to achieve groundwater sustainability (Robinson 2014). The SGMA defines sustainable groundwater management as managing groundwater in a manner that can be maintained without causing undesirable results. Undesirable results include chronic lowering of groundwater levels, reduction of groundwater storage, seawater intrusion, degraded water quality, land subsidence, and depletion of interconnected surface waters (CDWR 2015). It will take time for this legislation to stabilize groundwater extraction, and, with continued drought, groundwater levels will likely decline further before they rebound.

This paper examines the economic and operational implications of ending groundwater overdraft in California, particularly for the Central Valley where most overdraft occurs. We describe the optimization modeling approach we used, along with our assumptions for the base overdraft and No Overdraft cases. This approach seeks to minimize the economic costs of water operations and shortages to estimate the minimum physically possible total cost of ending groundwater overdraft. We then present a discussion of the modeling results in terms of operations and economic performance for the year 2050 and some policy and management implications.

METHODS AND ASSUMPTIONS

In this paper, we use the CALVIN (California Value Integrated Network) hydro-economic optimization model to compare operations and economic performance of California's water resource system under current overdraft conditions and for the case where long-term overdraft is ended in the Central Valley. The CALVIN model allows exploration of the different management possibilities of California's water-supply system under a wide range of conditions, without the extensive redevelopment of operating rules and priorities needed for simulation modeling. CALVIN's development began in the late 1990s and has been updated and improved periodically (Howitt et al. 1999). CALVIN models a 72-year time series of historical monthly inflows from 1921 to 1993, and currently covers 92% of California's population from Shasta to Mexico, with particular attention on San Francisco Bay, the Central Valley, and southern California. CALVIN models water-resource operations to minimize net system costs for California, given specified hydrologic conditions, environmental and infrastructure constraints, and economic water demands. The net system cost in CALVIN is the sum of operating costs (pumping and treatment costs, and hydropower as a negative operating cost) and economic scarcity penalties for agricultural and urban water shortages.

CALVIN employs the same regions as the Central Valley Production Model (CVPM) and the original USGS–CVGSM model for groundwater (Hatchett et. al. 1997). Each CVPM region represents a different groundwater basin. CVPM Regions 1 through 9 represent the Sacramento basin, the Sacramento–San Joaquin Delta, and areas east of the Delta. Regions 10 through 13 represent the San Joaquin River basin, and 14 through 21 the Tulare Lake basin. These regions and the CALVIN schematic appear in Figures 1 and 2.

Groundwater heads are not represented in CALVIN as in a groundwater model; changes in groundwater volumes are modeled instead (Draper et al. 2003). As such, groundwater basins are represented as lumped reservoirs with known capacities for storage, similar to surface reservoirs and fixed unit pumping costs and capacities. CALVIN represents groundwater–surface water and groundwater–groundwater interactions using several parameters, such as deep percolation and distribution loss factors, as well as time series for depletions and inter-basin flows, that have been extracted, calculated, and/or estimated from groundwater simulation models. Table 1 summarizes these parameters. More detailed descriptions of these terms and their calculations are found in Chou (2012) and Zikalala (2013). Figure 3 describes the terms and how they interact with groundwater in CALVIN.

Groundwater Sub-basins

As seen in Figure 3, surface water and groundwater deliveries are combined at a node to represent all irrigation-water deliveries to each agricultural demand area. These deliveries are then split between agricultural areas with surface water and groundwater return flows (Term #1). An on-farm and within-district irrigation re-use of return flows amplitude (Term #2) can be specified before this split. After water delivery to demand areas, the return flow fraction (Term #3) is the fraction of the water not used by crops in the demand area that is either returned to groundwater or surface water. External flows to groundwater (Term #4) include deep percolation from precipitation, inter-basin flows, boundary flows, stream leakage, subsidence, conveyance seepage, and non-recoverable losses (i.e., evapotranspiration and tile drain flows). Water pumped from the groundwater basin has capacity constraints (Term #6–7) and also a pumping lift (Term #8), based on CDWR monitoring well data, used to calculate pumping cost. The groundwater

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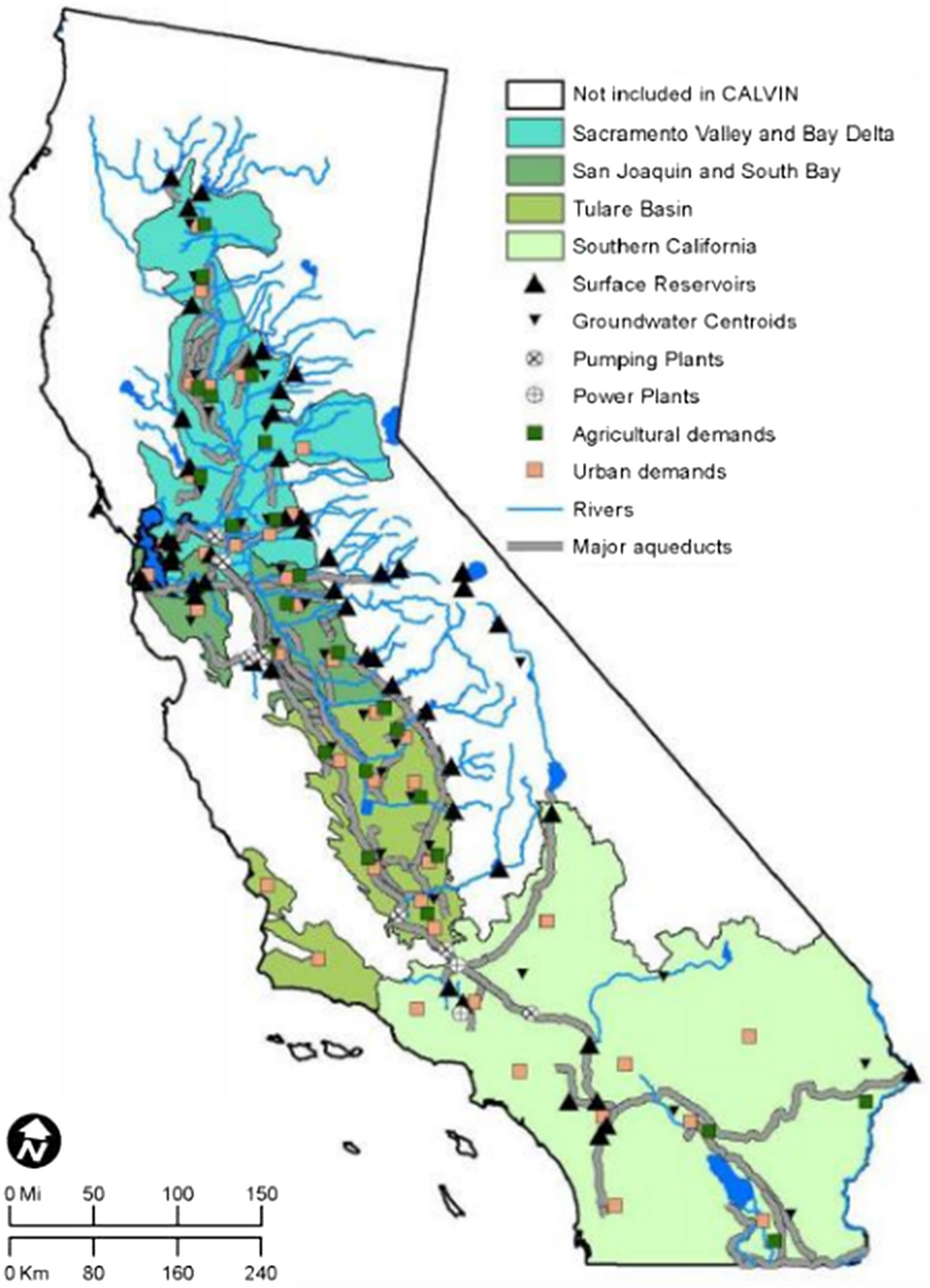
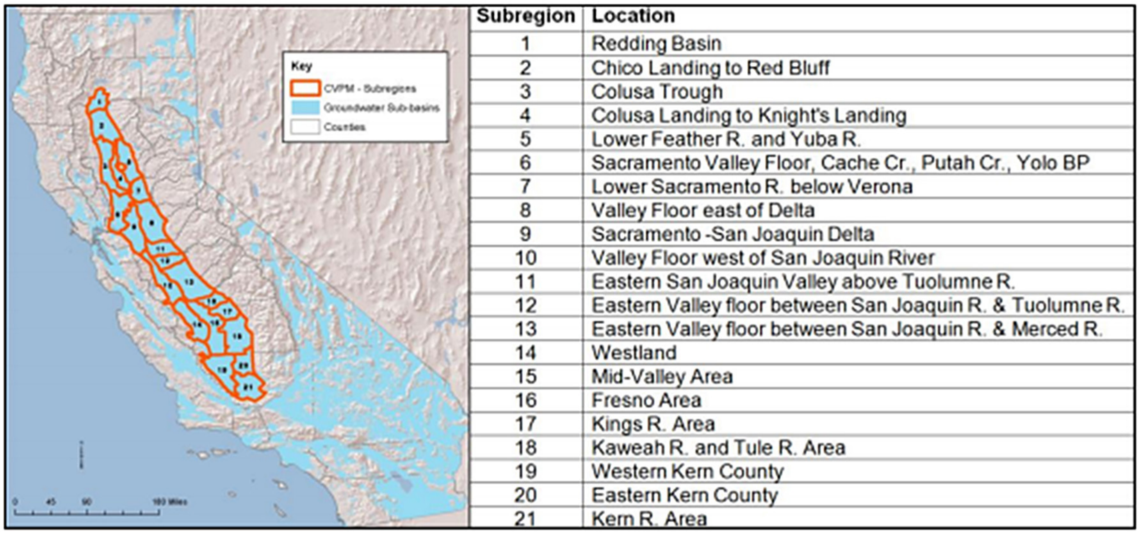


