Integrated Water Operations in California: Hydropower, Overdraft, and Climate Change

By

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B.S. (Dokuz Eylul University, Izmir, Turkey) 2011

THESIS

Submitted in partial satisfaction of the requirements for the degree of

MASTER OF SCIENCE

in

Civil and Environmental Engineering

in the

OFFICE OF GRADUATE STUDIES

of the

UNIVERSITY OF CALIFORNIA

DAVIS

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2015

Abstract

Several management and climate cases are evaluated with the updated CALVIN, a hydro-economic optimization model of California's inter-tied water supply infrastructure. Updates to the CALVIN model include new projected 2050 agricultural target demands and scarcity penalties, improvements to network-flow representation, especially agricultural, urban, and wildlife refuge demands, and extended surface and ground water hydrology, now covering an 82-year historical inflow hydrology. A new energy price scheme is applied to CALVIN, which incorporates hourly energy price variations into monthly CALVIN operations. Using one constant average price for a month underestimates hydropower revenue and overestimates pumping costs. Hourly-varying moving average prices improved representation of hydropower revenue without creating significant scarcities to agricultural and urban water users. Effects of ending long-term groundwater overdraft in the Central Valley are evaluated with several management cases using CALVIN. The cases include effects of Delta outflow and Delta exports from a "no overdraft" policy. The least cost overdraft that minimizes groundwater pumping and scarcity costs is calculated for the 82-year period. Prohibiting Delta exports result in severe water scarcities south of the Delta. Water operations are more economical when overdraft is ended with adaptations, such as more Delta exports, increased groundwater banking, and water trades, than historical operations with overdraft. Finally, climate change effects under a warmer and drier climate scenario are studied and results are compared to historical hydrology. A drier and warmer climate shifts the timing and magnitude of stream flows. Spring snowmelt decreases and winter flows increase. Modelled reduction in rim inflows averages about 28%. This warmer-drier climate increases water scarcities, but adverse effects can be diminished with water sales, higher Delta exports, more conjunctive use, and wastewater recycling.

Acknowledgements

I would like to express my sincere appreciation to my adviser and committee chair, Professor Jay R. Lund, for his enthusiasm, guidance, constant support, and invaluable comments, without which this thesis would have never been completed. Thanks also to my committee members, Professor Samuel Sandoval-Solis and Professor Jonathan Herman, for their editorial reviews.

Special thanks to Josué Medellín-Azuara, who was always available to answer my endless questions and provided assistance during my research. I would also like to thank to Karandev Singh, with whom I worked together while updating CALVIN model. Without his contribution, this work would have never been done. I am also thankful for his friendship, suggestions, and conversations on academic and daily life. I am grateful to members of CALVIN update project, Alessia Siclari, Lily Tomkovic, Chad Whittington, Andy Tweet, Eric Mork, Hillary Ships, and Stephanie Saiz. Also, special thanks to my officemates and the staff at the Center for Watershed Sciences.

Thanks to Ministry of National Education of the Republic of Turkey for providing me with full scholarship to pursue my academic goals.

Last but not least, I am so grateful to my family for their continuous encouragement, patience, and moral support during my stay in the U.S. Without their love, presence and support, I would never be successful.

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Abbreviations

AF - Acre-Foot

CAA - California Aqueduct

CDEC - California Data Exchange Center

CDFW - California Department of Fish and Wildlife

CDWR - California Department of Water Resources

CVP - Central Valley Project

CVPIA - Central Valley Project Improvement Act

DMC - Delta-Mendota Canal

GFDL - Geophysical Fluid Dynamics Laboratory

LAA - Los Angeles Aqueduct

MAF - Million Acre-Feet

MIF - Minimum In-Stream Flow Requirement

MWDSC - Municipal Water District of Southern California

NOAA - National Oceanic and Atmospheric Administration

NWR - National Wildlife Refuge

SWP - State Water Project

SWRCB - State Water Resources Control Board

TAF - Thousand Acre-Feet

USFWS - U. S. Fish and Wildlife Service

Chapter 1. Introduction

Modeling is common in water resources engineering and management. Models help operators and policy makers explore and compare different management alternatives, better operate complex water resources systems, and predict the future behavior of existing or proposed water systems (Loucks, 1992). Modeling and model use can increase benefits or decrease costs for managing water (Savic and Simonovic, 1991). These water-related benefits include agricultural, urban and wildlife water supply, hydropower, flood control, recreation, and navigation (Yeh and Becker, 1982). Yeh (1985), Wurbs (1993) and Labadie (2004) review water resources system models, including simulation and optimization models, ranging from small to large-scale. Integrated river basin management models provide a rational framework for efficiently allocating scarce water among different users, at different locations and time periods, considering economic and hydrologic variables (Ward and Lynch, 1996). Davis (2007) defines integrated water resources management as a facilitated stakeholder process to promote coordinated activities in pursuit of common objectives for better development and management. Marques and Tilmant (2013) point out that operational coordination is critical to maintain and increase system-wide benefits under uncertain conditions in multireservoir water systems.

California's inter-tied water supply network is complex. The Central Valley Project (CVP) and the California State Water Project (SWP) are among the largest water projects in the United States (Lefkoff and Kendall, 1996). The geographic and seasonal differences between the water availability in northern and eastern California and water demands in central and southern California have led to extensive water resources development (Jenkins et al., 2004). This mis-match in timing and magnitude of water availability make planning and management of water even more critical in California. To meet water demand and economically optimal operational criteria, reservoirs, canals, pumping and power plants have to be coordinated. Although California's many water facilities serve mostly for water supply, flood control and recreation, hydropower also provides large economic returns. Joint reservoir operations have a key role in optimizing water network management.

Hydropower is an important renewable energy source in California. The state's hydropower capacity of 14,116 MW is about 25 percent of California's electricity production capacity and approximately 15 percent of its generation (McKinney, 2003). Hydropower in California can be from plants fed by water from storage, pumped storage or run-of-river. Storage and pumped storage facilities are particularly valuable for peak time electricity demands (Phinney et al., 2005), whereas run-of-river plants run continuously, depending on stream flow conditions. Although most hydropower is generated at high-elevation systems, which are generally single-purpose hydropower plants (Madani, 2009), reservoirs in the lower foothills have much larger storage capacity and flow but less natural head and also serve water supply, flood control and other purposes (Phinney et al., 2005; Vicuña et al., 2009).

Computer-based models are useful in water planning and management to simulate different management cases and help decision-makers gain insights for system operations. CALVIN is a hydro and economics-driven optimization model for California's inter-tied water supply system (Draper et al., 2003). The CALVIN model covers about 88 percent of California's irrigated acreage and 92 percent of the state's urban population. Prescribed CALVIN operations are now based on 82 years of historical hydrologic data, extending the earlier 72 years of time-series data. The objective in CALVIN is to minimize statewide water scarcity and operating costs (Jenkins et al., 2004). The CALVIN model has been used to examine many water management alternatives. Draper (2001) studied reservoir operations with perfect and limited foresight. Newlin et al. (2002) and Pulido-Velazquez et al. (2004) explored water marketing options for southern California. Null and Lund (2004, 2006) evaluated water supply operations and restoration without O'Shaughnessy Dam, located in the Hetch Hetchy Valley of Yosemite National Park. Various studies examined climate change and drought effects (Connell-Buck et al., 2011; Harou et al., 2010; Medellín-Azuara et al., 2009; Medellín-Azuara et al., 2006; Medellín-Azuara et al., 2008; Medellín-Azuara et al., 2013; Tanaka et al., 2006). Several other studies focused on different management cases in California (Harou and Lund, 2008; Jenkins et al., 2004; Tanaka et al., 2011; Tanaka and Lund, 2003).

The CALVIN model was recently updated. The updates maintain functionality and applicability of the model in changing conditions and better represent California's water infrastructure. Updates include adding 10 more years to all hydrologic data, new representation of agricultural and urban demand areas, improvements in network-flow representation, new minimum in-stream flow requirements (MIF) from the CALSIM II model (Draper et al., 2004), new agricultural water target values and penalties for shortage from the updated SWAP model (Statewide Agricultural Production Model) (Howitt et al., 2012). These updates are on top of earlier updates on groundwater and regional flow estimates (Chou, 2012; Zikalala, 2013).

Water resources system models are generally either short-term or long-term models. Short-term models have an hourly to daily time step, while time steps for long-term models range from weekly to annual. Due to computational demands, long-term models rarely use hourly time-steps. For hydropower, long-term models usually use monthly or weekly average energy prices to optimize system operations or maximize power benefits. In short-term models, which have hourly time-step, using average energy prices for each time-step works well. However, in long-term models, with large time steps, using weekly or monthly average energy prices can be misleading (Olivares, 2008) since it does not reflect hourly price variability into model operations. Using weekly or monthly average energy prices can underestimate power revenue. This is because with economically optimal operations, reservoirs with an after-bay operate during the most economically advantageous hours (Tejada-Guibert et al., 1990), the so-called peak hours. However, for run-of-river hydropower plants, peak or off-peak hours may not be important because they operate at all times, as long as river flow is available. To solve this implied problem, Tejada-Guibert et al. (1990) used a method that incorporates energy prices with power plant's production capacity. They applied this method to CVPOP, a joint Cornell-PG&E nonlinear programming model, to optimize CVP hydropower operations. This model, however, included hydropower plants in the Sacramento Valley Region of the Central Valley and the only purpose of the model was hydropower maximization. A similar technique was utilized in the EBHOM model developed by Madani (2009), where energy price is a function of total hours of generation in a given month. He modeled California's high elevation hydropower systems under historical and different climate change cases. EBHOM models only California's high head hydropower plants located at high elevation with small storage capacities, and the objective is to maximize hydropower benefits, ignoring integrated water management and operations. Olivares (2008) developed a model that incorporates hourly price variations for a single reservoir with a large storage capacity, considering head effects on operations. His model also takes downstream minimum in-stream flow requirements into account and optimizes hydropower generation. When downstream environmental flow constraints are considered, operations become more complicated. Water allocation for environmental needs is continuous, whereas hydropower releases can vary depending on peak or off-peak hours (Olivares and Lund, 2012). He separated reservoir releases into environmental and hydropower releases. For environmental releases monthly average price can be used. Hydropower releases, on the other hand, are incorporated with variable energy prices. These studies concluded that there is a great benefit of incorporating hourly energy price variations in long-term models. This study extends the work of Tejada-Guibert et al. (1990), Madani (2009) and Olivares (2008), using the CALVIN model, to include joint state-wide hydropower and water supply operations for agricultural and urban users, under historical and warm-dry climate warming scenarios.

Conjunctive use of groundwater and surface water is a strategic water management tool that improves efficient use of resources. When surface water is abundant, water is mostly supplied from surface water resources, such as reservoirs and streams, for irrigation, residential, and industrial needs. In droughts, when surface water is scarce, water is pumped from groundwater to meet the water demand and reduce the water scarcity. However, with economic development and increased water demand, groundwater can be overexploited. Overexploitation or overdraft is the condition of a groundwater basin in which the amount of water withdrawn over long-term exceeds the amount of water that recharges the basin (CDWR, 2003), resulting in less groundwater storage. There are many negative consequences of groundwater overdraft, including increased pumping cost, higher water scarcity cost in dry years, deteriorated water quality, land subsidence, and sea water intrusion in coastal areas. Overdraft also affects streams that are hydraulically connected to aquifers (Konikow and Kendy, 2005). Several studies have evaluated groundwater overdraft and its effects in California (Custodio, 2002; Gorelick and Zheng, 2015; Grabert and Narasimhan, 2006; Harou and Lund, 2008; Zektser et al., 2005). In California, about 30% of total water demand is supplied from groundwater in an average year, and it exceeds 40% in dry years (CDWR, 2003; Grabert and Narasimhan, 2006). Some cities in California, such as Fresno, Davis, and Lodi, rely solely on groundwater for drinking water (CDWR, 2003). This study explores effects of ending groundwater overdraft in the Central Valley with several water management scenarios. The first scenario assumes no long-term overdraft in the Central Valley groundwater basins. The second scenario explores water operations without overdraft and reduction in the Delta outflow. Third case restricts Delta water transfers from Tracy and Banks pumping plants to historical rates and studies no overdraft effects. The last case assumes that there is no water transfers from the Delta through the Delta-Mendota Canal and California Aqueduct and explores water operations without long-term groundwater overdraft.

Climate warming is predicted to have major impacts on California's hydropower and water supply. Annual average river runoff and water availability are projected to decrease over semi-arid and arid areas, such as the western USA and Mediterranean Basin (Bates et al., 2008). Climate change effects on California's water resources are examined in many studies (Cayan et al., 2008; Dracup and Vicuna, 2005; Hanak and Lund, 2012; Lettenmaier and Sheer, 1991; Miller et al., 2003; VanRheenen et al., 2001; Vicuna and Dracup, 2007; Vicuna et al., 2010; Vicuna et al., 2007). As a result of climate warming, a higher percentage of precipitation will fall as rain rather than as snow in the Sierra Nevada Mountains, so more runoff will occur in winter rather than spring (Hancock et al., 2004). Since California's water system is substantially snowmelt-driven, it can suffer from climate warming (Dracup and Vicuna, 2005). California's energy demands are generally high in summer and lower in spring months due to climatic conditions and air conditioning use. Seasonal shifts from climate warming could alter hydropower management. Phinney et al. (2005) show that the increase in runoff in winter when electricity demand is lower compared to summer would increase hydropower generation in winter, but decrease in summer runoff significantly reduces hydropower potential, causing scarcity in hydropower supply. Given climate change projections and possible impacts to water resource systems, joint operations of hydropower with other reservoir purposes, such as water supply, flood control and recreation, become more important for maximizing overall system-wide benefits.

The objective of this thesis is to study California's inter-tied water supply system with different climate conditions and management alternatives and contribute to engineering and management solutions. The structure of the thesis is as follows: Chapter 2 describes the CALVIN model and presents recent updates to the model. Chapter 3 summarizes a historical hydrology case for CALVIN hydropower and water supply operations with 2050 water demands. It compares results with monthly average energy prices to variable price hydropower results. Chapter 4 discusses effects of ending the long-term groundwater overdraft on California's water supply system, and explores adaptations to mitigate water scarcities. Chapter 5 demonstrates perturbed hydrology development for a warm-dry climate change scenario and shows operations under climate warming. Finally, Chapter 6 presents concluding remarks, describes model limitations, and ends with possible extensions and future research.

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Chapter 2. CALVIN Model and Updates

Introduction

California Value Integrated Network (CALVIN) is a deterministic hydro-economic optimization model of California's integrated water supply and delivery system. The main goal of CALVIN is to support quantitative understanding of California's integrated water and economic system. CALVIN represents California's water infrastructure with 49 surface reservoirs, 38 groundwater reservoirs, 600+ conveyance links, 1250+ nodes, and 36 agricultural, 41 urban and 8 wildlife refuge water demand areas. CALVIN covers about 88 % of California's irrigated acreage and 92 % of the state's urban population (*Figure 1*). CALVIN is a linear programming model that uses a generalized network-flow optimization solver (HEC-PRM) developed by the U.S. Army Corps of Engineers. HEC-PRM is driven by convex cost-based piece-wise linear penalty functions (Wurbs, 1993). CALVIN operates and allocates surface and groundwater resources with deterministic hydrologic inflows under 2050 demand conditions, within physical and environmental constraints (Draper et al., 2003). CALVIN has an economics-driven objective (*Equation 1*) to minimize system-wide operating costs (such as pumping and treatment) and scarcity costs to water users. Scarcity volume is defined as the amount of water that the user is willing to pay for, but did not receive. Whenever a user's target demand is not met, scarcity occurs with a cost derived from the user's willingness to pay (Connell-Buck et al., 2011). Currently, agricultural and urban water target demands are estimated based on a 2050 level of development, which accounts for population growth, urban per-capita use, and agricultural land uses.

CALVIN objective function:

$$min\, Z = \sum_i \sum_j c_{ij} X_{ij} \qquad \textit{Equation 1}$$

Subject to:

$$\sum_i X_{ij} = \sum_i a_{ij} X_{ij} + b_i \qquad \textit{Equation 2}$$

$$X_{ij} \leq u_{ij} \qquad \textit{Equation 3}$$

$$X_{ij} \geq l_{ij} \qquad \textit{Equation 4}$$

where X_{ij} is a flow from node i to j, c_{ij} is an economic cost, a_{ij} represents gains or losses on flows in an arc, b_j is an external inflow to node j, u_{ij} and l_{ij} are upper and lower bounds on a link, respectively. First constraint (*Equation 2*) simply represents mass balance over a node, and second (*Equation 3*) and third constraints (*Equation 4*) account for maximum and minimum flow limits on a link.