Figure 1 CALVIN schematic and modeling area



Subregion	Location
1	Redding Basin
2	Chico Landing to Red Bluff
3	Colusa Trough
4	Colusa Landing to Knight's Landing
5	Lower Feather R. and Yuba R.
6	Sacramento Valley Floor, Cache Cr., Putah Cr., Yolo BP
7	Lower Sacramento R. below Verona
8	Valley Floor east of Delta
9	Sacramento -San Joaquin Delta
10	Valley Floor west of San Joaquin River
11	Eastern San Joaquin Valley above Tuolumne R.
12	Eastern Valley floor between San Joaquin R. & Tuolumne R.
13	Eastern Valley floor between San Joaquin R. & Merced R.
14	Westland
15	Mid-Valley Area
16	Fresno Area
17	Kings R. Area
18	Kaweah R. and Tule R. Area
19	Western Kern County
20	Eastern Kern County
21	Kern R. Area

Figure 2 CVPM regions in CALVIN

Table 1 Groundwater data employed by CALVIN for each groundwater sub-basin

Item	Groundwater components for CALVIN	Data type
1	Agriculture return flow split (groundwater and surface water)	Fraction (a + b = 1)
2	Internal agricultural area water reuse	Amplitude (>1)
3	Agricultural areas return flow of total applied water	Amplitude (<1)
4	Net external flows, sum of:	Monthly time series
4a	Inter-basin Inflows	
4b	Stream exchanges	
4c	Lake exchanges	
4d	Conveyance seepage	
4e	Deep percolation of precipitation	
4f	Boundary inflow	
4g	Subsidence	
4h	Tile drain outflow	
5	Groundwater basin storage capacity (initial, maximum, ending)	Number (volume)
6	Lower-bound pumping for agriculture (minimum)	Number value
7	Upper-bound pumping for agriculture (maximum)	Number value
8	Average pumping depth representative depth to groundwater (pumping cost)	Cost (2008 US dollars)
9	Surface water losses including evaporation and diversion losses to groundwater	Fraction (<1)
10	Artificial recharge operation cost	Cost (2008 US dollars)
11	Infiltration fraction of artificial recharge	Fraction (<1)
12	Urban return flow to groundwater	Fraction (<1)

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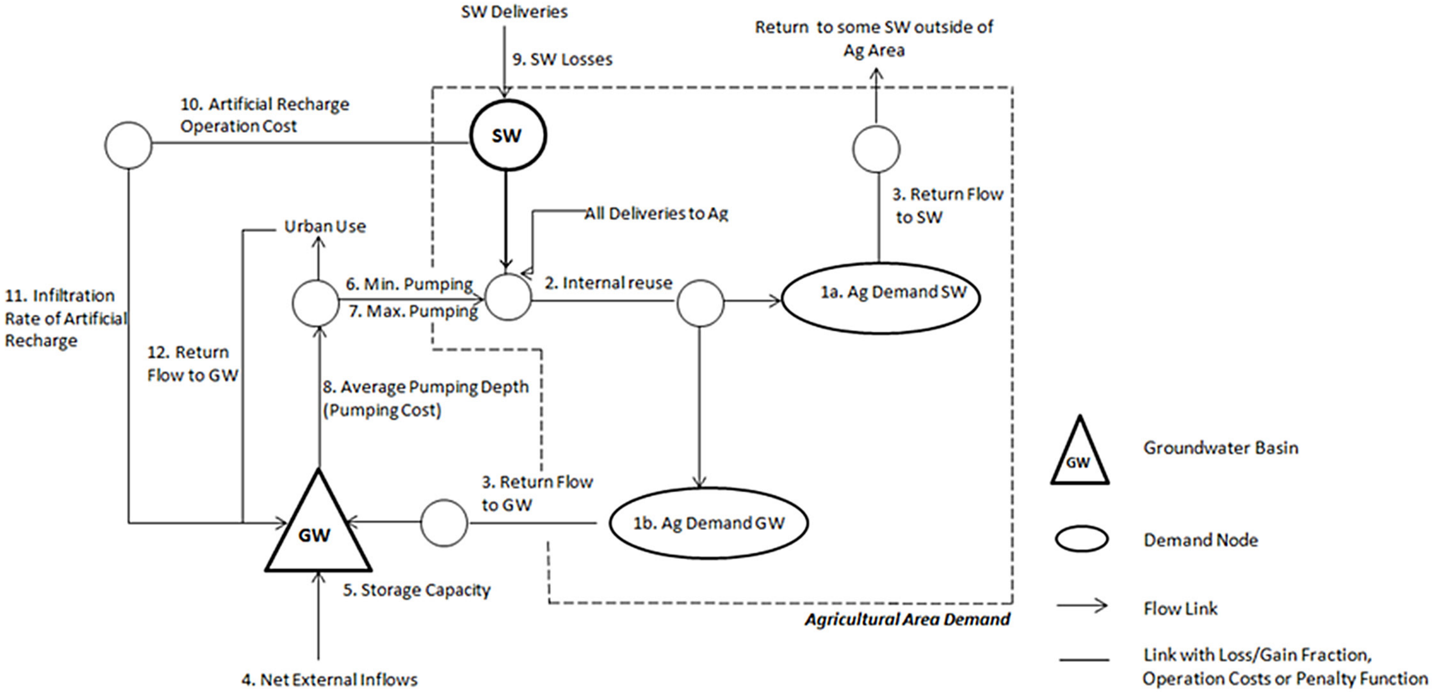

Figure 3 Flows and interactions in CALVIN groundwater sub-basins

basin itself has initial, ending, minimum, and maximum storage constraints (Terms #5). Surface water deliveries are reduced by a fraction (Term #9) that represents various losses, including groundwater seepage, which is added back into the system in Term #4. Artificial recharge is represented for groundwater basins in CVPMs 13 and 15–21 (see Figure 2) with a fixed operating cost, to reflect facility operations and land opportunity cost, (Term #10) and a fixed infiltration rate (Term #11) that determines outflow to the groundwater basin. Finally, urban return flow to groundwater (Term #12) also is represented as amplitude, similar to Term #3.

The CALVIN model integrates a wide variety of water-management activities, including: urban and agricultural water conservation, reservoir re-operation, conjunctive use of surface and groundwater, artificial recharge, water market transactions, wastewater reuse, and desalination. This approach allows CALVIN to manage water resources and related operations with flexibility, and to function like an economically efficient water market (Harou et al. 2009). Such a hydro-economic model produces numerous operational and economic insights for California's water system. These results can provide a more integrated understanding of complex water issues, with deeper and more extensive analysis of problems and potential solutions than is possible with simulation modeling alone.

Early CALVIN studies (Draper et al. 2003; Jenkins et al. 2004) show that regional and statewide water markets drastically reduce the user's willingness to pay for more water (particularly during droughts), thus greatly diminishing the economic need for additional imported water supplies and infrastructure investments. For each constraint, the generalized network flow algorithm also produces a shadow value, which represents the cost or benefit to the optimum solution of a unit change in a constraint. Shadow values can represent the benefit of a slightly larger storage or conveyance facility, the cost of slightly increasing a minimum environmental flow, or the marginal willingness to pay for additional water at a particular location and time.

The model was recently updated to better represent Central Valley groundwater based on CDWR's C2VSIM model and the USGS CVHM model

(Faunt et al. 2009; Chou 2012; Brush et al 2013; Zikalala 2013; Nelson 2014). We updated the terms in Table 1 and Figure 3 primarily using results from more recent years of a historical run of CDWR's C2VSIM (Zikalala 2013). This update eliminated 2.2 maf of annual calibration flows previously required to remove excess water from the system and prevent modeling infeasibilities. These calibration flows helped our necessarily imperfect model function, and reflected the uncertainty in our understanding of California's hydrology.

The previous groundwater representation (dating from a 1997 CVGSM model) had too much groundwater available, which was removed from the system through the calibration flows at no economic benefit. The new groundwater representation better reconciles surface hydrology, groundwater estimates, and water demands, producing better results of annual agricultural water scarcity and groundwater overdraft in the new base case. In addition to groundwater representation updates, we revised agricultural water demands based on the latest results of the SWAP crop production model (Howitt et al. 2012). Finally, Delta outflow and pumping constraints for Banks and Tracy were updated based on the CalSim II model (CDWR 2011).

The results in this paper are from two CALVIN model runs: a base case and a modified base case that eliminates groundwater overdraft over the 72-year modeling period (referred to as the "No Overdraft" case). More detailed presentation of the methods and results are in Nelson (2014), Chou (2012) and Zikalala (2013). The No Overdraft case constrains each groundwater basin in the Central Valley to begin and end the model run with the same storage value, thus avoiding long-term overdraft. Yearly overdraft can still occur, but must be balanced by additional groundwater recharge in other modeling years. For these runs, agricultural and urban economic water demands are estimated for 2050 based on agricultural and urban economic water demands adjusted for land use and population changes to 2050 and held constant between model runs (Jenkins et al. 2003; Howitt et al. 2012). The base case and No Overdraft case results presented here focus primarily on the economic and operational aspects of the water system. These results provide insights for managing overdraft in the Central Valley and illustrate how California's water system might respond economically to the recent state legislation to end long-term groundwater overdraft. Harou and Lund (2008) present results from an earlier and simpler CALVIN model run that focused on the Tulare basin, before the recent improvements in CALVIN's groundwater representation.

RESULTS

Demands, Deliveries, and Scarcities

Table 2 presents model results for annual average agricultural water demands, deliveries, water scarcities or unmet demands (demand–delivery), water-scarcity costs (economic losses from unmet demand), and averages of monthly maximum marginal willingness to pay (WTP) for additional

Table 2 Annual average agricultural water demands, deliveries, and scarcities for each region

		Base case				No overdraft		
	Agricultural demands	Delivery	Scarcity	Scarcity cost	Average max WTP	Increase in scarcity	Increase in scarcity cost	Increase in average max WTP
Region	**taf yr^{-1}**	**taf yr^{-1}**	**taf yr^{-1}**	**\$M yr^{-1}**	**\$ af^{-1}**	**taf yr^{-1}**	**\$M yr^{-1}**	**\$ af^{-1}**
Sacramento	7,386	7,382	4	0.2	16.9	+139	+9.7	+73.2
San Joaquin	4,620	4,471	149	6.3	31.4	+23	+1.4	+35.6
Tulare	8,664	8,458	207	11.4	70	+123	+11.6	+25.1
Southern CA	4,309	3,339	969	178.3	640.4	0	0	0
Central Valley	20,670	20,310	360	17.9	70	+285	+22.7	+55.9
Statewide	24,979	23,650	1,329	196.2	662.2	+285	+22.7	+7.2

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water for each region in the base case, as well as the relative changes in the No Overdraft case. In the base case, over 98% of annual Central Valley agricultural demands are met, while only 75% of agricultural demand in southern California is supplied (because of water sales to higher-valued urban demands). Within the Central Valley, water scarcities are highest in the drier southern regions. In the No Overdraft case, water scarcity increases in all Central Valley regions since less groundwater is available. In the Tulare basin, which depends heavily on groundwater, scarcity increases by about 60% from the base case; corresponding scarcity costs double. The Sacramento basin also sees significantly more water scarcity and scarcity cost as the model reduces Sacramento basin deliveries to allow more water exports south of the Delta, partially compensating for lost groundwater supply in other regions. Southern California sees no change in agricultural delivery because the Colorado River Aqueduct already operates at capacity.

Nelson (2014) also shows that urban water deliveries are relatively unaffected by restricted groundwater overdraft, because urban areas would purchase any lost water from agricultural water users. Though both cases have urban water scarcity in southern California, little additional scarcity occurs in the No Overdraft case. A small reduction in State Water Project (SWP) imports to southern California slightly increases urban scarcity for some southern areas.