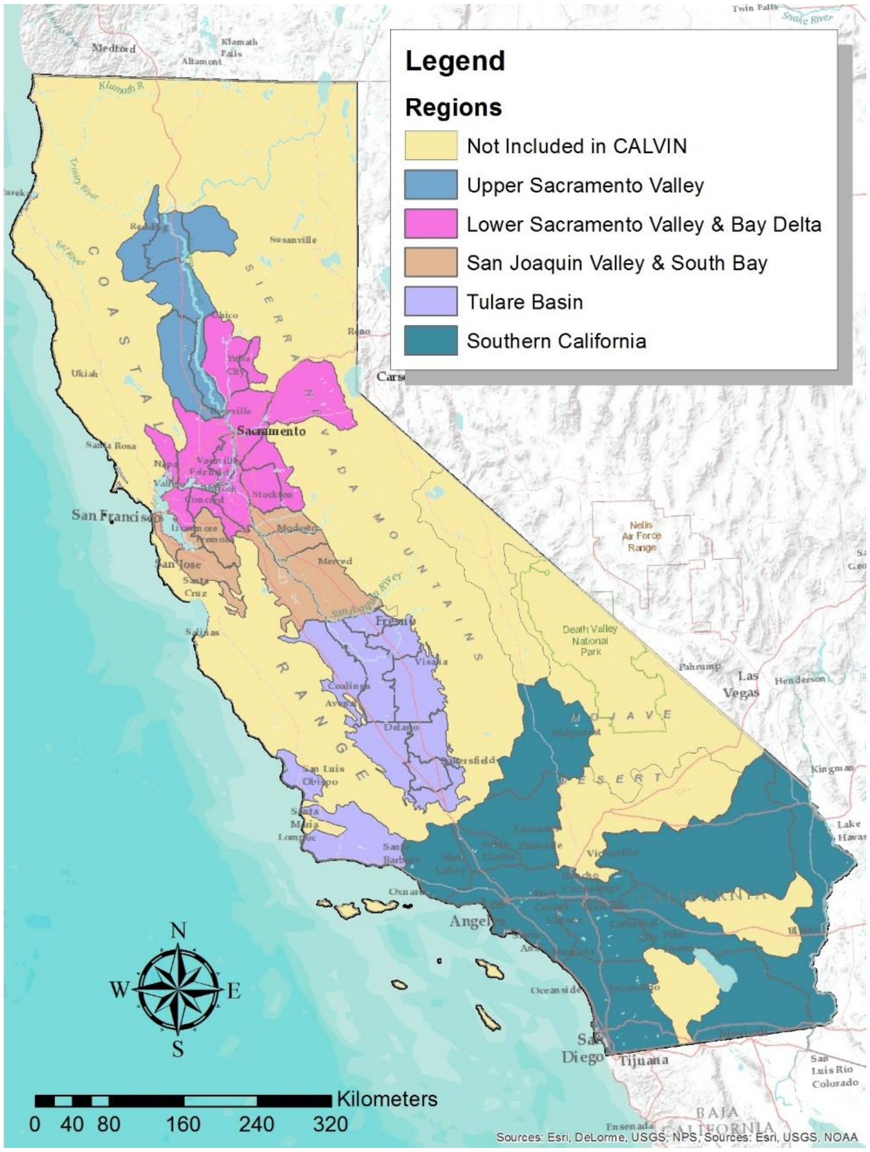

Figure 1. CALVIN regions

Data Flow

CALVIN is a hydro-economic optimization model with hydrologic and economic inputs and outputs. Hydrology-related inputs include surface and ground water hydrology, environmental flow constraints and wildlife water deliveries. Physical facilities of the system, such as reservoirs, pumping and power plants, aqueducts and treatment plants, have capacity constraints. Minimum in-stream flow requirements are represented as "lower bounds" in the model and wildlife refuges have fixed water deliveries, meaning that water is allocated to the environmental uses first. Agricultural and urban values of water and target demands are important inputs since the primary purpose of the model is to economically operate and allocate water to agricultural, residential and industrial users. Demand areas are assigned penalty functions that represent the cost of water scarcity to users. The difference between the target and actual delivery represents water scarcity, and the area under the economic water demand curve is defined as a scarcity cost (*Figure 2*), the cost of water being a scarce economic resource. Operating costs for CALVIN facilities are other economic inputs to the model. An operating cost can be simply a unit cost attached to flow in a link, or a monthly varying piece-wise linear cost curve for varying level of flows.

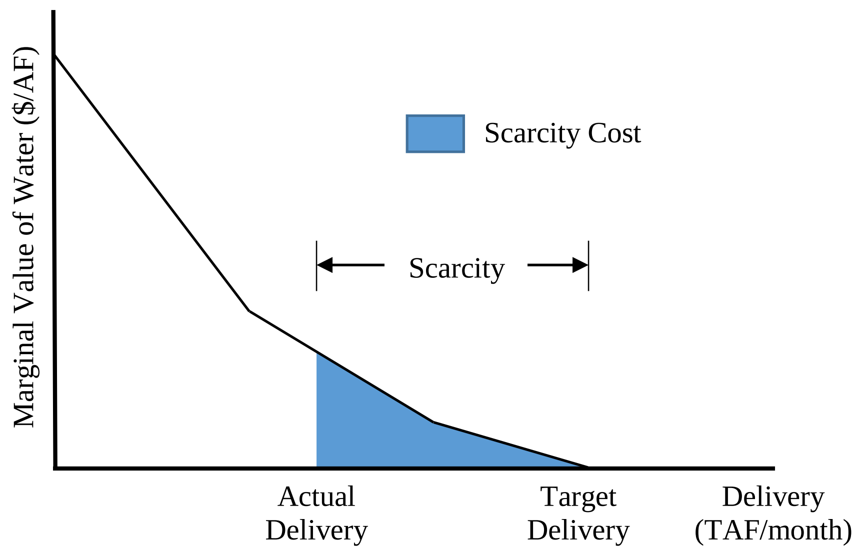

Figure 2. Economic value of water

Typical hydrologic CALVIN outputs are channel and delivery flow time-series, surface and ground water storages, and reservoir evaporation time-series (*Figure 3*). The model outputs include surface and ground water deliveries to agricultural users. Moreover, CALVIN provides a water supply portfolio for residential and industrial users, including surface water, groundwater pumping, desalination, and potable and non-potable water reuse and water conservation. Marginal values of increased physical capacity (from Lagrange multipliers), opportunity cost of water for agricultural and urban users, and costs of shortage are major direct economic outputs of CALVIN. The marginal values of water provide insights into expanding infrastructure capacity or lowering system constraints for planning or policy purposes. Hydropower generation and power benefits are represented in the objective function and also calculated more accurately in a separate post-processor based on reservoir storage and release time-series of CALVIN.

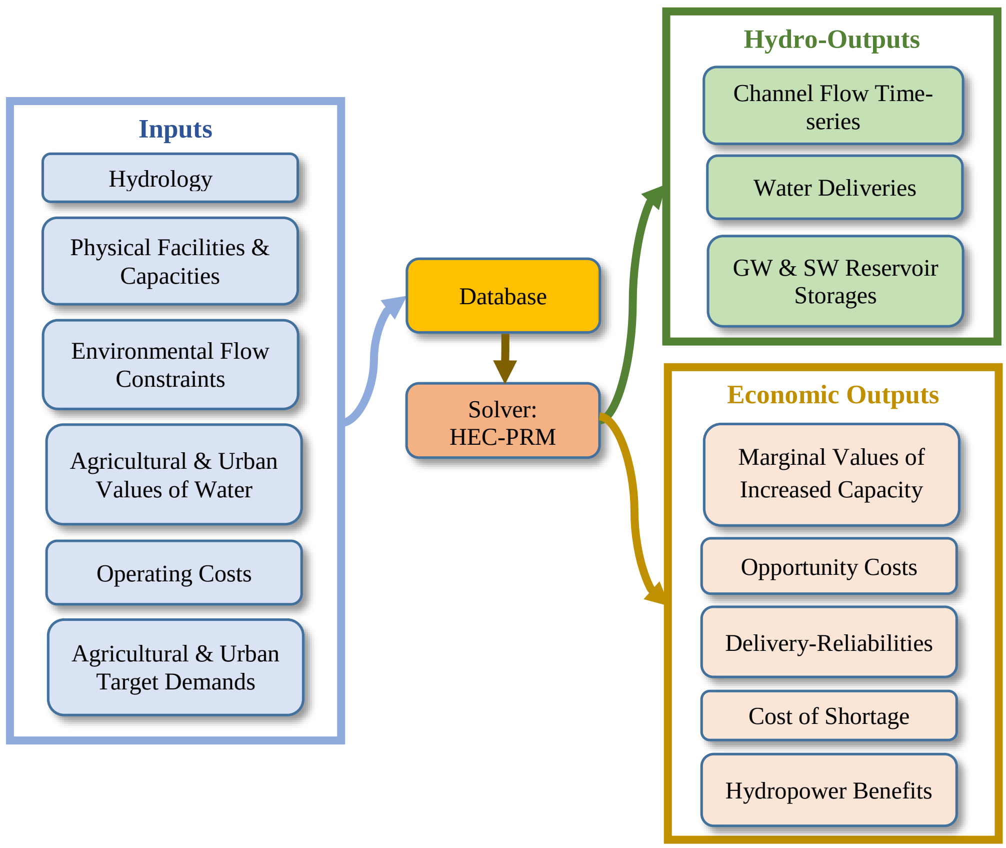

Figure 3. CALVIN data flow

Hydrology

CALVIN is now driven by 82 years of monthly historical surface and ground water hydrology data for the October 1921 through September 2003. This period represents a wide spectrum of hydrologic conditions of California (Draper, 2001). Hydrology components of CALVIN include surface water inflows (rim inflows), groundwater inflows and local inflows (*Figure 4*). Return flows from agricultural, urban and environmental uses are calculated during the system operations. Local inflows are mostly surface water accretions or depletions due to local precipitation and the interaction between groundwater and stream flow. Net evaporation rates for reservoirs and evaporation losses from canals also are included in the CALVIN hydrology. Rim inflows represent streams that cross the boundary of the physical system being modeled (Draper, 2000a). Historical hydrologic data come from several other sources. The recent updates integrated into CALVIN surface hydrology from the CALSIM II model, and groundwater hydrology from the C2VSim model.

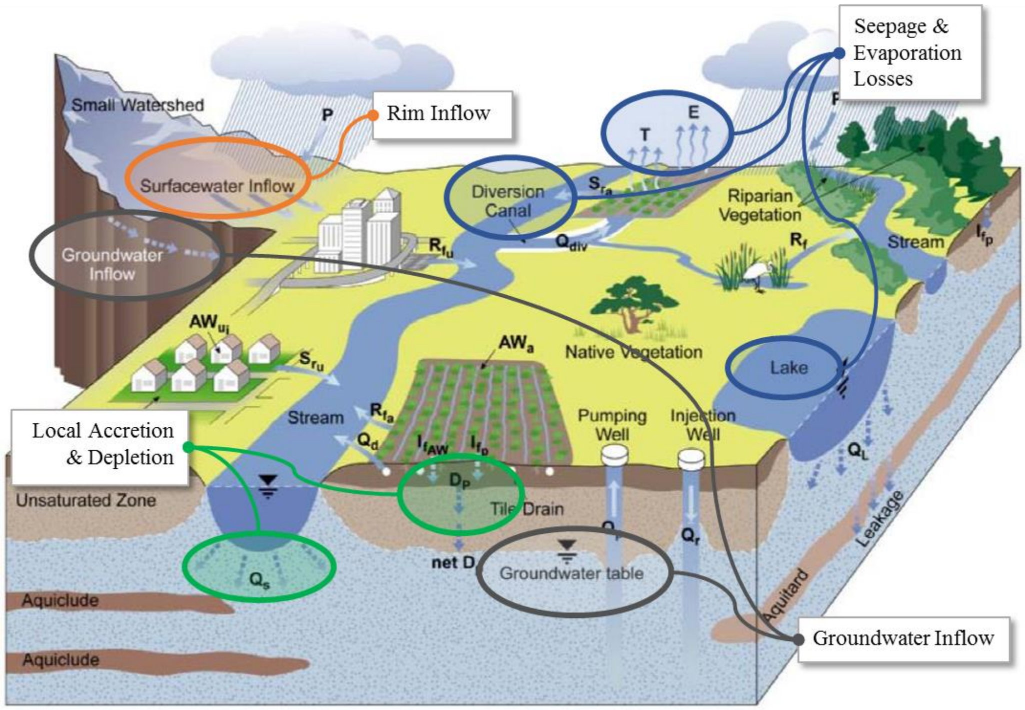

Figure 4. CALVIN hydrology (image source: CDWR (2014))

Limitations

Limitations are inherent in all models. The input data used in the CALVIN model for the hydrology, water demands, and other water allocation operations are limited by the quality of data sets. Weak or unavailable information affects the quality of outputs (Draper et al., 2003). CALVIN neglects flood control and recreation operations except for seasonal flood storage reservations (Tanaka et al., 2006). Deterministic linear programming has its own shortcomings (Ilich, 2008). CALVIN is too smart in knowing every hydrologic event in 82 years, and allocates water with perfect foresight although this does not dramatically affect many decisions (Draper, 2001). Furthermore, making non-linear curves piece-wise linear sacrifices some accuracy. CALVIN simplifies environmental regulations, water quality, and stream-aquifer interaction behavior due to its network-flow solver and data availability (Draper et al., 2003). Uncertainties in future water demand and climate change projections limit some insights. Despite the limitations, CALVIN provides insightful results for California's water management system. As a well-documented model, CALVIN can run various management and planning cases and provide insights for state-wide and regional water policy, planning, and management decisions.

Recent Model Updates

Water resources system models need to be constantly improved to maintain functionality and applicability. Updates adapt models to changing planning and management conditions and new policy requirements. In addition, data quality is important for computer-based models. As better data become available, models should be updated. The CALVIN model has been improved since its introduction in early 2000s (Bartolomeo, 2011; Chou, 2012; Connell, 2009; Nelson, 2014; Zikalala, 2013). These previous and current updates aim to better represent California's inter-tied water infrastructure and obtain more accurate results. The major updates to CALVIN can be categorized as;

- Hydrology,
- Network Representation,
- Agricultural Demand and Shortage Penalties,
- Hydropower.

Hydrology Updates

The CALVIN hydrology is updated, and the time period is extended from 1993 to 2003, now covering 82 years of hydrologic conditions. Several methods are employed in the update process. These methods include full and partial replacements of existing CALVIN time-series with data from other models and studies, regression analysis, and the extension based on Sacramento or San Joaquin Valley water year types (WYT). For the southern California region, the update method is mostly limited to monthly averaging the existing time-series. These updates are on top of earlier updates by Chou (2012) and Zikalala (2013) who updated groundwater hydrology, mostly using C2VSim model results for the Central Valley part of the model. This study maps and integrates surface water hydrology of CALVIN, including rim inflows, local inflows and net reservoir evaporation rates, to CALSIM II surface water hydrology. If corresponding data is not available in the CALSIM II model, other methods are employed. For regression analysis, data is acquired from California Data Exchange Center (CDEC). A few unimpaired rim inflow time-series are gathered from CDWR (2007). Water year type index-based extension of time-series is available for Sacramento and San Joaquin regions of CALVIN. Water year indices (*Table 1*) are determined based on runoff of major rivers in Sacramento and San Joaquin Valleys and are helpful to assess the amount of water originated in those basin (CDWR, 2009). When extending CALVIN time-series with the water year type (WYT) method, extension period years (1993-2003) are mapped to index years (1921-1992), and index year data are used in the corresponding year. Mapping criteria require that WYT index, total water year runoff and WYT adequately match.

Table 1. Sacramento and San Joaquin Valley Water Year Types

Water Year Type	**Water Year Index**	
	Sacramento Valley	San Joaquin Valley
Wet	$WYI \geq 9.2$	$WYI \geq 3.8$
Above Normal	$7.8 < WYI < 9.2$	$3.1 < WYI < 3.8$
Below Normal	$6.5 < WYI \leq 7.8$	$2.5 < WYI \leq 3.1$
Dry	$5.4 < WYI \leq 6.5$	$2.1 < WYI \leq 2.5$
Critical	$WYI \leq 5.4$	$WYI \leq 2.1$

Table 2 shows water year mapping process. Index and corresponding water years, and extension method for each hydrology time-series and their data sources are listed in Appendix A.

Table 2. Water year type extension method mapping

Water Year	Index	Total Runoff (maf)	Type	
1921	9.2	23.8	AN	
:	:	:	:	
1969	11.05	26.98	W	
1970	10.40	24.06	W	Existing
1971	10.37	22.57	W	
:	:	:	:	
1993	8.54	22.21	AN	
1994	5.02	7.81	C	
1995	12.89	34.55	W	
1996	10.26	22.29	W	Extension
1997	10.82	25.42	W	
:	:	:	:	
2003	19.31	8.21	AN	

Network Representation

The main update to the CALVIN network is to standardize the representation of agricultural and urban demand areas using a new supply structure and naming convention. Groundwater pumping and surface water diversions are available water sources for agricultural users (*Figure 5*). Agricultural demand areas are divided into two parts based on their return flows to either the underlying groundwater basin or downstream surface water. For agricultural areas, node names are updated based on the new naming convention. Return flows to underlying groundwater basin from agricultural and urban uses are aggregated into one node for each groundwater basin. Groundwater pumping cost and consumptive use estimates are updated based on the SWAP model (Howitt et al., 2012). (Appendix B). Pumping costs include energy costs per lift, operating and maintenance costs, and other fixed costs. 70 percent pumping efficiency is assumed. Groundwater pumping costs and agricultural non-consumptive uses are updated only for the Central Valley agricultural demand units. Demand areas in the southern California remain to use earlier prices and return flow ratios. Groundwater pumping costs are in 2008 dollars.

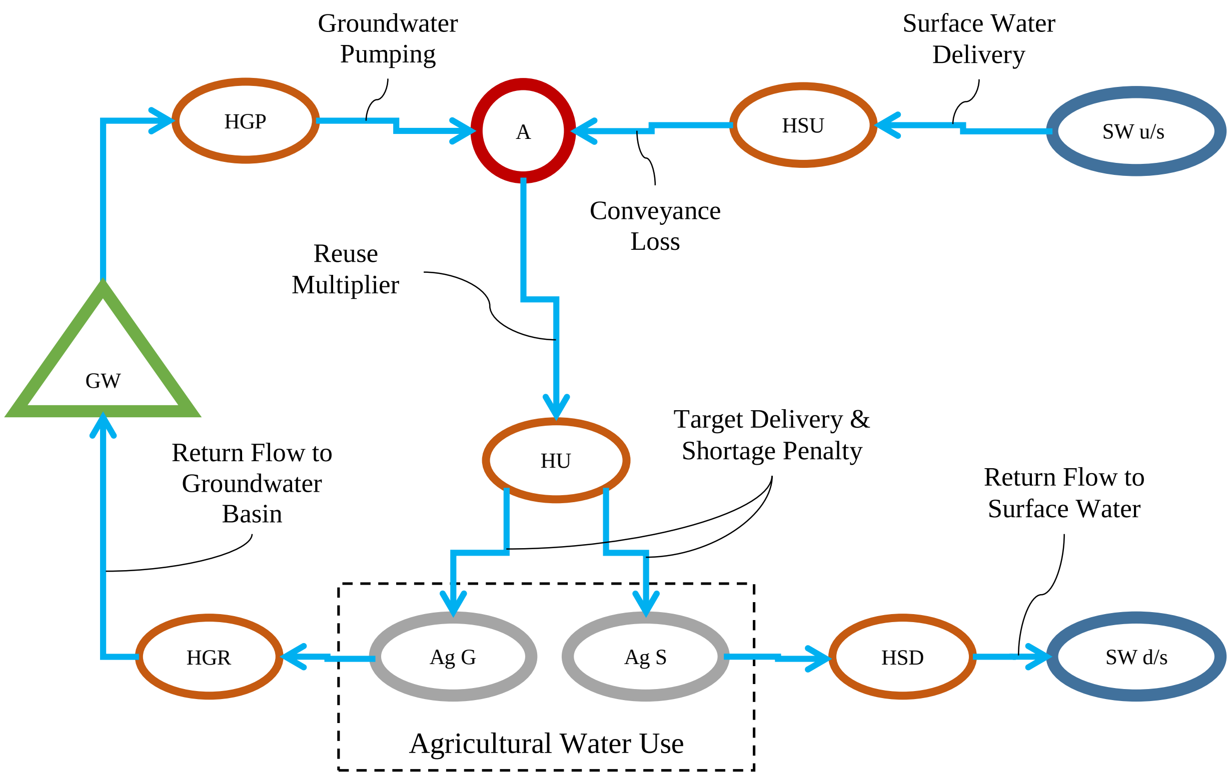

Figure 5. CALVIN updated agricultural demand area representation

Urban demand areas in CALVIN consist of three types of uses: exterior, interior and industrial (*Figure 6*). Return flows from exterior residential water use recharge directly to the underlying groundwater table, while interior residential and industrial return flows are first treated in a wastewater treatment plant, and then, reused or discharged in the system. In an urban water supply portfolio, groundwater pumping, surface water diversion, desalinated water, potable and non-potable water, and water conservation options are available. However, non-potable water is only available for exterior and industrial uses, whereas potable water is available for all three uses. Updates to urban demand areas include adding, removing and modifying the existing network based on a standardized urban representation and naming convention. Now, urban demand areas have more explicit water and wastewater treatment plant representation, and potable and non-potable use demonstration. Moreover, groundwater pumping, conveyance, water and wastewater treatment costs are updated. If groundwater pumping cost is not available for an urban area, the corresponding agricultural area's unit pumping cost is used. Old CALVIN combined water treatment and distribution costs are separated with this study. Wastewater treatment costs vary depending on the level of treatment. Treatment for potable water has the highest cost, while surface and ground water discharges from wastewater plants have basic treatment costs. Updated water and wastewater treatment costs are listed in Appendix B. However, some elements, such as water and wastewater treatment plants, may not exist for some demand areas. CALVIN includes only existing and planned physical facilities of California.

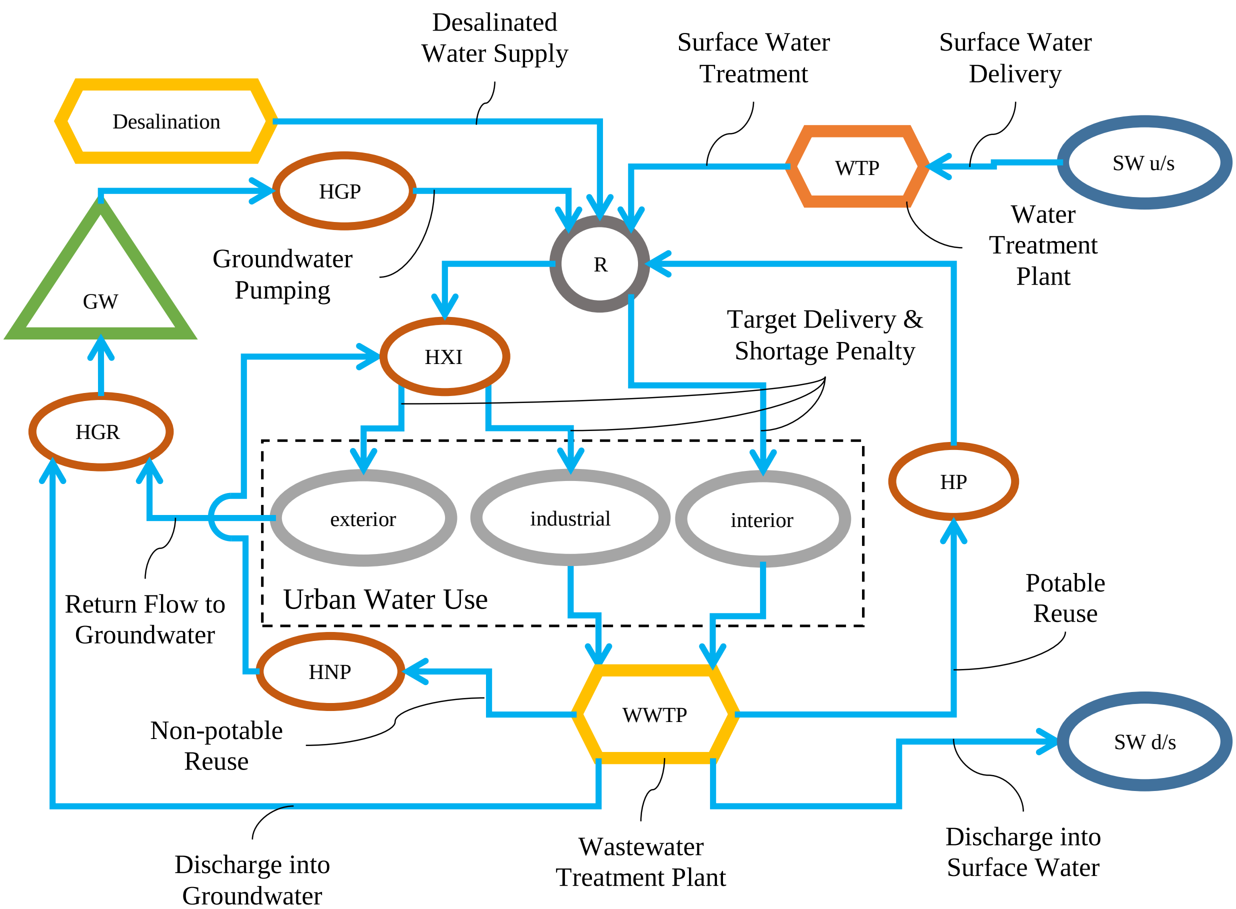

Figure 6. CALVIN updated urban demand area representation

Wildlife refuge demand areas now have three types of water sources: surface water, groundwater and return flow from agricultural use (*Figure 7*). All supplies are aggregated into one node and delivered to demand area after applying reuse capabilities. The current model assumes no on-site reuse for all wildlife refuges. Refuge areas share the same groundwater pumping costs as the surrounding agricultural areas. Similarly, surface water seepage and evaporation losses are obtained from surrounding conveyances. After consumptive use, return flow is discharged to surface water. Wildlife refuges are aggregated into 8 demand areas based on delivery sources.

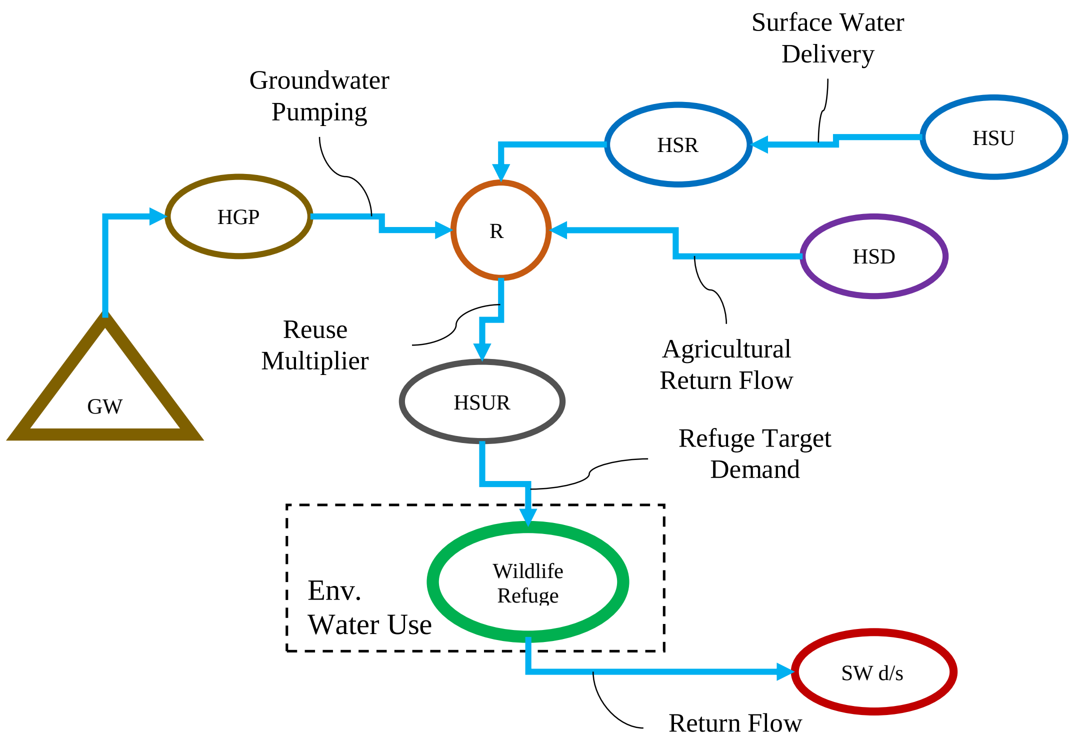

Figure 7. CALVIN updated wildlife refuge demand area representation

The Old CALVIN had a coarse representation for the upper Bear River watershed in the lower Sacramento Valley region. There was no network element between Node (C35) and Camp Far West Reservoir, and all upstream diversions were combined in one arc. After updates, Boardman, Combie and Bear Canal diversions are explicitly represented. Rollins Reservoir and Lake Combie are aggregated into a single reservoir and located upstream of Camp Far West Reservoir. New minimum in-stream flow requirements (MIF) are added at four different locations along Bear River (*Figure 8*). All time-series data are acquired from the CALSIM II model.

The intertie between Delta Mendota Canal (DMC) and California Aqueduct (CAA), completed in 2012, is added to the CALVIN network. The federal and state-shared intertie, located in west of the city of Tracy in San Joaquin Valley, pumps water from DMC to CAA, adding the flexibility and improving reliability of the CVP and SWP operations.

Another important improvement is that minimum in-stream flow requirements (MIF), locations, and required Delta outflow time-series are updated. Additional Vernalis Adaptive Management Plan (VAMP) requirements are added to the CALVIN network. All MIF time-series data are acquired from CALSIM II model, with exceptions for Yuba and Mokelumne River MIFs. State Water Resources Control Board (SWRCB) orders flow requirement on Yuba River at Marysville and Smartville flow gages. MIF time-series is generated based on water rights decision 1644 by SWRCB (2003). Mokelumne River MIF is constructed based on SWRCB water right decision 1641 (2000). This regulation specifies minimum flow requirements downstream of Camanche Reservoir. Updated CALVIN MIFs, their locations, and sources can be found in Appendix B.

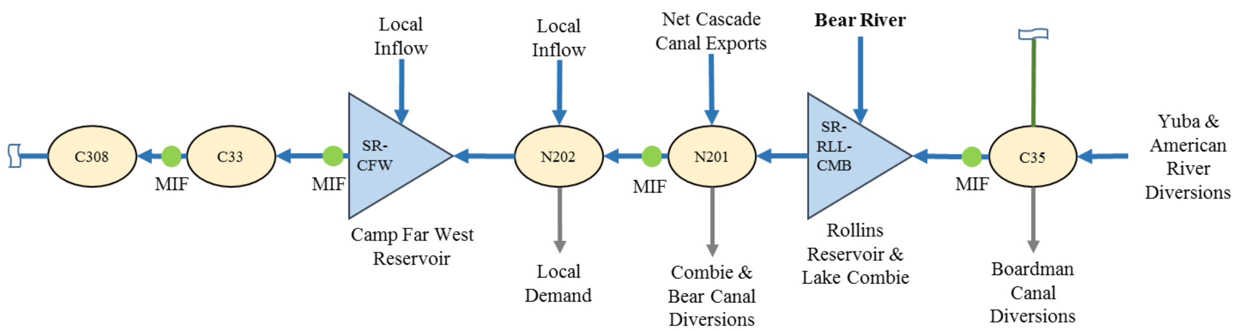

Figure 8. Updated Bear River watershed of CALVIN

Agricultural Demand and Shortage Penalties

CALVIN's agricultural representations are based on the Statewide Agricultural Production model (SWAP). The CALVIN model now has 36 agricultural demand areas, stretching from the northern Central Valley to Imperial Valley in southern California. For each demand area, SWAP calculates the net cost of lost production for various levels of water supply. This agricultural production loss is represented as a penalty function for CALVIN. The agricultural target demand constructed based on the agricultural penalty data is the point where the value of the marginal product of water is zero (Draper, 2000b). CALVIN's agricultural target demand time-series and shortage penalties are updated based on the most recent SWAP run. *Figure 9* shows old and new average regional agricultural target demands.

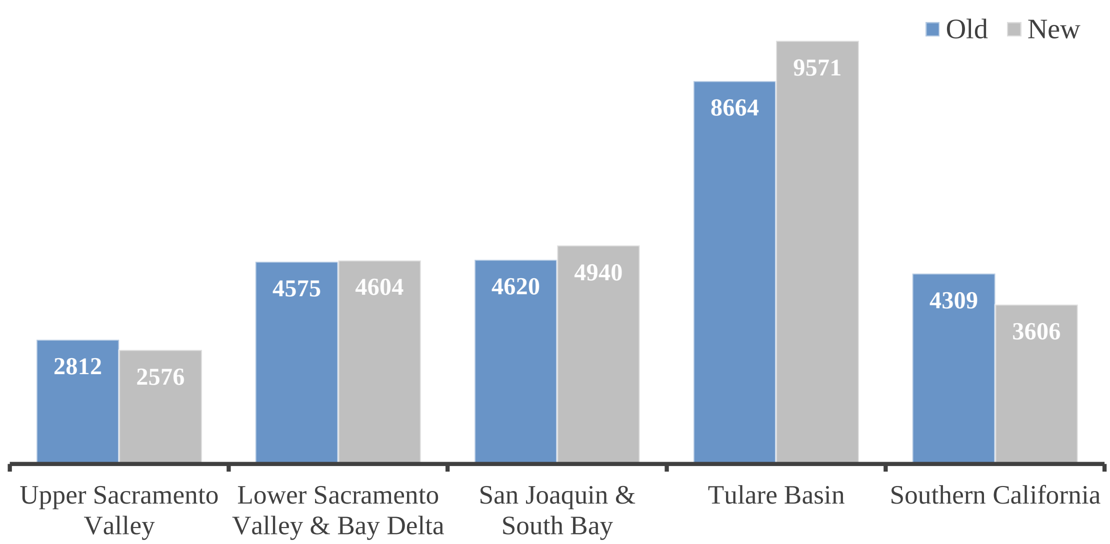

Figure 9. Old and new agricultural annual target demands (TAF/year)

With recent updates to SWAP, five demand units within the Central Valley are divided into smaller units for finer representation. The present study applies these refinements to the CALVIN network (*Table 3*). In addition, a new demand area, named Bard Water District (WD), is added to the network. Bard WD is in the Bard Valley on the southeastern border of California (*Figure 10*). CALVIN allocates water for Bard WD from the Colorado River.