The WTP for additional water delivery is another output from the hydro-economic model available for each location and time step. It represents a water user's economic willingness to pay for an additional acre-foot of water delivery. As water becomes scarcer, its availability impinges on higher-valued uses, which increase the price that water users are willing to pay for additional water. The average maximum marginal WTP is the monthly average of the maximum regional WTP values for each month. WTP directly depends on water scarcity in a region; with higher scarcity, users will pay more for additional water. In the base case, southern California has the greatest water scarcity and the highest marginal WTP for additional water, while the Sacramento basin has little scarcity and low economic value for additional water. In the No Overdraft case, greater scarcity increases marginal WTP in the Central Valley. Because of geographic separation from the Central Valley and an already high value for deliveries, southern California sees no increase in scarcity or WTP. In the Sacramento basin, average maximum WTP increases significantly with the No Overdraft case, almost exceeding WTP in the Tulare basin. More detailed regional results appear in Nelson (2014).

Water Scarcity Costs, Operating Costs, and Hydropower Benefits

As a hydro-economic optimization model, CALVIN seeks the most economically beneficial water operation and allocation, within physical and policy constraints. This requires system operating costs to be balanced with water shortage penalties in demand areas. Table 3 shows net system costs for each region in the base case, and the corresponding change in the

Table 3 Annual average system costs and benefits for each region

	Operating costs		Total scarcity cost		Hydropower benefits		Net system costs	
	$\$M\ yr^{-1}$							
Region	**Base case**	**Increase without overdraft**	**Base case**	**Increase without overdraft**	**Base case**	**Increase without overdraft**	**Base case**	**Increase without overdraft**
Sacramento	188.1	−3.3	0.6	+9.7	−211.2	+1.2	−22.5	+7.5
San Joaquin	438.8	+52.4	6.3	+1.4	+43.3	−5.5	401.8	+48.4
Tulare	502.4	−22.1	11.4	+11.6	0	0	513.7	−10.4
Southern CA	2,174.1	+1.7	362.5	+1.9	−465	+0.7	2,071.6	+4.3
Central Valley	1,129.3	+27	18.3	+22.7	−254.4	−4.4	893	+45.5
Statewide	3,303.3	+28.8	380.8	+24.6	−719.4	−3.7	2,964.6	+49.8

No Overdraft case. Base case Central Valley overdraft in the CALVIN model is 1.2 maf yr^{-1}; various studies have estimated Central Valley overdraft to be in the range of 1 to 2 maf yr^{-1}. Operating cost is the sum of expenses related to surface water pumping, groundwater pumping, water treatment, artificial recharge, desalination, and recycling. Total scarcity cost refers to the economic penalties generated for not meeting full agricultural and urban demand targets. In the No overdraft case, California's total net system costs increase on average by about $50 million per year (M yr^{-1}) from additional scarcity costs ($20 M yr^{-1}) and additional operating costs ($30 M yr^{-1}). As this optimization model assumes ideal management of a complex system, these costs may underestimate the actual total cost of ending overdraft.

Average scarcity costs increase by about $20 M yr^{-1} primarily because agricultural deliveries in the Central Valley are reduced with less groundwater pumping, along with a slight increase in urban scarcity for Southern California. With the No Overdraft constraints, groundwater pumping falls about 884 thousand acre-feet per year (taf yr^{-1}) and pumping costs drop by $30 M yr^{-1}. However, increasing Delta exports requires more surface water pumping, which costs an additional $60 M yr^{-1}. Most additional surface water pumping costs are from the Banks and Tracy pumping plants, which export water south of the Delta. Operating costs for the Gianelli Pumping Plant also rise because more water needs to be stored in San Luis Reservoir. Hydropower benefits increase slightly, because additional Delta exports in San Luis Reservoir are released into the California Aqueduct.

Supply Sources

Table 4 shows surface water and groundwater use for agricultural and urban deliveries in each region. In the base case, groundwater use is highest in the Tulare Lake basin, accounting for 41% of all regional deliveries. When overdraft is restricted, less groundwater is used in all Central Valley regions, and total groundwater use falls by 744 taf yr^{-1}. The Sacramento basin has a slight decrease in surface water deliveries, because more surface water is exported (sold) south of the Delta, while the San Joaquin and Tulare basins see more surface-water use (mostly from additional Delta imports). Even with overdraft restrictions, the Tulare basin still depends on groundwater for 37% of water deliveries, but this is supplemented by additional artificial recharge to aquifers with imported surface water. In both cases, southern California agriculture relies mostly on surface water from the Colorado River, and is unaffected by groundwater limitations. For urban water deliveries, the Sacramento basin shifts slightly from groundwater to surface water, although less dramatically than the agricultural shift, while the Tulare basin urban areas slightly reduce surface water use and increase groundwater use.

Table 4 Average agricultural and urban surface and groundwater deliveries for each region

	Agricultural surface water		**Agricultural groundwater**		**Urban surface water**		**Urban groundwater**	
	taf yr^{-1}	**%**	**taf yr^{-1}**	**%**	**taf yr^{-1}**	**%**	**taf yr^{-1}**	**%**
Region	**Base case**	**Increase without overdraft**	**Base case**	**Increase without overdraft**	**Base case**	**Increase without overdraft**	**Base case**	**Increase without overdraft**
Sacramento	5,528	−0.2%	1,420	−9.2%	1,266	+5.9%	345	−22.0%
San Joaquin	3,303	+5.1%	1,089	−17.4%	518	0.0%	1,038	0.0%
Tulare	4,822	+5.4%	3,590	−10.8%	387	−10.6%	695	+5.9%
Southern CA	3,196	0.0%	186	0.0%	4,635	−0.3%	2,191	0.0%
Central Valley	13,653	+3.1%	6,100	−11.6%	2,171	+1.6%	2,078	−1.7%
Statewide	16,849	+2.5%	6,286	−11.3%	6,806	+0.3%	4,269	−0.8%

Delta Export Response

From the Sacramento–San Joaquin Delta, water can be pumped into the CVP Delta Mendota Canal through Tracy to serve the southern Central Valley, or into the SWP California Aqueduct through Banks to serve the Tulare basin and southern California. Table 5 summarizes Banks, Tracy, and total Delta pumping, as well as average yearly outflow from the Delta. CALVIN prefers to pump water through Banks rather than Tracy, because Banks has lower overall pumping costs. In the base case, most Delta exports go through Banks, while Tracy is only about 15% of total average yearly pumping. During droughts, less water is available, even in the northern regions, which reduces Delta exports. In non-drought periods, exports increase slightly at both facilities to store more water in southern reservoirs for future drought years.

In the No Overdraft case, the San Joaquin and Tulare basins depend much more on water from the Delta, particularly in non-drought years. Total Delta pumping increases by about 900 taf yr^{-1} without overdraft on average. Most additional pumping occurs at Tracy in months when Banks is already at capacity. In drought years, Delta exports increase by about 200 taf yr^{-1} (+5.6%) from the base case: in non-drought years, Delta exports increase by about 1 maf yr^{-1} (+18.2%). Despite greater use, the value of expanding either pumping plant remains small since both pumping plants rarely reach capacity at the same time. The higher Delta exports leave less water for Delta outflow, especially in non-drought periods. On average, Delta outflow falls by about 950 taf yr^{-1} (–8%) from the base case. Figure 4 shows the comparison of annual Delta outflow over time for both the base case and the No Overdraft case.