Table 3. Refined CALVIN agricultural demand units

Old Demand Area	Refined Demand Area
CVPM 03	CVPM 03A, CVPM 03B
CVPM 14	CVPM 14A, CVPM 14B
CVPM 15	CVPM 15A, CVPM 15B
CVPM 19	CVPM 19A, CVPM 19B
CVPM 21	CVPM 21A, CVPM 21B, CVPM 21C
-	Bard WD

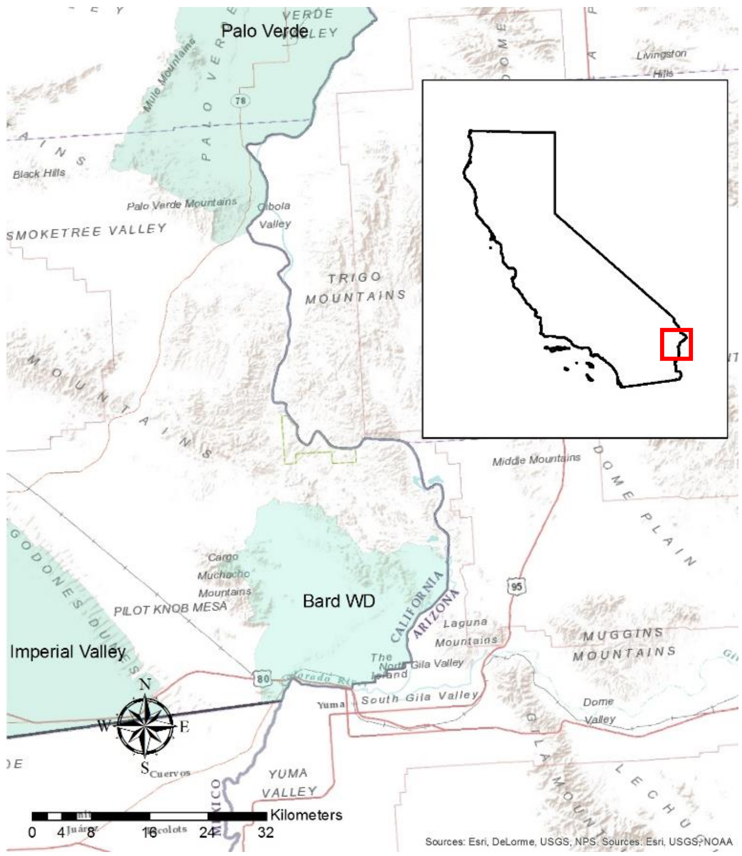

Figure 10. New demand area: Bard WD

Hydropower Improvements

Most California hydropower facilities are in northern California and throughout the Sierra Nevada and Coastal mountain ranges. CALVIN has a fairly simple hydropower representation because of the size and complexity of the system, yet it is often sufficiently accurate and tractable for planning and policy purposes. CALVIN models 33 hydropower plants with generating capacities greater than 30 megawatts (MW) (Ritzema, 2002), including storage, pumped storage, and run-of-river facilities. Most CALVIN plants are in the lower foothills with a large storage capacities. *Equation 5* shows the economic benefit function from hydropower at any point in time as a function of the price of electricity, the unit weight of water, the flow rate through the system, the head difference, and the efficiency. The head is also a function of storage for variable head facilities. CALVIN's objective is to minimize system-wide operating and scarcity costs, requiring that hydropower benefits be modeled as penalty functions. Penalties for hydropower represent the loss of benefits from not generating energy.

$$B_t = p_t \gamma Q_t H(S_t) e \qquad \textit{Equation 5}$$

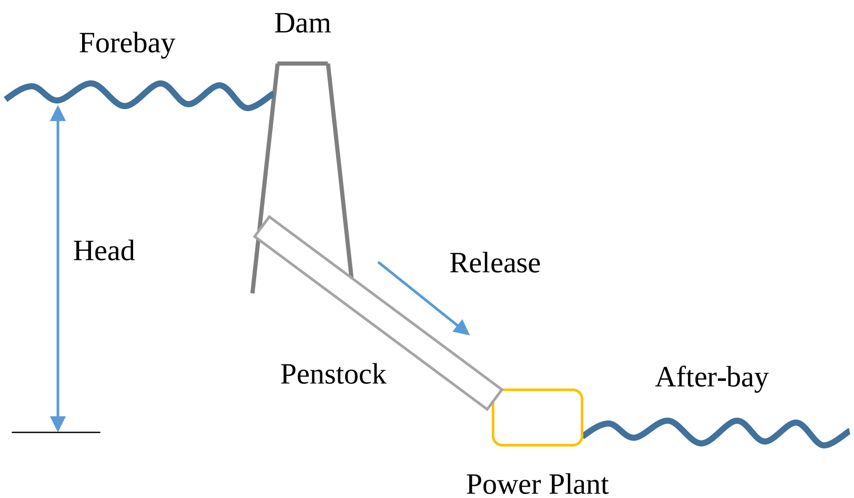

Figure 11. A typical hydropower system layout

Table 4. CALVIN hydropower facilities (Adapted from Ritzema (2002))

CALVIN Region	Name	Location	Operator	Capacity (MW)
1	Shasta	Shasta Res.	CVP[1]	629
1	Spring Creek	Spring Creek Tunnel	CVP	180
1	Judge Francis Carr	Clear Creek Tunnel	CVP	154
1	Trinity	Trinity R., Clair Engle Res.	CVP	140
1	Keswick	Sacramento R. below Shasta	CVP	117
2	Hyatt	Feather R., Oroville complex	SWP[2]	644
2	Colgate	New Bullards Bar Res.	YCWA[3]	325
2	Folsom	American R., Folsom Res.	CVP	199
2	Thermalito	Feather R., Oroville complex	SWP	115
2	New Narrows	Yuba R., Englebright Res.	YCWA	49
2	Nimbus	American R.	CVP	14
2	Thermalito Divers.	Feather R., Oroville complex	SWP	3
3	Gianelli	San Luis/ Cal. Aqueduct	SWP, CVP	424
3	New Melones	Stanislaus R., New Melones Res.	CVP	300
3	Don Pedro	Tuolumne R., Don Pedro Res.	TID[4],MID[5]	203
3	Dion R. Holm	Tuolumne R., Cherry Lake	HHW&P[6]	157
3	R C Kirkwood	Tuolumne R., Hetch Hetchy Res.	HHW&P	122
3	Moccasin	Tuolumne R.	HHW&P	104
3	New Exchequer	Merced R., Lake McClure	MID[7]	95
3	O’Neill	San Luis/ Cal. Aqueduct	CVP	25
4	Pine Flat	King's R., Pine Flat Res.	KRCD[8]	190
5	Castaic	Off Cal. Aqueduct, Castaic Lake	SWP, LADWP[9]	1247
5	Devil Canyon	Cal. Aqueduct	SWP	280
5	William E. Warne	Pyramid Lake	SWP	78
5	San Francisquito 1	Los Angeles Aqueduct	LADWP	76

5	San Francisquito 2	Los Angeles Aqueduct	LADWP	47
5	Control Gorge	Inyo, Owens River	LADWP	38
5	Middle Gorge	Mono Basin	LADWP	38
5	Upper Gorge	Mono Basin	LADWP	36
5	Mojave Siphon	Cal. Aqueduct	SWP	32
5	Drop 4	All American Canal	IID[10]	18
5	Alamo	Cal. Aqueduct	SWP	17
5	Wadsworth	San Diego Canal	LADWP	40

[1] State Water Project, California Dept. of Water Resources
[2] Central Valley Project, US Bureau of Reclamation
[3] Yuba County Water Agency
[4] Turlock Irrigation District
[5] Modesto Irrigation District
[6] Hetch Hetchy Water & Power
[7] Merced Irrigation District
[8] King's River Conservation District
[9] Los Angeles Department of Water and Power
[10] Imperial Irrigation District

Hydropower improvements include new energy prices, updated penalty curves for all hydropower facilities, and a new hydropower post-processor. Old CALVIN had monthly average energy prices for 2002 (Ritzema, 2002). Bartolomeo (2011) inflated CALVIN's operating costs to 2008 dollars; however, monthly electricity prices for hydropower were not updated. This study updates monthly average electricity prices to 2009 (*Figure 12*). Prices are obtained from the LongTermGen model, an energy post-processor for CALSIM II model.

Figure 12. 2009 average monthly electricity prices ($/MWh) from the LongTermGen model

Assuming constant head and efficiency, CALVIN uses piece-wise linear penalty curves for fixed-head hydropower facilities; penalty is a function of varying flow rates. A variable-head hydropower plant's energy generation depends on storage and release. Therefore, variable-head hydropower penalty is a sum of independent linear storage and release penalties. *Figure 13* shows penalty curves for Castaic, a fixed-head power plant, and Shasta, a variable-head power plant in CALVIN.

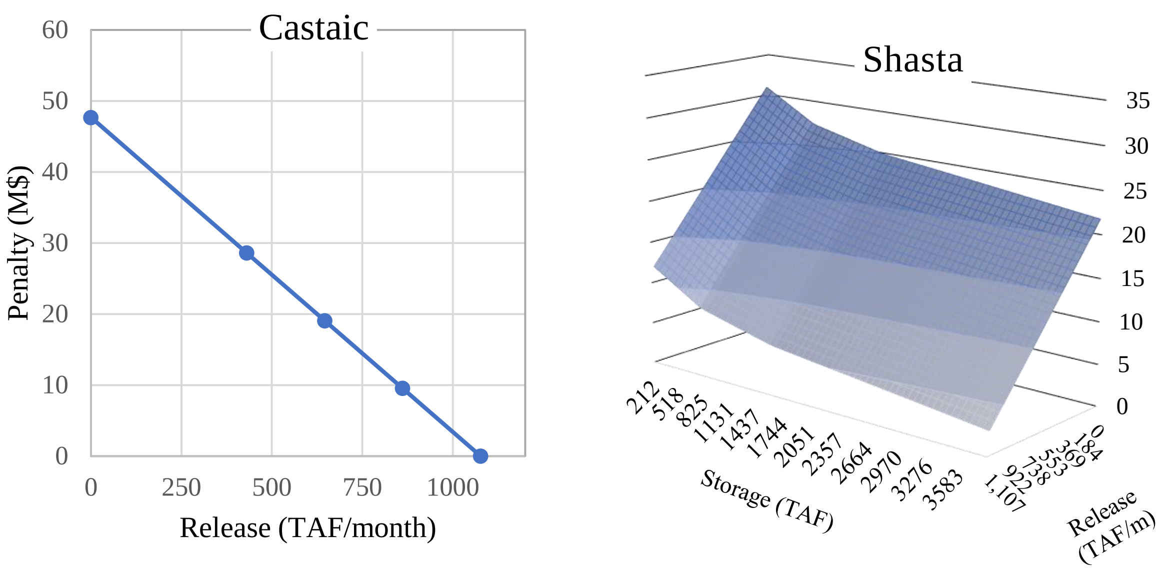

Figure 13. Hydropower penalties for Castaic and Shasta

Although hydropower generation is a built-in feature in HEC-PRM and it is modeled within CALVIN with penalty curves, power capacity, energy generation and revenue are calculated in a separate Excel-based post-processor. Due to the size and complexity of the system, the solution can easily become infeasible. A new hydropower post-processor retrieves storage and release data from the CALVIN output file and provides power capacity, monthly energy generation and revenue, spilled water amount and total used turbine capacity as time-series for each CALVIN facility. For facilities in the Central Valley, the new post-processor shows results for different water year types, ranging from wet to critical. It also shows regional statistics and plots generation-reliability curves.

CALVIN's main hydropower data sources are DWR's LongTermGen model and the California Data Exchange Center (CDEC). Parameters for hydropower facilities in the SWP and CVP are obtained from the LongTermGen model. This model provides energy factors that incorporate head and plant efficiency. Energy factors, a function of storage level and tail water elevation, give energy generation when multiplied by the flow rate. 17 of the 33 CALVIN hydropower facilities utilize energy factors. Remaining variable-head power plants use a polynomial relationship between storage and elevation to estimate the head. Storage and elevation data are from CDEC. For these remaining plants, a constant efficiency of 85 % is assumed if not known. *Figure 14* shows energy factors for Trinity and the head calculations for Don Pedro hydropower plants.

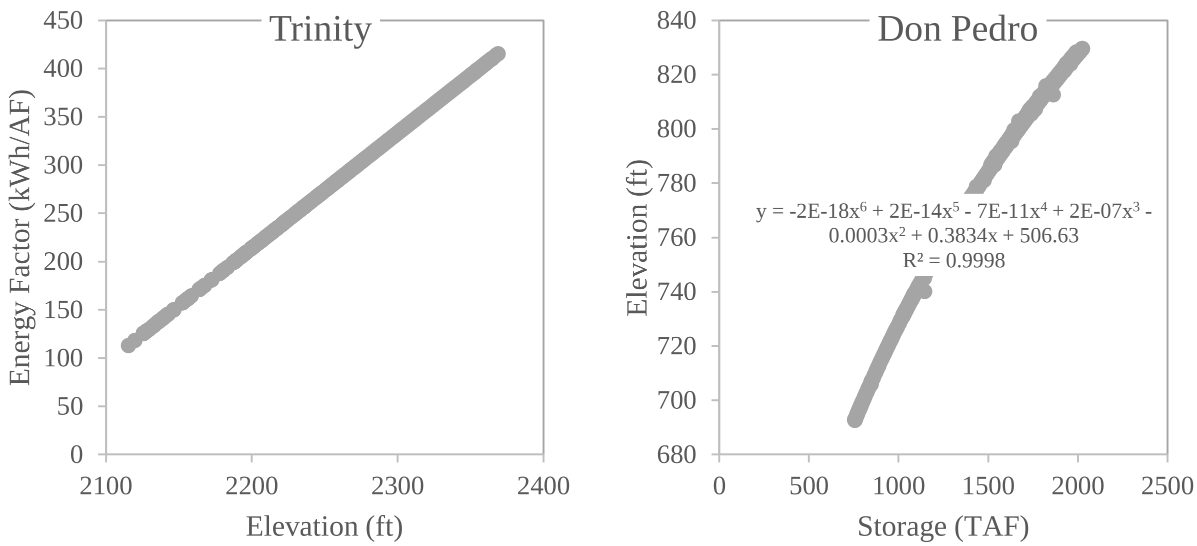

Figure 14. Energy factor and the head (CDEC, 2015).

Conclusions

CALVIN is a large integrated model that needs constant improvements to preserve functionality and applicability. Updates to CALVIN model increased quality of California's inter-tied water infrastructure representation and accuracy of results. Since CALVIN uses historical data, extending hydrology dataset enhances the reliability of water operations. Data sources and extension methods are clear and easily accessible. With a new 2050 target demand and scarcity penalty and refined demand areas, agricultural demand representation is improved. These updates removed calibrations flows, which were added for mass balance feasibility, making the model more transparent. CALVIN's hydropower representation is simple yet sufficient for large-scale management and operating decisions, which is also improved during this effort.

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Chapter 3. Reflecting Hourly Energy Price Variability in Long-Term Hydropower Operations

Introduction

Water resources system models use different time scales, varying from hourly to annual. Hourly or shorter peak time and energy value rates are important for hydropower release decisions. Short-term models with hourly time-steps and time horizons of a few days can directly represent hourly price variations in their operations. However, problems arise when using monthly average energy prices for long-term planning and management. Assuming one single representative price for a month can underestimate hydropower revenue (Olivares, 2008). However, hourly price variations can be represented with a method that uses different prices depending on capacity use (Olivares, 2008). The method assumes that to maximize revenue, a hydropower plant with reservoir storage and an after-bay allocates hydropower releases preferentially to the peak price times, when energy demand and prices are highest. Also, the reservoir operator is assumed to have good short-period foresight of energy prices, allowing revenue-maximizing releases during peak times, and cannot influence prices. Tejada-Guibert et al. (1990) used such a method to maximize the Central Valley Project (CVP) energy revenue. A monthly capacity factor for each plant is assigned to the price duration curve factors, assuming each plant can be dispatched and operated during the most economically valued hours in a month. They concluded that using variable energy prices rather than constant prices increased overall hydropower revenue. Olivares (2008) studied the representation of energy prices in long- and medium term hydropower operations. His model for a single reservoir relates hourly energy prices with the proportion of hours that energy can be generated monthly. Hourly-varying prices are estimated with a moving average method, a function of the percentage volume allocation. Madani (2009) used energy prices that vary with the number of hours of operation in EBHOM, an optimization model for California's high-elevation hydropower plants. The model assumes that a power plant will release first at high-valued times and only allocate water at lower-valued times when water is abundant if the objective is only to operate for hydropower.

This chapter presents in corporation of hourly electricity price variations in operations of CALVIN, a long-term model that uses a monthly time-step over a hydrologic period of 82 years. CALVIN is useful for integrated planning, management, and policy studies. It integrates and economically optimizes reservoir, power plant, pumping plant, and other water supply operations. CALVIN is operated with constant and hourly-varying energy prices, and generation, revenue, agricultural and urban water scarcity, and reservoir storages are compared to determine the best price representation for the long-term models.

CALVIN Operations with Hourly-Varying Electricity Prices

The objective in CALVIN is to minimize statewide operating and scarcity costs. Hydropower in CALVIN is modeled with penalty curves that incorporate the benefits lost from not generating hydropower. 2002 hourly average retail electricity prices obtained from Pacific Gas and Electricity Company website (PG&E, 2002) are modified to represent 2009 hourly electricity prices by incorporating with 2009 monthly price estimates from the California Department of Water Resources (DWR) in the LongTermGen model. The moving average method (MA) (Olivares, 2008) is used to calculate hourly-varying energy prices. This method relates the percentage of hours of generation at turbine capacity with a price duration curve. Prices are averaged up to percent use. As seen in *Figure 16*, marginal variable energy prices decrease with increased hours of generation, which represents decentralized electricity market operations. Small releases have more marginal benefits, and as hours of operation in a given month increase, marginal hydropower revenue decreases, whereas marginal revenue does not change with constant average prices. For economically optimal hydropower operations with hourly-varying prices, CALVIN makes small releases when marginal energy price is high, and the lowest average price occurs when energy is generated at turbine capacity (Madani and Lund, 2009). CALVIN is a deterministic model with known monthly price fluctuations, and allocates water when it is most profitable. Total hydropower revenue in month i can be calculated as:

$$B(Q_i, h_i, f_i) = \sum_{I(f)} P_i \cdot \varepsilon \cdot \gamma \cdot Q_i \cdot h_i \cdot \Delta t \qquad \textit{Equation 6}$$

where Q is release, h is head, f is percentage of hours of generation, P is price obtained from moving average price curve, ε is efficiency, γ is specific weight of water, and Δt is time period.

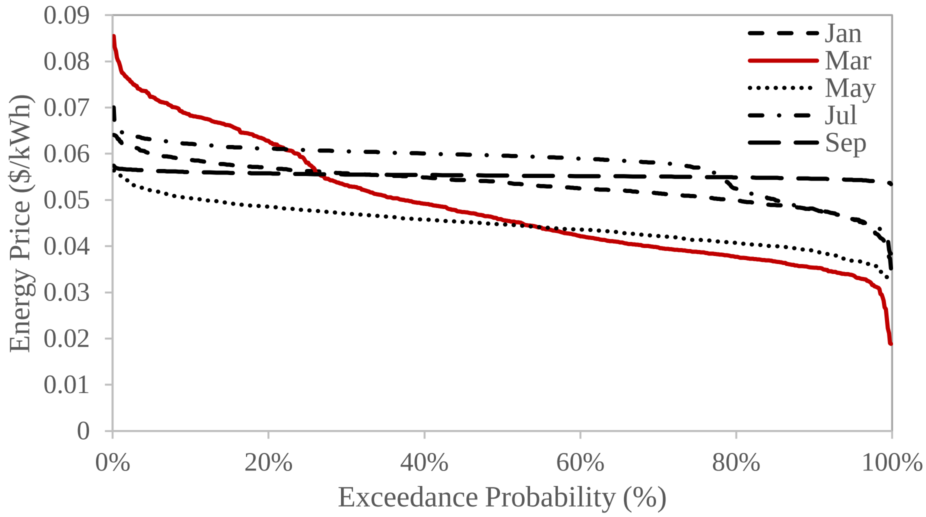

Figure 15. Price duration curve of hourly energy prices in 2009

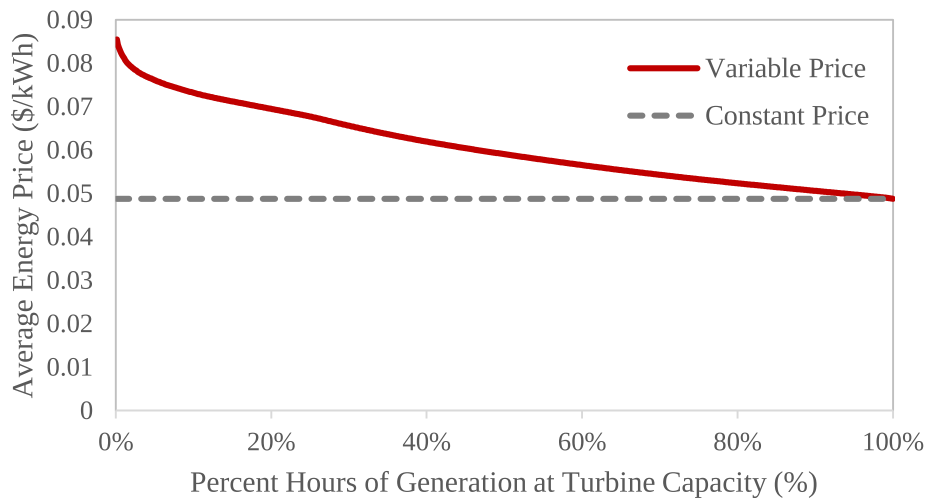

Figure 16. Moving average curve of March 2009 prices

Several California hydropower facilities pump water from the after-bay into the reservoir in non-peak hours and release water from the reservoir in higher-valued peak hours (Ritzema, 2002). These power plants are useful to meet peak time electricity demand. 13 of 33 CALVIN facilities with a large storage capacity and an after-bay are modeled with hourly-varying energy prices in CALVIN (*Table 5*). Remaining facilities, including run-of-river hydropower plants, use monthly constant average energy prices. Run-of-river plants are not modeled with hourly-varying electricity prices because they are operated continuously, depending on stream flow conditions.

Table 5. CALVIN hydropower facilities modeled with variable energy prices

Region	Facility	Storage Capacity (MAF)	Power Capacity (MW)
1	Shasta	4.55	629
1	Spring Creek	2.40	180
1	Trinity	2.47	140
2	Hyatt	3.54	644
2	Colgate	0.93	325
2	Folsom	1.01	199
3	New Melones	2.40	300
3	Don Pedro	2.03	203
3	Holm	0.30	157
3	Kirkwood*	0.36	122
3	Gianelli+	2.04	424
3	Moccasin*	0.36	104
3	O'Neill+	2.04	25

* Hetch Hetchy Reservoir

\+ San Luis Reservoir

Results

Power Generation and Revenue

CALVIN is run with both monthly constant average prices and hourly-varying prices, and results are compared. Since the model tends to allocate small releases, with higher hydropower benefits, statewide total hydropower generation with hourly-varying prices is slightly less than generation with monthly constant average prices, but energy revenue is greater (*Table 6*). Statewide annual electricity generations are 16.09 and 15.86 TWh/y, with corresponding hydropower revenue of $849 and $862 million per year for constant and hourly-varying energy prices, respectively.

Table 6. Statewide hydropower operations with constant and hourly-varying prices

Price Type	Generation (TWh/y)	Revenue (M$/y)
Constant Price (CP)	16.09	849
Variable Price (VP)	15.86	862

Figure 17 shows monthly statewide modelled hydropower generation and revenue with constant and variable prices. Overall, monthly generation and revenue patterns do not differ significantly. Generation and revenue have a similar monthly trend, higher in the summer and lower fluctuating the rest of the year. However, hydropower generation with variable prices is more in spring months, when average energy

prices are the lowest but hourly price fluctuations are the highest. In other months, constant price has higher hydropower generation and revenue. As hourly price fluctuations decrease, the moving average of variable prices converges with constant average prices. Months that have the same power generation or revenue can be useful for comparison. For example, March power generations in both price schemes are quite close, 1.38 TWh and 1.39 TWh for constant and variable prices, respectively. However, there is a big difference on the revenue. In March, with constant prices, the revenue is about $67 million, while, the revenue with variable prices is $76 million. Similarly, in October, January, and February, the revenue with variable prices are fairly small, although generation with constant prices is higher. Using constant monthly average prices rather than hourly-varying prices underestimates hydropower revenue.

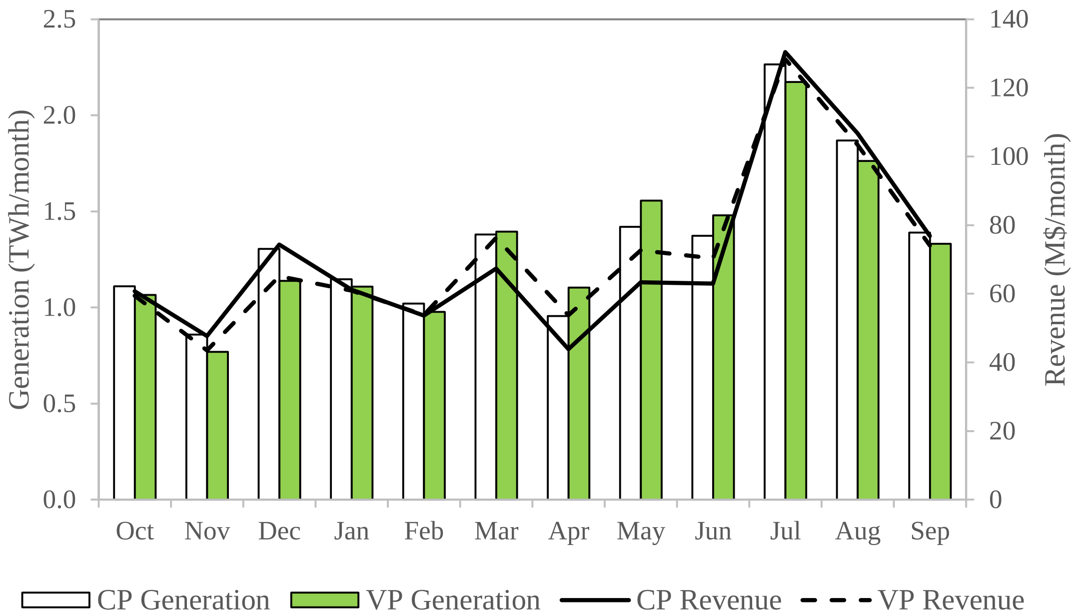

Figure 17. Statewide monthly hydropower generation and power revenue

Monthly average power revenue from Shasta over the 82-year period, depending on releases at turbine capacity, head, and monthly and hourly-varying electricity prices, is shown in *Figure 18*. The non-linear trend curve depicts decreasing marginal benefits as the percentage of hydropower releases at turbine capacity increases. Most revenues are concentrated between 15% and 90% capacity uses. Average turbine capacity use of Shasta is about 38.5%. The highest capacity use is 99.8% with revenue of $25.7 million, while the highest revenue of $26.5 million corresponds to 96.98% turbine capacity use in 82-year operations. The reason why the highest capacity use does not have the highest revenue is monthly price variations. Summer energy values are higher than other seasons. Effects of downstream Sacramento River minimum in-stream flow (MIF) requirements are not taken into account when calculating hydropower benefits, but these impacts are dampened by any downstream after-bay.

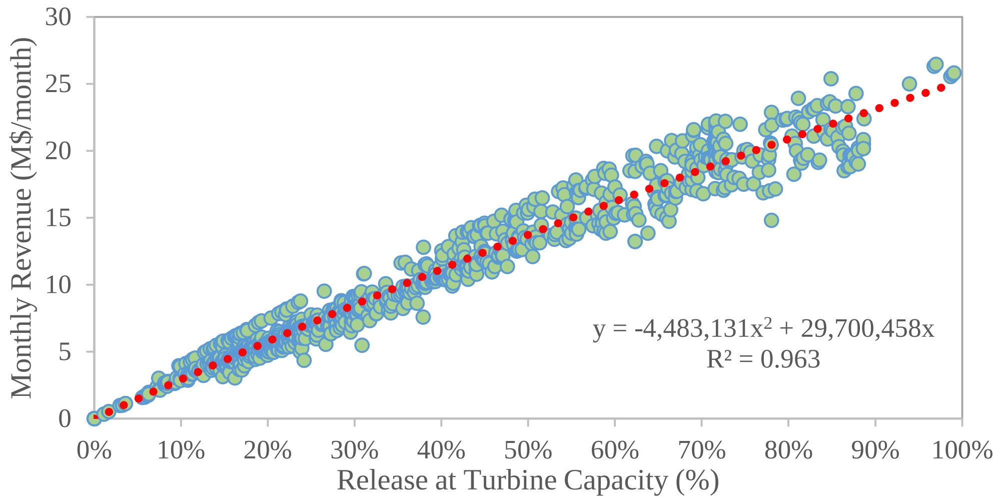

Figure 18. Monthly average revenue curve of Shasta over the 82-year period with variable prices given turbine capacity use

Figure 19 shows generation reliabilities of selected CALVIN hydropower facilities from integrated hydropower and water supply operations. Differences between varying and constant average price generation reliabilities are quite small, although some variations in Shasta and Hyatt occur at low probabilities. Hyatt is operated more at turbine capacity with variable prices, but still only 3% of time. Steeper slopes show sudden decrease in power generation, making the plant less reliable. High generations have steeper slopes, while slopes become flat as generation decreases and probabilities increase. Water availability dramatically affects hydropower generation. In wet years, generations are close to turbine capacity, whereas generations are minimal in dry years. Hyatt generates more than Shasta in wet years. However, as surface water shortage increases at higher exceedance probability levels, Shasta's monthly average power generation exceeds Hyatt's generation.

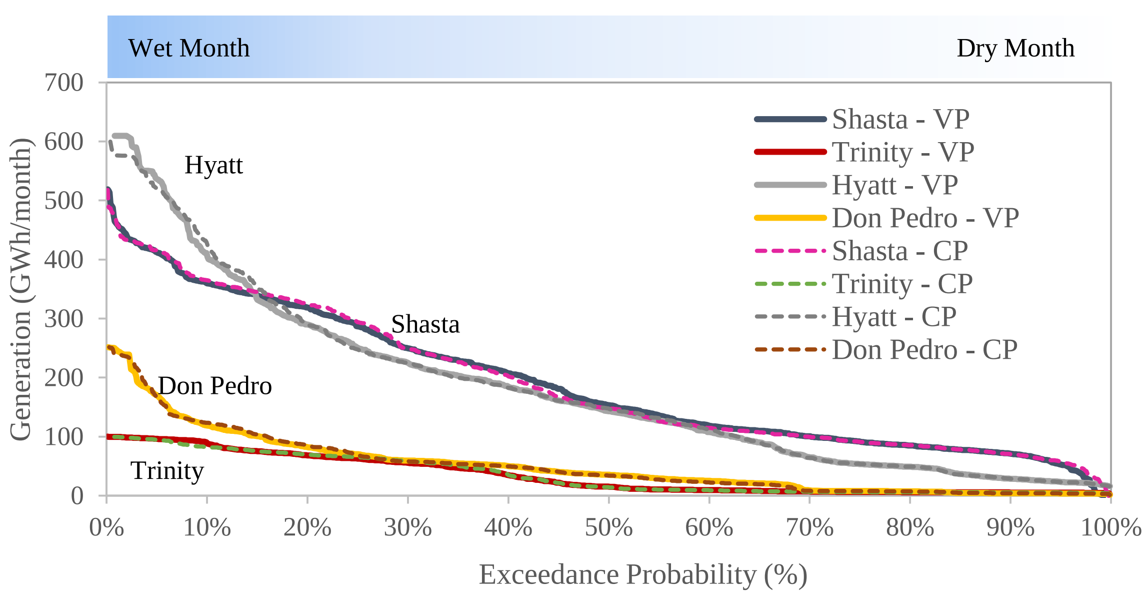

Figure 19. Monthly generation-reliability curves of selected facilities

CALVIN assumes a decentralized energy market in California. Each facility allocates hydropower releases during the most valuable hours, also considering water scarcity costs to agricultural and urban users, and downstream minimum in-stream flow requirements. Hydropower and water scarcity penalty curves dictate the economically optimal release time and volume. *Table 7* summarizes annual hydropower operations from CALVIN with hourly-varying energy prices. The statewide annual average hydropower generation is about 15.9 TWh/y, and corresponding revenue is about $862 million per year. Most hydropower is generated in the Sacramento Valley. On average, 46% of system-wide turbine capacity is used over the 82-year operating period. The highest annual average power generation of 2.29 TWh/y occurs at Shasta, with annual average revenue of $126.3 million per year. Spills show lost hydropower generation. Monthly average spills are higher with hourly-varying prices (*Figure 20*). Discrepancies increase especially at lower probability levels. Annual average spills are higher in the lower Sacramento Valley (Region 2) and San Joaquin Valley (Region 3). Statewide annual average spill is about 1.25 MAF/y. Thermalito Diversion Dam has the highest average turbine capacity use, about 98%, and average 113 TAF water is spilled from the plant. Nimbus has the highest annual spill, about 375 TAF/y.

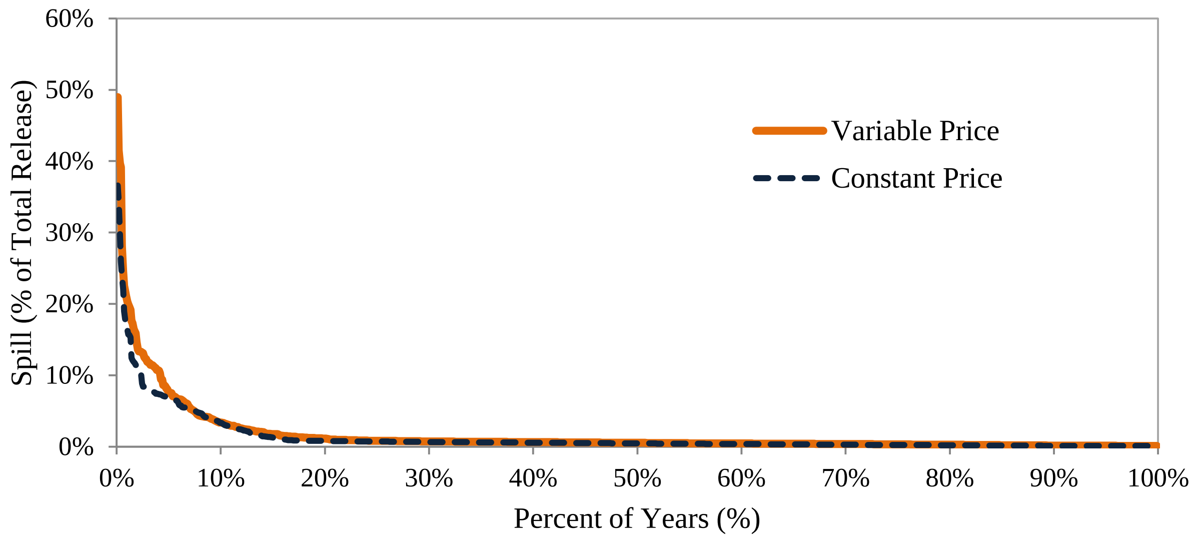

Figure 20. Exceedance probability of spill as a percent of total release

Table 7. Summary of annual average generation, revenue, capacity use, and spill values