Figure 5 shows average monthly pumping from the Banks and Tracy pumping plants for each model run. In the No Overdraft case, average monthly Delta pumping is higher than in the base case for almost all months. In the base case, average pumping ranges from 400 to 550 taf per month for most of the year, except in November when it falls below 300 taf per month. For the No Overdraft case, average monthly pumping remains fairly constant in summer, but increases significantly in winter and spring. Increasing Delta exports in summer would divert supplies from other areas, so the model responds by pumping additional water in the winter and spring, when supplies are more abundant. The additional exports are then stored in the San Luis Reservoir and elsewhere to await higher summer water demands. These results are likely optimistic since CALVIN under-represents the water quality and environmental regulations governing the Delta, but it illustrates the additional demands on the Delta from ending overdraft.

Groundwater Overdraft and Storage

Table 6 shows total overdraft and average annual overdraft for both model runs over the entire modeling period and for several drought periods. Figures 6 through 8 show overall net groundwater storage change in October, for each Central Valley region over a repeat of the historical hydrology from 1921 to 1993, with negative changes indicating overdraft. In the model, overdraft primarily occurs during droughts when surface supplies are scarce. The most severe droughts on record are 1929–1934, 1976–1977, and 1987–1992. In years just before a drought, the optimization increases groundwater storage slightly since CALVIN has foresight of the drought and can prepare for it. In the base case, the largest overdraft is in the first severe drought in 1929–1934, with 20, 15, and 40 maf of overdraft in the Sacramento, San Joaquin, and Tulare basins, respectively. Over the next 57 years, overdraft occurs more slowly. At the end of the simulation period, the Sacramento and San Joaquin basins have about 15 maf of overdraft each, while the Tulare basin has 55 maf. Overall, the base model run ends with 84.4 maf of cumulative overdraft, averaging about 1.2 maf of overdraft per year. In the No Overdraft case, significant net withdrawals still occur during droughts, but more recharge occurs in wetter years. Since the No Overdraft case requires there be no cumulative overdraft at the end of the 72-year period, the model must plan recharge to balance

Table 5 Annual average Delta water exports and Delta outflow

	Overall average flow		Drought average flow		Non-drought average flow		Capacity reached	
	taf yr^{-1}						% of months	
	Base case	Increase without overdraft	Base case	Increase without overdraft	Base case	Increase without overdraft	Base case	Increase without overdraft
Banks pumping (SWP)	4,537	+172	3,172	+198	4,867	+165	51%	+15%
Tracy pumping (CVP)	788	+711	374	+6	888	+881	6%	+2%
Total Delta pumping	5,325	+883	3,546	+204	5,755	+1,047	6%	+2%
Delta outflow	11,711	–946	4,392	–27	13,477	–1,167	NA	NA

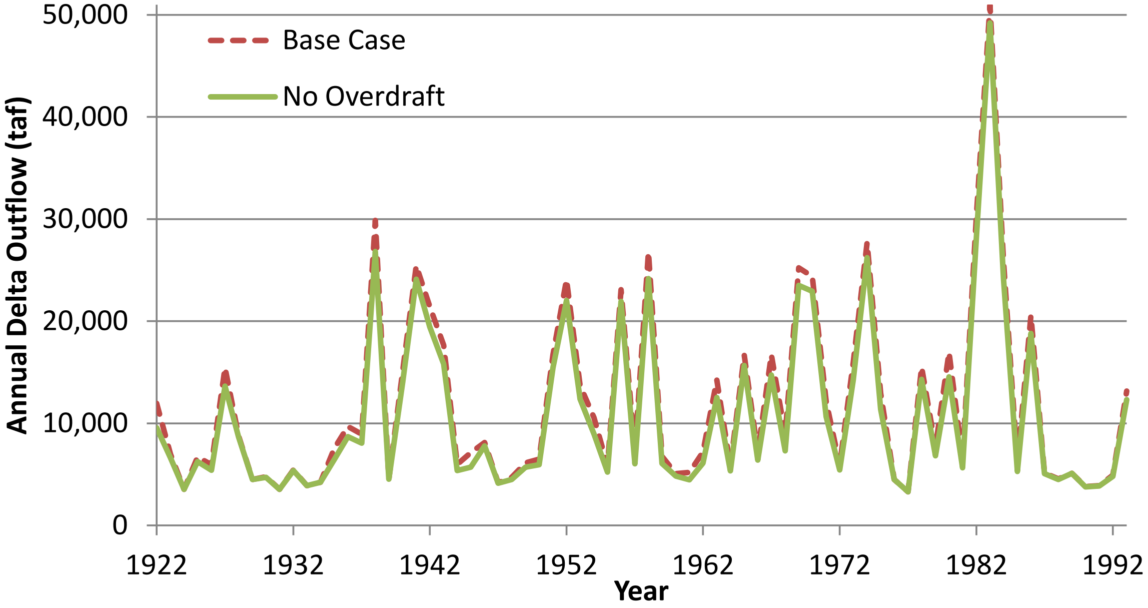

Figure 4 Annual Delta outflow time series

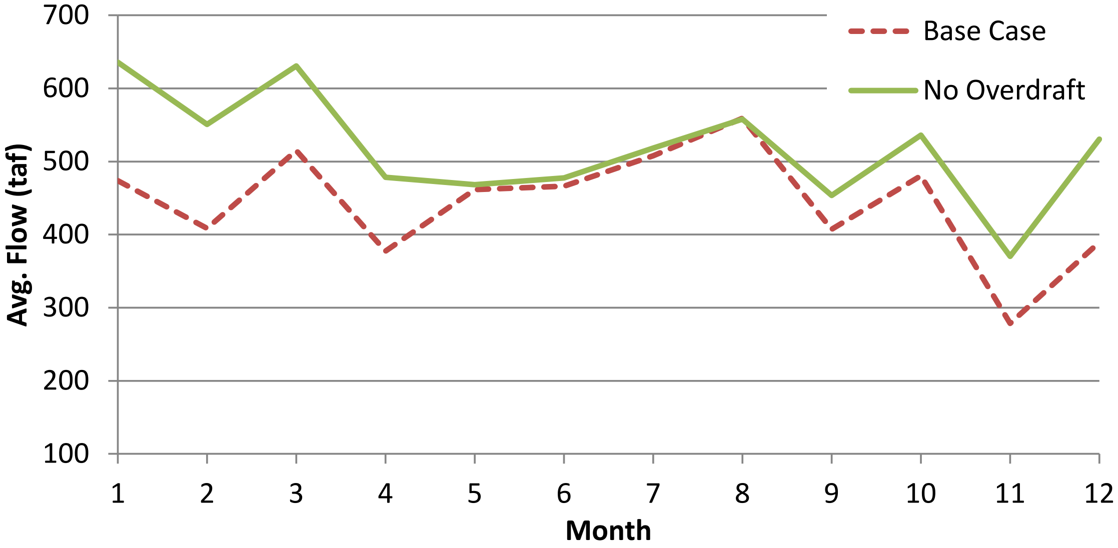

Figure 5 Average total Delta pumping each month

Table 6 Modelled total and annual average overdraft in the Central Valley

	Cumulative overdraft maf		Annual average overdraft maf yr^{-1}	
	Base case	Increase without overdraft	Base case	Increase without overdraft
Overall	84.4	−84.4	1.2	−1.2
Drought years	104.6	-6.9	7.5	−0.5
Non-drought years	−20.2	−77.5	−0.3	−1.3
1929–1934	52.3	−3.1	8.7	−0.5
1976–1977	14.4	−1.3	7.2	−0.6
1987–1992	37.9	−2.5	6.3	−0.4