Region	Facility	Plant Capacity (MW)	Generation (GWh/y)	Revenue (M$/y)	Capacity Use (%)	Spill (TAF/y)
1	Shasta*	629	2,285	126.3	38.5%	32.2
1	Spring Creek*	180	381	22.3	21.9%	0
1	Carr	154	354	19.7	25.7%	0.02
1	Trinity*	140	409	22.4	36.3%	20.5
1	Keswick	117	464	24.3	49.2%	101.0
2	Hyatt*	644	2,183	122.3	29.1%	36.6
2	Colgate*	325	1361	74.8	43.5%	42.3
2	Folsom*	199	653	35.8	40.2%	157.7
2	New Narrows	49	277	14.4	49.4%	131.9
2	Thermalito Fore/Afterbay	115	290	15.2	27.1%	19.1
2	Nimbus	14	78	4.0	54.5%	375.0
2	Thermalito Diversion Dam	3	3	0.2	98.1%	112.7
3	New Melones*	300	496	27.9	14.8%	2.2
3	Don Pedro*	203	610	33.4	21.2%	23.4
3	Holm*	157	673	34.5	54.0%	108.4
3	Kirkwood*	122	355	18.7	60.3%	0
3	New Exchequer	95	277	14.4	40.0%	22.1
3	Gianelli*	424	0	0.0	0%	0
3	Moccasin*	104	167	8.8	68.9%	0
3	O'Neill*	25	9	0.5	23.7%	0.5
4	Pine Flat	190	444	22.4	26.0%	64.5
5	Castaic	1,247	872	48.0	28.7%	0
5	Devil's Canyon	280	1,051	55.8	80.8%	0
5	Warne	78	522	28.1	75.0%	0
5	San Francisquito 1&2	123	629	34.6	63.5%	0.04
5	Gorges	112	366	19.2	30.5%	0
5	Mojave	32	90	4.8	65.7%	0
5	All American Canal	18	355	18.3	30.9%	0
5	Alamo	17	132	6.9	94.5%	0
5	Wadsworth	40	74	3.9	97.4%	1.2
	Statewide	6,135	15,857	862	46.3%	1,251

* Modeled with hourly-varying prices

The Sacramento Valley hydropower facilities are responsible for more than half of the CALVIN's hydropower generation (*Figure 21*). With constant prices, the Sacramento Valley annually generates 8.75 TWh energy, and the generation slightly reduces to 8.74 TWh/y with hourly-varying prices. Most large-scale CALVIN power plants, such as Shasta, Hyatt, Colgate, and Folsom, are in this region. Power generation of San Joaquin plants are 18% and 16% of statewide annual average modelled hydropower production of 16.09 TWh/y and 15.86 TWh/y, with constant and hourly-varying prices, respectively. Variable prices considerably affect the San Joaquin Region's generation. Annual average generation reduction is about 227 GWh/y in this region. Tulare Basin contributes to 3% of modelled electricity generation in both price schemes. Most hydropower facilities in southern California use head created from pumped water. For instance, energy used to pump State Water Project water over the Tehachapi Mountain range is partially recovered by series of hydropower plants, reducing water supply cost to southern California water users (Ritzema, 2002). Plants in southern California generate about 4,090 GWh energy per year, corresponding to 25% and 26% of system-wide modelled hydropower production with constant and variable prices, respectively.

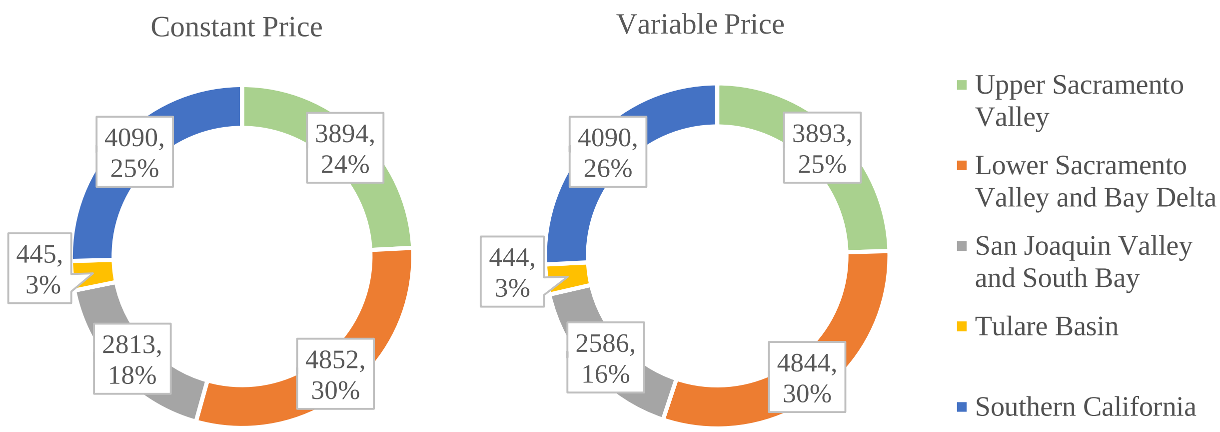

Figure 21. Annual average hydropower generation (GWh/y) and percentages of total generation

Water year types (WYT) are indices of runoff in the Sacramento and San Joaquin Valleys. WYT analysis provides expected values of power generation in different water year types, varying from wet to critically dry depending on the Sacramento and San Joaquin Valley indices. Southern California is excluded from WYT analysis. Hydropower generation increases as years become wetter. Annual average hydropower generation of Central Valley facilities of CALVIN in different water year types are shown in *Table 8*. In wet and above normal years, generation with constant monthly prices is slightly higher, whereas generation in other year types is fairly similar. When water is abundant, hydropower operations become more prominent. As water becomes scarce, water supply operations for agricultural and urban users, dominates over hydropower operations, so more hydropower production is incidental. As water availability decreases from wet to critical years, discrepancies in generation and revenue between the two pricing types increase. In wet years, revenues are highest, while average annual generation with constant prices, 16.3 TWh/y, is greater than generation with variable prices, 15.7 TWh/y. When WYT is below normal, average annual generations are equal, although revenue with variable prices, $600.8 million per year, exceeds annual average revenue of $577.7 million per year with constant prices. Only in dry years does variable price generation exceed constant price generation. Since water year types are not evenly distributed, overall average generation and revenue with constant and variable prices are not the same as historical averages.

Table 8. Generation and power revenue in different water year types

Year Type	**Average Generation (TWh/y)**		**Average Revenue (M$/y)**	
	Constant P.	**Variable P.**	**Constant P.**	**Variable P.**
Wet	16.3	15.7	845.0	844.7
Above Normal	12.8	12.4	671.9	680.0
Below Normal	10.9	10.9	577.7	600.8
Dry	9.4	9.5	499.1	525.1
Critical	7.3	7.2	390.0	404.0
Overall Average	11.4	11.2	596.7	611.0

Scarcity and Operating Costs

Scarcity occurs when a user's demand is not completely fulfilled. CALVIN has flow targets which incorporate 2050 development, land use, and population estimates, for each agricultural and urban demand area. The difference between target demand and actual delivery is defined as the water shortage or scarcity amount. CALVIN's objective is to minimize statewide scarcity and operating costs. Less hydropower generation with variable prices implies that less water is released from reservoirs. Even though water supply decreases with variable price CALVIN operations, annual average agricultural and urban scarcity costs do not change, at $49 and $93 million per year, respectively (*Table 9*). Constant price annual average operating cost, including surface water and groundwater pumping, water and wastewater treatment, is $1 million per year greater than operations with hourly-varying prices. Annual average hydropower revenue is $14 million per year more with variable prices. Having the same amount of scarcity costs but higher hydropower revenue implies better hydropower representation with hourly-varying energy prices. Overall, variable price operations provide more economical results with lower statewide net costs.

Table 9. Annual average statewide scarcity and operating costs, and hydropower benefits

Average Cost (M$/y)	Constant Price	Variable Price
Agricultural Scarcity Cost	49	49
Urban Scarcity Cost	93	93
Operating Cost	4,948	4,947
Hydropower Benefit	849	862
Net	4,241	4,227

Surface Water Storage

Average surface storages over 82-year period are compared with constant and hourly-varying prices (*Figure 22*). CALVIN stores more water with variable prices. Reservoirs generally fill in the winter and spring with precipitation and snowmelt runoff, and draw down in the summer to meet irrigational, urban, and environmental water demands, and generate hydropower. Both price storages peak in May, which are 21 MAF and 21.2 MAF for constant and variable prices, respectively. Storage differences are less in the spring and summer and higher in winter. The biggest storage difference of 399 TAF is in December, while the storage discrepancy is the lowest in June. Since variable price generation is higher in March through June, when hourly price variabilities are large, the marginal decreases on storage differences are greater. CALVIN chose to store more water with variable prices since releasing did not have statewide economic benefits. Having more reservoir storage can benefit several purposes, such as recreational uses, water sports, and fisheries, although they are currently not included in CALVIN. Water temperature decreases as storage increases, and water quality usually improves with lower water temperature in ecosystem management. In California, colder water releases improve downstream water quality.

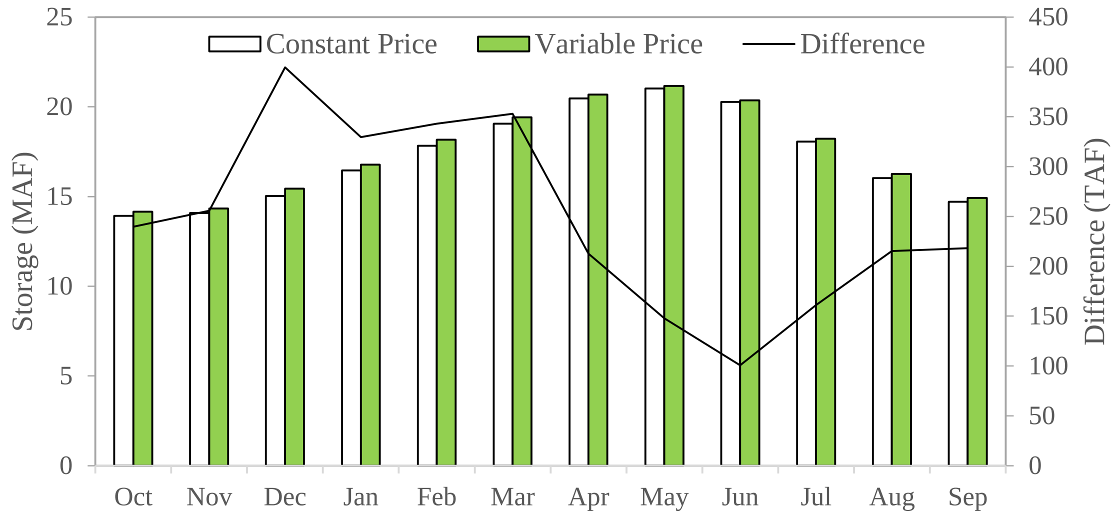

Figure 22. Total CALVIN surface storages with constant and variable prices

Several factors affect reservoir storage levels. Location of reservoirs, whether they are in parallel or series, is important in hydropower management. Electricity prices and agricultural and urban demands determine the timing and magnitude of allocations. Downstream flow regulations also control releases from reservoirs. Considering all these effects, CALVIN decides on release amounts and timing. *Figure 23* shows filling and drawdown periods of selected CALVIN facilities modelled with each price scheme. Except Shasta and Trinity, all selected reservoirs are on west side streams of the Sierra Nevada Mountains, where snowmelt drives reservoir operations. Each reservoir has characteristic storage and release patterns. Located on the Sacramento River, Shasta starts releasing earlier than other reservoirs. Shasta storages peak in April, while others generally reach the highest storage in May. For both price methods, storage peaks coincide, with an exception in New Don Pedro. New Don Pedro has fewer monthly storage variations, although storage differences on constant and variable storages increase from May through November. Overall, variable prices store more water in the filling season, and release less in the drawdown season than constant prices.

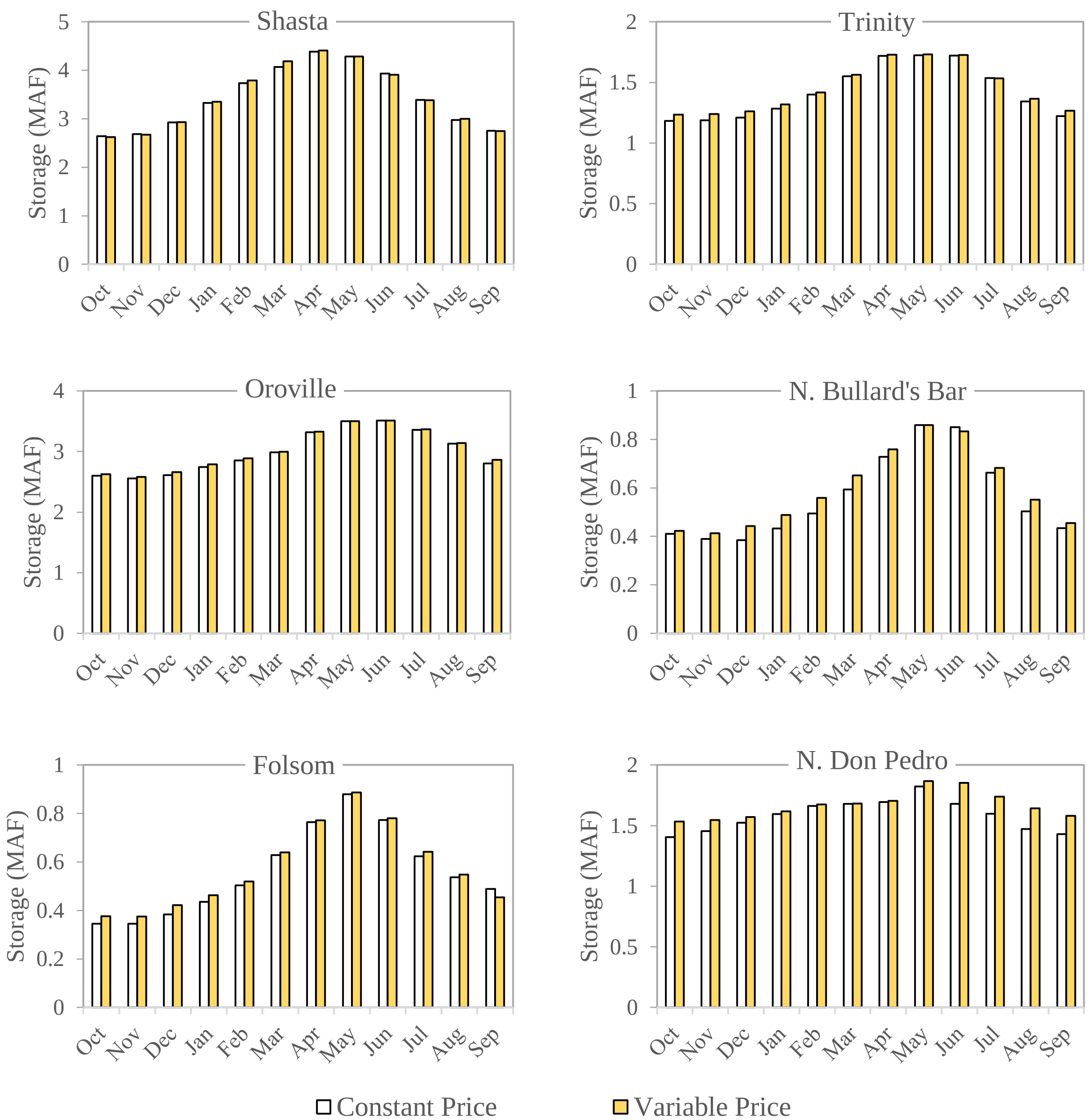

Figure 23. Average storages of selected facilities operated with constant and variable prices

Conclusions

A simple method to reflect hourly-varying electricity prices in long-term, large-scale model operations was presented. The method was applied to CALVIN operations for California. The method uses price duration curves and estimates hourly-varying prices as a function of hours of operation at turbine capacity. The proposed method captures hourly price variations in models with large time-steps and better represents real-time hydropower operations. This method can be applied to any model that represents a hydropower facility with an after-bay and improves the integration of hydropower operations into longer-term water resource system models. Using constant monthly average price underestimates hydropower benefits, and system-wide hydropower revenue can be increased by using variable electricity prices. Especially in wet years, when hydropower becomes more important in reservoir operations, generation discrepancies increase. Constant prices generate more power with underestimated benefit. The proposed method did not increase water shortages. The new method has slightly less statewide annual average operating costs. Total statewide net cost is less with the proposed method. The new price scheme increased average statewide surface storage. Although the total benefit of reflecting hourly price variability in hydropower operations is slight, it becomes more critical in long-term planning and management decisions, especially in wet years. The inverse of the proposed method can also be applied to large pumping plants with a forebay, such as some CVP and SWP pumping plants. Hours of operations at pumping plant capacity can be related to price duration curve, and overall pumping cost can be minimized with operations when prices are lowest.

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Chapter 4. Groundwater Overdraft Management in the Central Valley

Introduction

Overdraft occurs as a result of unsustainable use of groundwater. The term "overdraft" is defined as the case where groundwater extraction through pumping exceeds aquifer recharge over a long period (CDWR, 2003). Groundwater is important in water management because it is easily accessible, often has better water quality compared to surface water, requiring less treatment cost, and cheaper in many regions. In an average year, groundwater supplies about 30% of California's water, and this rate increases to 40% or more during dry years in some regions. Many small towns and cities rely entirely on groundwater supply (CDWR, 2003). Groundwater also adds flexibility to water operations, especially in drought years when surface water is scarce. However, due to few statewide regulations in California, groundwater use is generally uncontrolled. In many regions, groundwater extraction amounts are not accurately known (CDWR, 2003). Water users commonly pump groundwater when their demands cannot be met by surface water supplies (Chou, 2012, Knapp and Vaux, 1982). Overdraft has several negative consequences, including higher pumping cost, water quality degradation, land subsidence, flow reduction in streams, wetlands, and springs that are hydraulically connected to underlying groundwater aquifer, and salt intrusion in coastal areas (Harou and Lund, 2008b; Konikow and Kendy, 2005). Several regions suffer from overdraft in California. Annual statewide overdraft is estimated between 1 to 2 million acre-feet (MAF) (CDWR, 2003). Extensive groundwater use by farmers along the Cosumnes River has lowered the groundwater table, depriving the river of base flow during the dry season. As a result, Chinook salmon encounter inadequate streamflow when they migrate from the ocean (Zektser et al., 2005). The Tulare Basin, a productive and intensively used agricultural region in the U.S., experiences overdraft despite water imports and groundwater banking (Harou and Lund, 2008b). The San Joaquin Valley sees severe land subsidence. A remedy to solve the issue is to withdraw less water from the aquifer. However, with high streamflow variability and frequent droughts, water users often overexploit groundwater (Zektser et al., 2005).