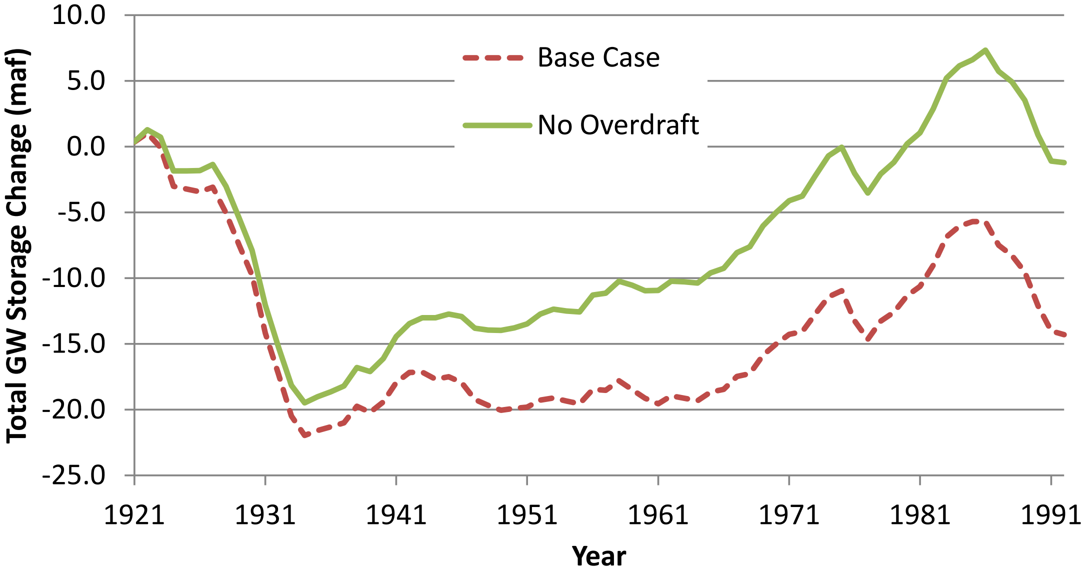

Figure 6 Sacramento Basin October net groundwater storage over 72 years

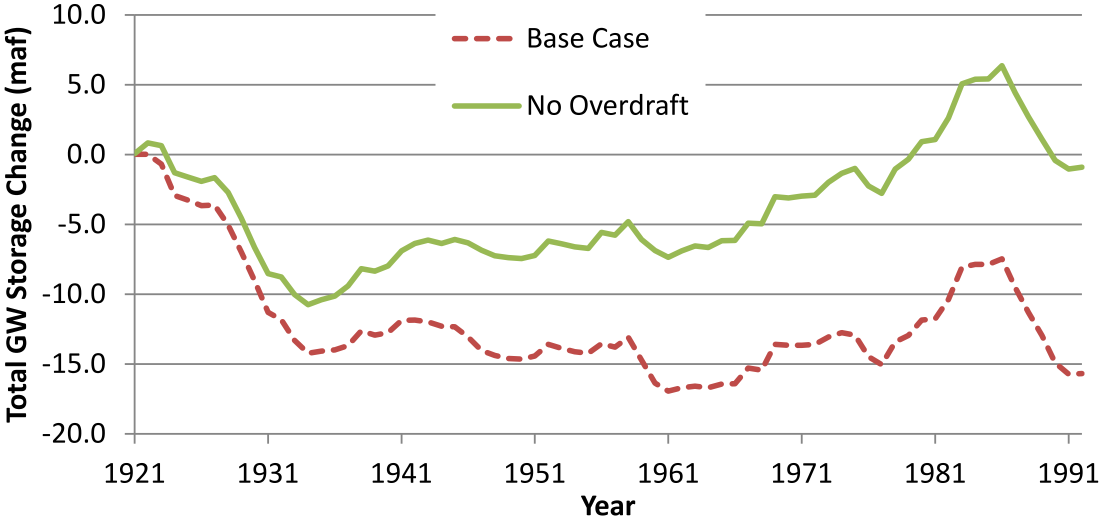

Figure 7 San Joaquin Basin October net groundwater storage over 72 years

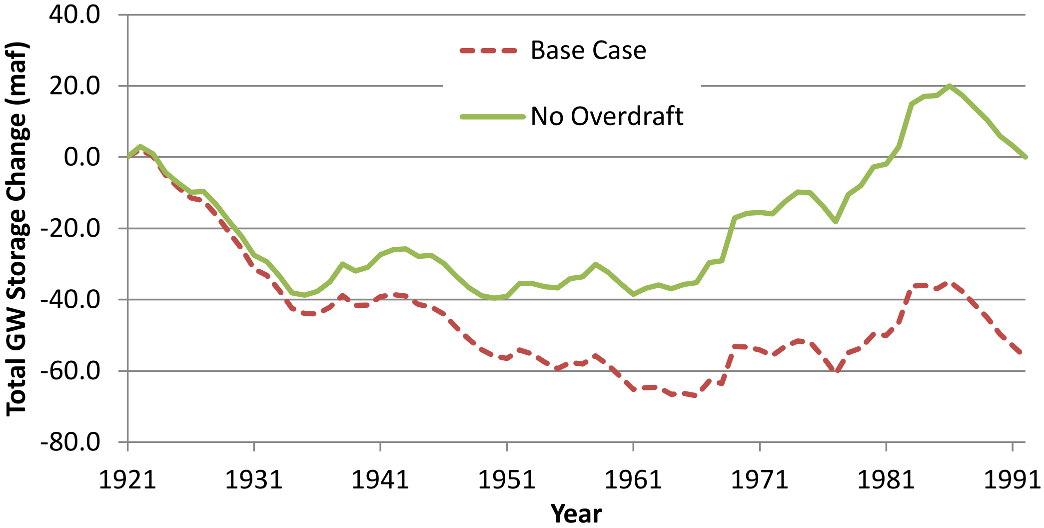

Figure 8 Tulare Basin October net groundwater storage over 72 years

long-term groundwater pumping. Using the C2VSIM model, Zikalala (2013) found that the CALVIN No–Overdraft case is optimistic, and some overdraft would still occur with the operations and deliveries CALVIN suggests.

Groundwater Recharge

Overdraft can be reduced by decreasing groundwater pumping (discussed above) or by increasing in-lieu and artificial groundwater recharge. In-lieu recharge occurs when surface water enters aquifers through deep percolation of surface irrigation or stream aquifer interactions. Artificial recharge refers to deliberately storing surface water in aquifers through spreading basins or injection wells, usually at a cost. CALVIN represents artificial recharge capabilities for most of the Tulare basin and parts of the San Joaquin basin.