This chapter examines groundwater overdraft in California's Central Valley by evaluating various management scenarios by using CALVIN model. Harou and Lund (2008b) discussed overdraft and its cessation in the Tulare Basin with several management alternatives, including effects of different levels of conjunctive use infrastructure development, and showed that although temporary overexploitation can be economically beneficial in some cases, overdraft must end in the long term to manage resources sustainably. Water scarcities increase without overdraft, but with new conjunctive use infrastructure, such as pumping and artificial recharge, water scarcity costs can be reduced. In a later study, Chou (2012), Zikalala (2013), and Nelson (2014) studied economical and physical effects of overdraft in the Central Valley with improved groundwater representation of CALVIN. Chou evaluated historical overdraft, no overdraft, and high overdraft scenarios, and concluded that primary adaptations to ending overdraft are increased Delta exports and artificial recharge. The present study uses the updated CALVIN model to study various management cases described below to find the economically optimal solution for ending long-term groundwater overdraft in the Central Valley.

Management Scenarios

Four hypothetical "no overdraft" scenarios, besides base operations with overdraft, are evaluated under projected 2050 water demands using 82-year monthly historical hydrology (*Table 10*). Groundwater overdraft in the 82-year modelled period is estimated as 84 MAF with base operations (Chou, 2012). With "no overdraft" cases, the long-term overdraft is set to zero in the Central Valley aquifer. The first management case discusses water operations without overdraft. The second case prohibits reduction in Sacramento-San Joaquin Delta (Delta) outflow, in addition to ending overdraft. Modelled historical Delta outflow time-series with the base case are used as a lower-bound. The third case evaluates water operations without overdraft and without additional Delta exports. The Delta exports from Banks and Tracy pumping plants are restricted to base case exports in CALVIN. The last case limits Delta exports, where water is pumped from Delta to Delta-Mendota Canal (DMC) and California Aqueduct (CAA) from Tracy and Banks pumping plants, respectively, to 5% of total pumping capacity. When fixed environmental deliveries, conveyance and evaporation losses, and higher-valued urban deliveries taken into account, very little water is allocated to agricultural areas from DMC and CAA under no overdraft and almost no Delta exports operations. Although the last case dramatically increases water scarcities south of the Delta, it enhances Delta outflow. Thus, it is also called the "almost no export" case. Delta outflow is important for the environment, Delta restoration projects, and salinity control in the Bay-Delta.

Table 10. Water management scenarios evaluated in the study

Scenario	Description
Base Case	Base CALVIN operations with overdraft
NoOD	No Overdraft (OD)
NoODRD	No Overdraft & No Reduction in the Delta Outflow
NoODAD	No Overdraft & No Additional Delta Exports
NoODDE	No Overdraft & No Delta Exports*

*Delta exports from Banks and Tracy pumping plants are limited to 5% of the total capacity.

Method

Water management cases to analyze overdraft impacts in the Central Valley are evaluated with California's statewide hydro-economic water supply model, CALVIN (Draper et al., 2003). CALVIN represents California's inter-tied water infrastructure, and uses groundwater and surface water to maximize statewide economic benefits within physical, environmental, and policy constraints. CALVIN is a large-scale optimization model that provides economically optimal time-series of surface and groundwater allocations. CALVIN employs network-flow optimization solver for its 82-year-based monthly operations. CALVIN is a large-scale integrated model. Agricultural, residential, industrial, and environmental water demands are represented. CALVIN provides ideal marketing operations, artificial recharge, and alternative water use options, such as desalinated, potable and non-potable recycled water. Limitations of the model are discussed in previous chapters. The model does not represent dynamic groundwater flows. Instead, it uses fixed inflows for each groundwater sub-basin obtained from Central Valley Groundwater-Surface Water Simulation Model (C2VSim) (Brush and Dogrul, 2012). CALVIN also does not incorporate head differences for pumping costs. It uses a fixed-unit pumping cost derived from the Statewide Agricultural Production Model (SWAP) (Howitt et al., 2012). CALVIN groundwater subbasins are shown in *Figure 24*.

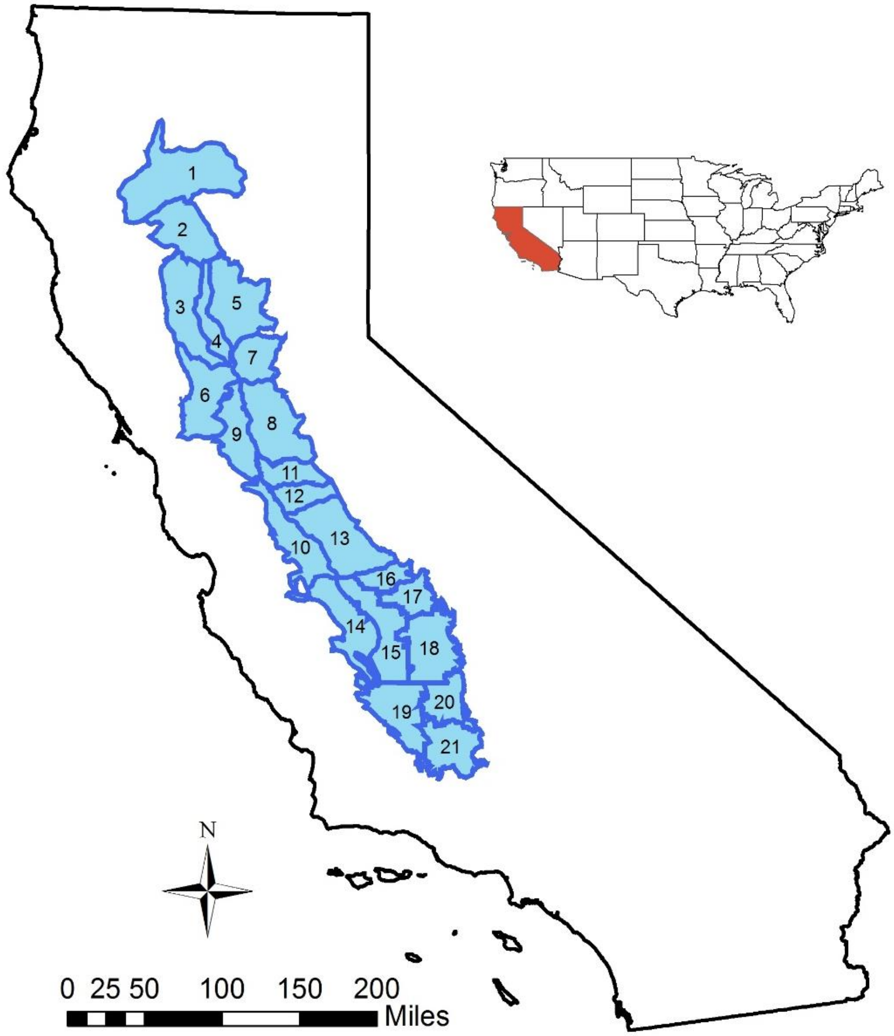

Figure 24. Central Valley groundwater sub-basins in CALVIN

Study Area

Bounded by the Cascade Range to the north, Sierra Nevada to the east, Coastal Range to the west, and Tehachapi Mountains to the south, the Central Valley is one of most productive agricultural lands in the world (Faunt, 2009; Vasconcelos, 1987). Sacramento and San Joaquin Rivers drain the Central Valley's water to the San Francisco Bay, creating the Sacramento-San Joaquin Delta (the Delta). The Central Valley can be divided into three parts as Sacramento Valley in the north, the San Joaquin Valley, and Tulare Basin in the south. Climate is an arid-to-semiarid Mediterranean Climate; hot and dry in the summer and cool and damp in the winter, with most precipitation falling in the winter and spring (Faunt, 2009). Intense agricultural activities in the Central Valley lead to vast water resources projects. The Central Valley Project (CVP) and the State Water Project (SWP) are among large-scale water projects, transferring water across the State (Hanak et al., 2011; Lefkoff and Kendall, 1996). CVP and SWP are multi-purpose projects, including water supply, flood control, hydropower, and recreation. A primary objective of the CVP and SWP was to end the groundwater overdraft in the Central Valley when first launched in the 1930s (CDWR, 2003). However, with population growth, economic development, and increased irrigation demand, overdraft was never ended; on the contrary, it has increased in the Central Valley, especially in the San Joaquin Valley and Tulare Basin.

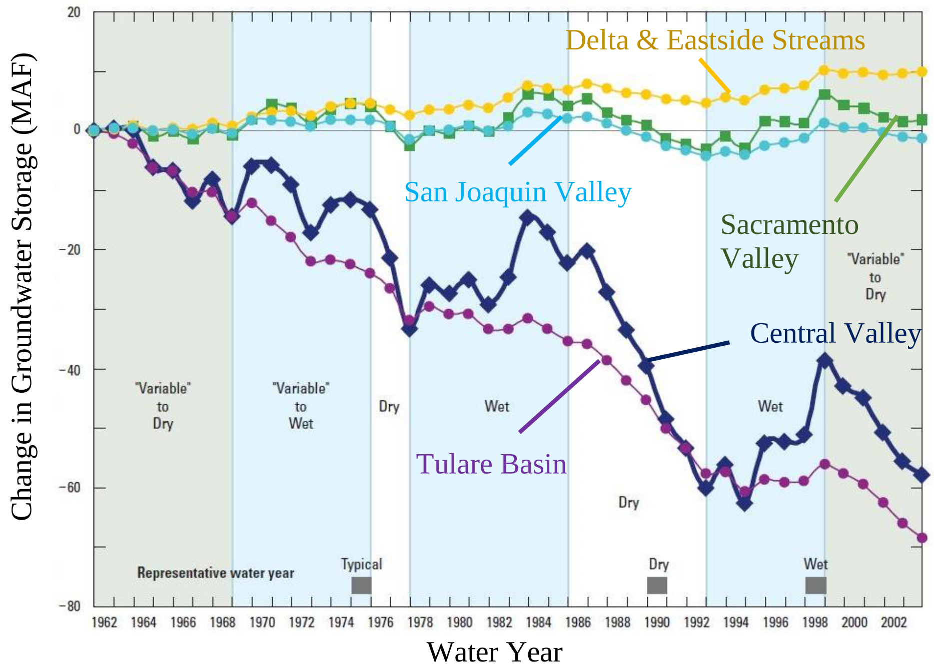

Figure 25, Cumulative change in the Central Valley groundwater storage between 1961 and 2002 (Source: Faunt (2009))

The Sacramento and San Joaquin Rivers drain Central Valley's water to the Delta (*Figure 26*). The Delta is a hub for water operations in California. Giant CVP and SWP pumps, Tracy and Banks, export the water from the Delta to southern regions, San Joaquin, Tulare, and southern California, through Delta-Mendota Canal and California Aqueduct. In CALVIN, Delta outflow is divided into required and surplus amounts. The required Delta outflow is a minimum flow requirement that must be met. Required outflow is important for salinity management and aquatic species in the Delta. Surplus outflow is the difference between total and required Delta outflows. Annual average required Delta outflow is about 5 MAF/y, and surplus outflow under base CALVIN operations averages about 9.4 MAF/y.

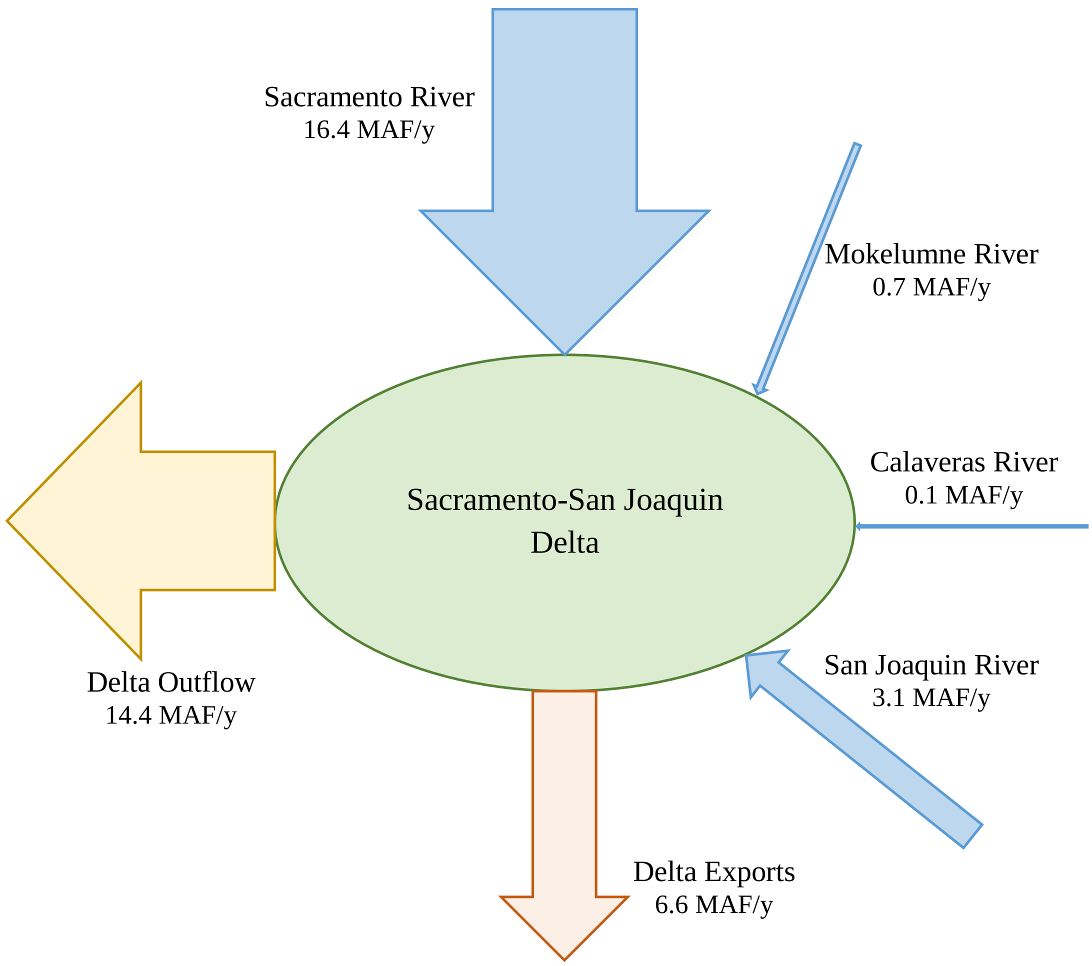

Figure 26. A simple representation of the Delta with major rivers, outflow to the Bay, and exports

To simulate the long-term "no overdraft" effects in the Central Valley, CALVIN's Central Valley groundwater basins' end-of-period storages (2003) are set to initial 1921 storages. *Table 11* shows initial and ending groundwater storage values with long-term overdraft. Current 82-year overdraft is about 84 MAF in the Central Valley. The highest overdraft is in Tulare groundwater sub-basins, GW-19, GW-20, and GW-21. In some northern sub-basins, however, such as GW-01, GW-06, and GW-09, the long-term storages are slightly increased. Southern California groundwater basins are not included in this chapter, as they are mostly in rough balance.

Table 11. Central Valley groundwater sub-basins and storage capacities (Chou, 2012)

Sub-basin	Initial Storage (MAF)	Ending Storage (MAF)	Overdraft (MAF)	Change in Storage (%)
GW-01*	38	39	1.0	2.6%
GW-02	136	136	0	0%
GW-03	133	132	-0.9	-0.7%
GW-04	61	61	-0.2	-0.4%
GW-05	91	90	-0.7	-0.7%
GW-06*	175	175	0.3	0.2%
GW-07	57	51	-5.3	-9.4%
GW-08	191	183	-7.8	-4.1%
GW-09*	139	140	0.4	0.3%
GW-10	90	87	-3.2	-3.5%
GW-11	59	58	-0.6	-1.0%
GW-12	43	41	-1.7	-4.1%
GW-13	138	129	-9.7	-7.0%
GW-14	179	172	-6.8	-3.8%
GW-15	310	307	-3.0	-1.0%
GW-16	65	64	-0.3	-0.4%
GW-17	97	94	-3.6	-3.7%
GW-18	321	321	0	0%
GW-19	142	128	-13.5	-9.5%
GW-20	137	125	-11.9	-8.7%
GW-21	341	324	-16.8	-4.9%
Central Valley	2,943	2,858	-84	-2.9%

* Negative overdraft

Results

Management scenarios are examined from several perspectives. Overdraft effects on water delivery and scarcity are analyzed with a portfolio approach. Scarcity costs and operating costs rise. Groundwater storages, conjunctive use management, and artificial aquifer recharge operations are discussed. Delta exports from Tracy and Banks pumping plants without overdraft are presented. Finally, overdraft effects on the Delta outflow are portrayed for different management cases.