Table 7 shows the in-lieu and artificial recharge of groundwater in the CALVIN model for the Central Valley. In the base case, artificial recharge averages 484 taf yr^{-1} to aquifers, costing about \$3.2 M yr^{-1}. In the No Overdraft case, average in-lieu recharge increases by about 154 taf yr^{-1} while artificial recharge increases by about 134 taf yr^{-1}, costing an additional \$0.9 M yr^{-1}. Overall, groundwater recharge increases by 288 taf yr^{-1} on average. Recharge falls significantly during droughts since immediate needs outweigh future ones, while recharge is much higher in non-drought periods when surface water is more available. With additional Delta exports in non-drought years, some is stored as additional artificial recharge for use during droughts. Areas with the highest agricultural demands and more dependence

Table 7 Artificial and natural groundwater recharge by region

	In-lieu recharge		Artificial recharge		Artificial recharge cost	
	taf yr^{-1}				\$M yr^{-1}	
Basin	Base case	Increase without overdraft	Base case	Increase without overdraft	Base case	Increase without overdraft
Sacramento	1,083	−22	0	0	0.0	0.0
San Joaquin	1,111	−3	30	+24	0.2	+0.2
Tulare	1,432	+179	453	+109	3.0	+0.8
Total	3,626	+154	484	+134	3.2	+1.0

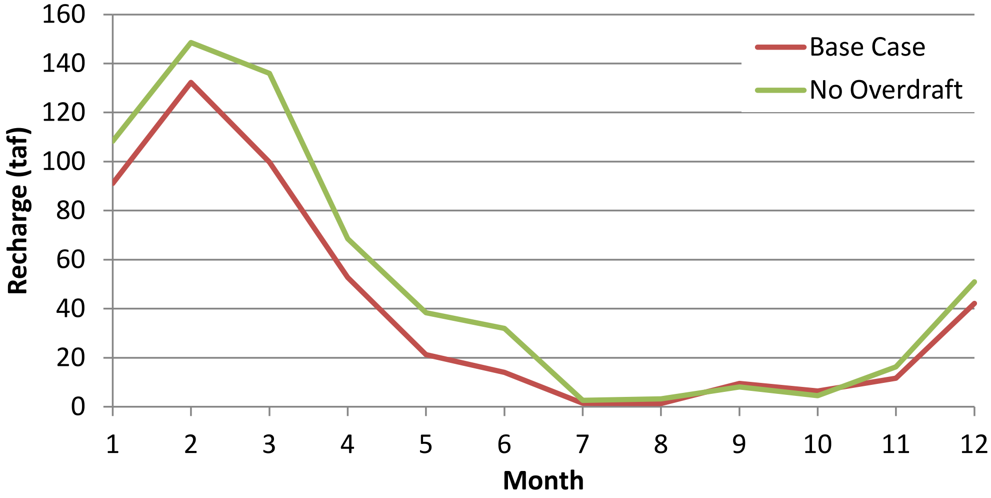

Figure 9 Monthly average artificial recharge in the Central Valley

on groundwater supplies tend to have the greatest increase in artificial recharge in wetter periods for the No Overdraft case. Figure 9 shows average artificial recharge in the Central Valley for each month for both model runs. Most artificial recharge is in winter and spring when more water is available before the summer demands.

DISCUSSION

Continued overdraft would have significant consequences for California's economy and environment. Farmers in particular will be affected as wells dry up and permanent crops become less sustainable during droughts. However, ending overdraft is not simple, especially for those who depend on groundwater but do not have access to surface water. The main obstacle is a lack of available inexpensive surface water that could replace reduced groundwater pumping. Alternative water sources such as recycling and desalination are commonly too expensive and energy-intensive, require large facilities, and could supply only a small fraction of the needed water.

Ending groundwater overdraft will increase operating and water shortage costs for the state and for water users. Ending overdraft in the Central Valley alone will cost at least \$50 M yr^{-1} (or \$25 per acre-foot per year) and probably much more. Operational changes increase net cost by \$30 M yr^{-1} from greater surface water pumping in the Delta used to offset some reductions in groundwater pumping. Another \$20 M yr^{-1} in scarcity costs is from reduced agricultural water deliveries and lost agricultural production. Such costs are not large compared to overall system operating costs of about \$3 billion per year, and total groundwater pumping costs of about \$500 M yr^{-1}, as represented in CALVIN. Actual resulting costs are likely to be higher because the CALVIN estimates are optimized to minimize total costs and water exports from the Delta are likely to be more limited. When Central Valley water use was reduced by 1.5 maf during the 2014 drought, scarcity costs increased by roughly \$1 billion for the year (Medellín–Azuara et al. 2015) A 2.7-maf reduction in agricultural deliveries in 2015 resulted in an estimated \$1.8 billion loss of net agricultural revenues (Howitt et al. 2015).

Water management in California includes many local and regional actions, but also encompasses broader measures across the state. Since surface water supplies are unevenly distributed, southern and western areas depend on large-scale operations to import water from other regions. Most of California's water system is interconnected, so changing one component can cause operational shifts throughout the network. Eliminating groundwater overdraft significantly reduces water supply for the southern Central Valley and California is likely to redistribute some supplies from other areas to mitigate this loss.

Table 8 summarizes modeled shifts of California's water system as a result of limiting groundwater overdraft. Reducing overdraft by 1.2 maf yr^{-1} would decrease groundwater pumping by 0.9 maf yr^{-1}

Table 8 Summary of average shifts in water operations with no overdraft

Operational shift	Quantity (taf yr^{-1})	Source of action	Quantity (taf yr^{-1})
Reduced overdraft	1,172	Increased recharge	288
		Reduced groundwater pumping	884
Increased recharge	288	Increased artificial recharge	134
		Increased in-lieu recharge	154
Reduced groundwater pumping	884	Reduced groundwater deliveries	742
		Reduced Kern groundwater transfers to southern CA	142
Reduced groundwater deliveries	742	Increased SW deliveries	457
		Increased scarcity	285
Increased scarcity	285	South of Delta	146
		Sacramento Valley	139
Increased Delta exports	883	Increased Recharge	288
		Increased SW deliveries south of the Delta	387
		Reduced Kern groundwater transfers to southern CA	142
		Other uses	66
Reduced Delta outflow	947	Increased Delta exports	883
		Increased SW deliveries north of the Delta	64

and increase groundwater recharge by 0.3 maf yr^{-1}, as represented by CALVIN results. Approximately 0.15 maf yr^{-1} of additional in-lieu recharge occurs while 0.13 maf yr^{-1} is artificially added to aquifers as long-term drought storage. Reducing groundwater pumping requires a 0.75 maf yr^{-1} reduction in groundwater deliveries in the Central Valley, along with a 0.15 maf yr^{-1} reduction in groundwater transfers from Kern to Southern California. The effects of lower groundwater deliveries in the Central Valley are mitigated by an additional 0.45 maf yr^{-1} of surface water deliveries from the Delta, but there is still a 0.3 maf yr^{-1} increase in water scarcity. About half of the additional scarcity is south of the Delta in the San Joaquin and Tulare basins while the other half is in the Sacramento basin.

In response to reduced groundwater supply, if water demands are kept constant Delta outflow falls by about 0.95 maf yr^{-1} (–8%) from the base case. This water that would have entered the San Francisco Bay increases Delta exports by 0.9 maf yr^{-1} instead, while the other 0.05 maf yr^{-1} remains upstream in the Sacramento basin to increase surface-water deliveries. The additional Delta exports increase surface-water deliveries in the San Joaquin and Tulare basins by 0.4 maf yr^{-1}, provide 0.3 maf yr^{-1} in additional groundwater recharge, and replace 0.15 maf yr^{-1} of Kern groundwater transfers to southern California.

Figure 10 summarizes the above responses. If the system is operated only to minimize net economic costs, roughly 23% of lost groundwater pumping is accommodated by reduced agricultural water use (increased shortage) and 77% by reduced net Delta

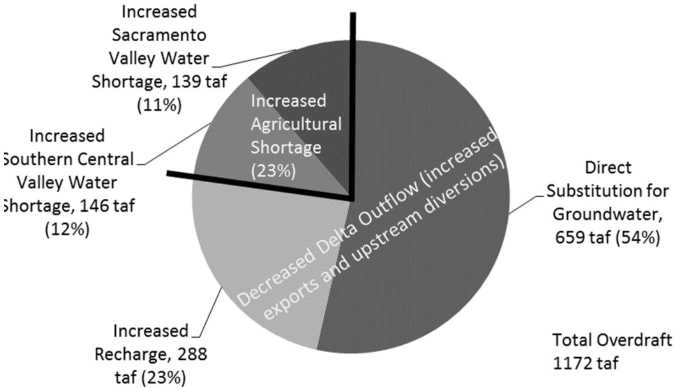

Figure 10 Average annual changes to accommodate ending groundwater overdraft of 1.2 maf in California's Central Valley (taf yr^{-1})

outflow. The retained Delta outflow is used to directly substitute 54% of groundwater supplies lost from ending overdraft, and to increase the groundwater recharge, accounting for the remaining 23% of the lost supply. Even if it is not politically and environmentally possible to provide such substantial shifting of Delta outflows to accommodate ending groundwater overdraft, these results show that substantial pressure to increase (and not reduce) Delta exports is a likely result of recent state legislation on groundwater sustainability.

Ending Groundwater Overdraft of 1.2 maf in California's Central Valley

Restricting groundwater pumping and changing Delta operations could cause other operational shifts. More conjunctive use could preserve groundwater storage and bank excess water between wet and dry periods. Increased artificial recharge in wetter years, supplied mostly from greater Delta exports, could supplement in-lieu recharge to prepare for droughts. Changes in surface-water storage operations also may be needed, especially to accommodate variability in increased Delta imports (Lund et al. 2014). As the primary storage facility on the California Aqueduct, San Luis Reservoir could see increased storage from the Delta during winter. Other storage facilities in drier areas may decrease long-term storage in favor of short-term demands. Additional water-management responses could include improvements in urban water-use efficiency, changes in environmental policy, increased interstate water transfers, and investment in new technology and infrastructure.

Ending overdraft does not greatly increase the value of expanding surface storage and most conveyance capacities (Nelson 2014). With increased surface water use, less excess water is available to be stored from year to year and most reservoirs fill to capacity less often. Even San Luis Reservoir never fills to capacity in the model, despite significant increases in winter storage. Artificial recharge is used more when ending overdraft, but there seems little value in expanding it beyond what is already possible.

California's interconnected water system, particularly the Delta, physically allows for water operations and transfers that can greatly reduce the cost of ending groundwater overdraft. The Delta is the central hub in California's water-supply network, buffering water supplies when limitations are placed on local sources (i.e., restricting groundwater pumping). Individually, southern Central Valley agriculture would suffer the most economic losses from ending overdraft. In the absence of environmental considerations, increased Delta exports could facilitate inter-regional water transfers to reduce the overall economic effect of ending overdraft. The Delta has similar importance and potential for mitigating effects of climate change in California (Tanaka et al 2006; Medellín–Azuara et al. 2008; Harou et al 2010).

However, the Delta has only a finite water supply. Additional exports would take resources from other beneficial uses in the Delta and upstream. CALVIN accounts mostly for the economic costs of water management and has only a simple representation of environmental regulations. Increased Delta exports may lead to non-monetary costs and environmental effects. Reducing annual Delta outflow (mostly in wetter years) may have environmental costs for fish in particular. Further environmental investigation and modeling of these operations is needed.

One limitation of CALVIN is its perfect hydrologic foresight. CALVIN currently optimizes water management in one simultaneous optimization, with foreknowledge of coming wet and dry periods. As a result, the value of expanding facility capacities tends to be lower than it should be (Jenkins 2001), although these effects are often surprisingly small (Newlin et al. 2002; Draper 2001). Other limitations of the CALVIN model include uncertain hydrologic data for some parts of the state and a very approximate representation of in-Delta water-management regulations. Most of CALVIN's hydrologic data is from established large simulation models and historical records. Data from different sources do not always agree, and inaccuracies are inherent in many hydrologic estimates, particularly regarding groundwater balances.

CONCLUSIONS

Eliminating long-term groundwater overdraft is a major objective of California's 2014 SGMA. This requires the development of plans for each of the state's overdrafted basins to bring withdrawals and recharge into balance. Improving long-term water balance in California's aquifers is potentially expensive in the short term, although it should help sustain agricultural and urban groundwater supplies through droughts in the long-term and provide environmental benefits. The CALVIN hydro-economic optimization model of California's extensive and integrated water supply system provides a modeling platform to explore the operational and economic effects of ending overdraft in the Central Valley, the most overdrafted of California's many aquifers. Comparing a base case with 2050 water demands, and current modeled overdraft conditions with a No Overdraft case provides insights on how the system might respond to more limited groundwater supplies or restrictive groundwater use.

CALVIN results highlight that significant changes in the operations of California's water system will be needed to accommodate the loss of water currently supplied by groundwater overdraft, especially in the southern Central Valley. Ending overdraft requires reducing net water use or increasing surface-water imports. Economically, CALVIN results suggest that ending groundwater overdraft could only moderately decrease water use in the southern Central Valley (averaging 150 taf yr^{-1} in additional scarcity), but greatly increase demands for water exports from the Sacramento–San Joaquin Delta (averaging 900 taf yr^{-1}). Most of the increased Delta exports comes from reduced Delta outflows during non-drought years (averaging 950 taf yr^{-1} in reductions), but some also comes from reduced water use in the Sacramento basin (averaging 140 taf yr^{-1} in additional scarcity). The increased Delta exports occur mostly in winters of wetter years, and are stored in San Luis Reservoir as seasonal storage for summer demands. Additional artificial recharge south of the Delta provides over-year storage for future drought years.

Ending long-term overdraft will have significant costs. In this analysis, additional water scarcity costs in the Central Valley and higher operating costs for Delta exports increase net system costs by at least \$50 M yr^{-1}. This estimate is likely a lower bound on these costs, because it results from an optimization model that assumes the system has operational flexibility to allow significant increases in Delta exports. If the entire modeled 1.2 maf yr^{-1} of average annual Central Valley overdraft was to come only from reductions in human net water use, the scarcity and operating costs of ending overdraft would be much higher. A 2014 study found that reducing water use by 1.5 maf in the Central Valley during the drought, increased water scarcity or delivery shortage costs by roughly \$1 billion for the year (Medellín–Azuara et al. 2015).

These results highlight some economic and policy issues arising from California's efforts to make groundwater use more sustainable. In this endeavor, California can benefit from the use of its interconnected water system to reduce water shortages and redistribute supplies in economical ways. Further analysis of ending overdraft might restrict the ability to reduce Delta outflow or divert additional Delta water (Tanaka et al. 2011; Dogan 2015). In addition, environmental studies on the potential effects of changing Delta operations and how climate change will affect these operations will be essential.

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