Water Delivery and Scarcity

Less groundwater withdrawal is available to agricultural and urban water users with no long-term overdraft policy, resulting in water scarcities, mostly to agricultural users. Ending overdraft does not have large effects on urban water supplies even though most urban areas depend solely on groundwater. This is because urban water supplies have less shortage elasticities and high user willingness-to-pay for water. So, scarcities are concentrated on agricultural users (*Table 12*). Under base operations, agricultural areas see scarcities, and with no overdraft cases, scarcities increase, depending on the scenario. When exports from the Delta are limited to 5% of capacity, vast water shortages are observed south of the Delta, whereas north of the Delta agricultural users benefit from limited Delta exports. The first case, with no overdraft only, has the lowest annual average scarcity in the Central Valley among no overdraft cases. When no reduction is allowed on Delta outflow, water sales occur, transferring water from agricultural and hydropower users in Sacramento Valley to south of the Delta users. The last case with no overdraft and little Delta exports has considerable effects on agricultural and urban deliveries in San Joaquin Valley and Tulare Basin, especially in areas supplied by the California Aqueduct and Delta-Mendota Canal (SWP and CVP). However, upper

Sacramento Valley agricultural users benefit some from limited Delta exports by reducing their water scarcities.

Table 12. Annual average agricultural and urban water scarcities under five management scenarios

Scarcity (TAF/y)	**Base Case**		**NoOD[a]**		**NoODRD**		**NoODAD**		**NoODDE**	
Region	**Agr.**	**Urban**	**Agr.**	**Urban**	**Agr.**	**Urban**	**Agr.**	**Urban**	**Agr.**	**Urban**
Upper Sac.	20	0	32	0	98	0	21	0	12	0
Lower Sac. & Delta	89	0.9	124	0.9	277	0.9	125	0.9	155	0.9
San Joaquin & South Bay	20	0	122	0	168	0	168	0	2,085	93
Tulare Basin	146	6.3	242	6.3	376	6.3	376	6.3	3,650	28
Southern California	152	98	152	102	152	133	152	133	168	496
Central Valley	274	7.2	520	7.2	920	7.2	690	7.2	5,902	122

[a] Scenarios: *NoOD* no overdraft, *NoODRD* no overdraft & no reduction in Delta outflow, *NoODAD* no overdraft & no additional Delta exports, *NoODDE* no overdraft & no Delta exports

Most agricultural deliveries are from surface water in Central Valley, varying from 71% in the upper Sacramento Valley to 60% in Tulare Basin under base allocations (*Figure 27*). A no overdraft policy reduces groundwater supplies. Under base operations, about 33% of agricultural delivery is from groundwater in the Central Valley. This ratio reduces to 31% with the first no overdraft case, 32% with second and third no overdraft scenarios where reduction in Delta outflow and additional Delta exports are prohibited, but increases to 46% when both overdraft and Delta exports are ended (partly because total deliveries decrease). The base case allocates an annual average of 7 MAF/y from groundwater. Without Delta exports annual average deliveries from groundwater increase to 7.36 MAF/y. Although less groundwater storage is available in the last case, more artificial recharge enhances groundwater deliveries, as discussed later in this chapter.

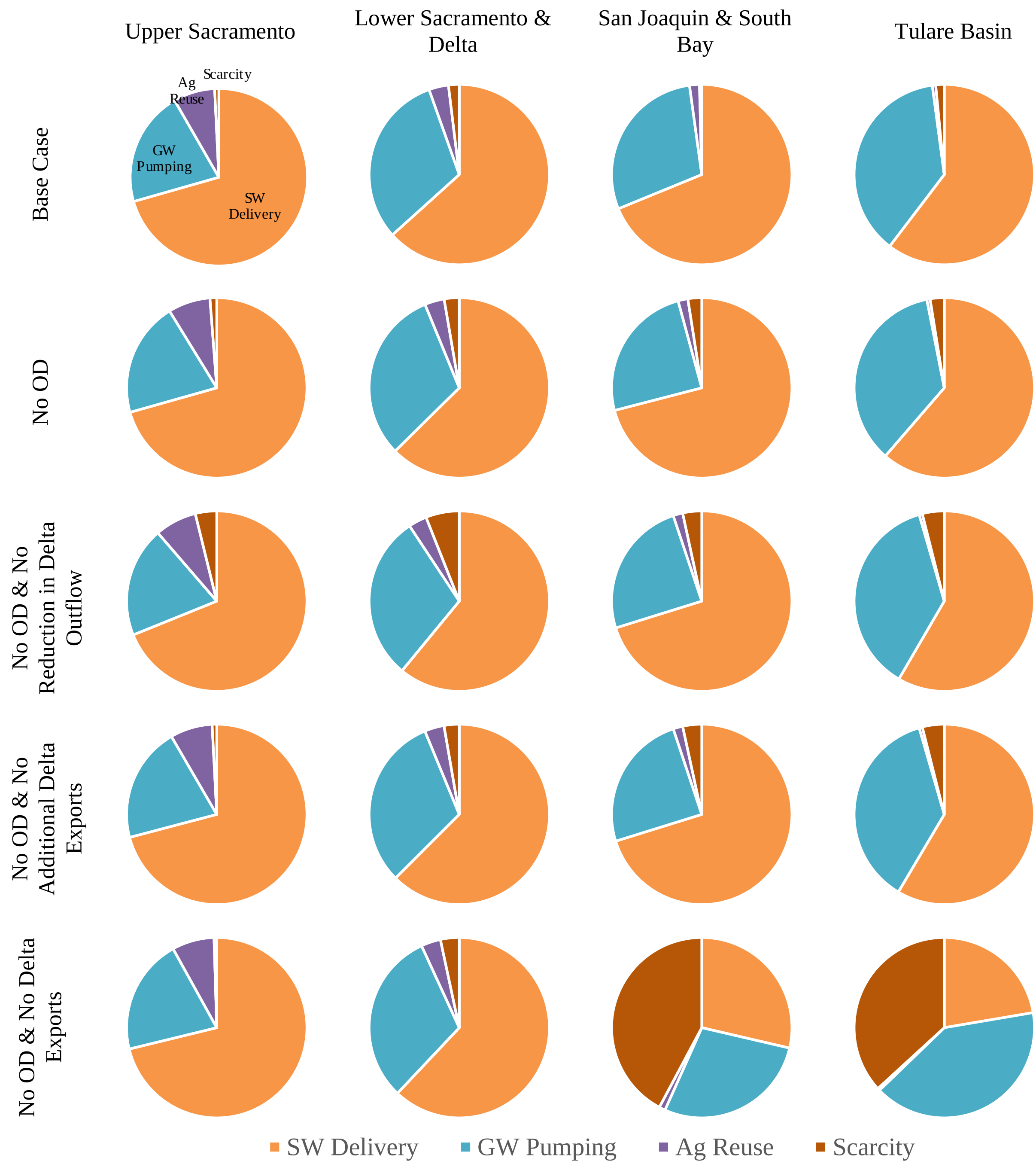

Figure 27. Agricultural water supply portfolios and scarcities

Scarcity costs from lost agricultural production increase when long-term groundwater overdraft is not permitted (*Table 13*). In Sacramento Valley, the highest scarcity costs occur when Delta outflow is not reduced (second no overdraft scenario), although scarcity costs would be largely compensated financially with water sales to south of the Delta. In San Joaquin and Tulare Basins, scarcity costs increase with no overdraft cases and skyrocket when Delta exports are largely ended. Sacramento Valley has lower scarcity costs in the no overdraft case where there is no additional Delta export than the case with fixed Delta outflow. However, south of Delta scarcity costs are almost the same in those cases. This is because additional Delta exports from Sacramento Valley are sold south of the Delta when reduction in Delta outflow is not allowed. Annual average agricultural scarcity costs without Delta exports are $864 million and $1.8 billion per year in San Joaquin Valley and Tulare Basin, respectively.

Table 13. Annual average agricultural water scarcity cost

Region	**Annual Average Scarcity Cost (K$/year)**				
	Base Case	**NoOD**[a]	**NoODRD**	**NoODAD**	**NoODDE**
Upper Sacramento Valley	441	942	3,847	519	285
Lower Sacramento Valley	6,075	8,928	15,117	9,016	15,324
San Joaquin Valley	1,269	8,592	11,722	11,697	863,710
Tulare Basin	12,662	22,520	35,281	35,279	1,791,191
Central Valley	20,447	40,981	65,966	56,511	2,670,510

[a] Scenarios: *NoOD* no overdraft, *NoODRD* no overdraft & no reduction in Delta outflow, *NoODAD* no overdraft & no additional Delta exports, *NoODDE* no overdraft & no Delta exports

Agricultural scarcity costs are not evenly distributed in Central Valley (*Table 14*). The higher scarcity costs are focused south of the Delta. Under historical base operations, south of the Delta agricultural users have an annual average total scarcity cost of $14 million per year. However, this scarcity cost increases to $31 million per year south of the Delta when overdraft is ended. Although some users in Sacramento Valley have scarcity costs with base operations, a no overdraft policy does not greatly increase them. Delta exports become much more important with a no overdraft policy. Scarcity costs of agricultural areas along the along the California Aqueduct and Delta-Mendota Canal escalate considerably, even when more water is exported from the Delta under no overdraft cases. Some users in Tulare Basin have annual average scarcity costs of $11.6 million per year, and regional total average scarcity cost is about $22.5 million per year.

Table 14. Distribution of annual average agricultural scarcity costs with and without overdraft

	Area	Annual Average Agricultural Scarcity Cost (K$/y)				
		Base Case	**NoOD[a]**	**NoODRD**	**NoODAD**	**NoODDE**
	CVPM01	3	11	104	6	0
	CVPM02	346	668	1,259	348	233
	CVPM03A	0	0	340	0	0
	CVPM03B	52	52	328	52	52
	CVPM04	40	210	1,816	113	0
	CVPM05	451	446	3,482	450	375
	CVPM06	36	51	1,075	36	21
	CVPM07	0	0	670	0	0
	CVPM08	5,588	5,631	6,930	5,588	5,588
	CVPM09	0	2,799	2,960	2,941	9,340
Delta						
	CVPM10	9	770	2,858	2,858	83,743
	CVPM11	0	0	0	0	447,738
	CVPM12	1,117	2,191	2,754	2,754	118,577
	CVPM13	142	5,631	6,109	6,084	213,652
	CVPM14A	723	2,057	3,194	3,194	12,222
	CVPM14B	0	0	0	0	420,831
	CVPM15A	0	0	0	0	87,408
	CVPM15B	297	2,517	2,541	2,541	30,734
	CVPM16	0	31	8,360	8,307	170,714
	CVPM17	1	1	389	392	3,072
	CVPM18	11,640	11,640	12,495	12,502	431,888
	CVPM19A	1	4,121	4,481	4,522	59,364
	CVPM19B	0	0	0	0	23,057
	CVPM20	0	0	1	1	140,334
	CVPM21A	0	2,152	3,820	3,820	390,695
	CVPM21B	0	0	0	0	15,233
	CVPM21C	0	0	0	0	5,639
	Central Valley	20,447	40,981	65,966	56,511	2,670,510

[a] Scenarios: *NoOD* no overdraft, *NoODRD* no overdraft & no reduction in Delta outflow, *NoODAD* no overdraft & no additional Delta exports, *NoODDE* no overdraft & no Delta exports

Groundwater Storage

The Central Valley aquifer has a modelled overdraft 84 MAF over the 82-year operating period. Groundwater sub-basins in Tulare Basin have the highest long-term overdrafts. On the other hand, some sub-basins, especially north of the Delta, are managed sustainably and have zero or negative overdraft. With no overdraft scenarios, differences between initial and ending groundwater storages are constrained to zero. *Figure 28* shows cumulative change in groundwater storage of the Central Valley aquifer, with filling and drawdown periods. Total storage generally increases in wet years, when recharges from surface water is highest, and decreases in drought years with pumping. Base case total storages are lower than other cases in any year. Storages with no overdraft cases are quite close, with an exception of no overdraft and no export case, although some differences are observed in from 1930 to 1950, and from 1984 to 1990. Groundwater storages under no Delta export operations are higher between 1930 and 1953, but lower between 1957 and 1990. Storage differences between base and other no overdraft cases constantly increase after 1931, and become the highest at the end of 82-year operational period.

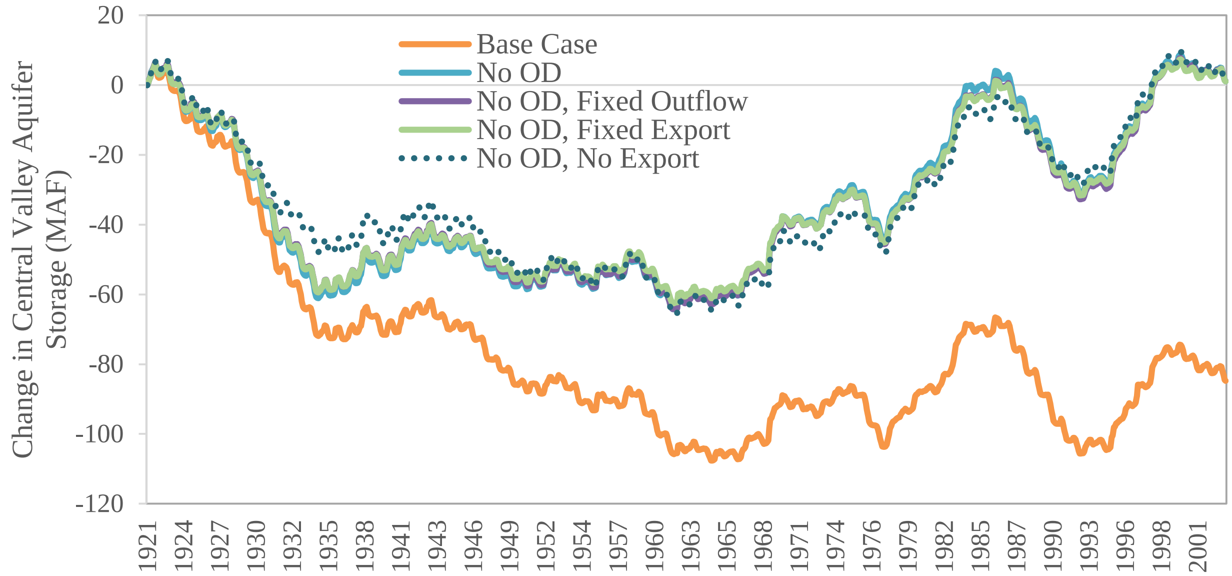

Figure 28. Change in Central Valley aquifer storage over the 82-year period

Artificial Recharge

Artificial recharge (AR) of groundwater basins is important in conjunctive use water management. AR increases effectiveness and reliability of groundwater supply, and ameliorates adverse impacts of overdraft by making more use of available surface water. Recharge is defined as addition of water to an aquifer from the overlying unsaturated zone or water body (Scanlon et al., 2006). Surface water can be artificially recharged with injection wells or less expensively with percolation ponds in wet months/years, and then pumped in dry months/years to reduce water scarcities. Groundwater banking relies on the AR of excess surface water into aquifer for later extraction (Meillier et al., 2008). Several regions have artificial recharge capability in the Central Valley (*Figure 29*). For example, Kern Water Bank in Tulare Basin a has large-scale groundwater banking in the United States (Meillier et al., 2008).

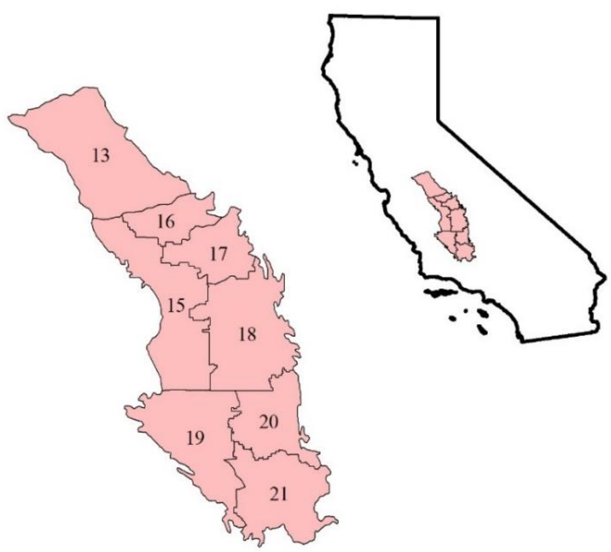

Figure 29. Central Valley groundwater sub-basins with artificial recharge

In the current CALVIN network, Tulare Basin and southern California groundwater sub-basins have artificial recharge (AR) capability. Return flows to groundwater from exterior residential water use, wastewater treatment plants, and agricultural uses are not included in AR calculations. *Figure 30* shows monthly average AR patterns for base and no overdraft cases. AR is lower under base CALVIN operations and increases with no overdraft scenarios. Monthly average AR peaks in winter, except for the no overdraft and no Delta export case. AR rates dramatically increase from January through June in no overdraft cases where Delta exports are not allowed although surface water exports decrease. Under no overdraft and no Delta export operations, annual average AR in the Central Valley is 1.9 MAF/y, about six times more than base case AR. Groundwater sub-basin 18 has the most AR, recharging water from Tule and Kaweah Rivers and Friant-Kern Canal (*Table 15*). Under base operations, annual average 155 TAF of water flows into the Tulare Lake, while with no overdraft where Delta exports are eliminated (No OD, No Export), return flow to the lake bed is 68 TAF/y. Annual average return flow to Buena Vista Lake is 661 TAF and 174 TAF per year with base case and no overdraft without Delta exports case, respectively. The reduction is due to more diversion or higher artificial recharge. The model also recharged water instead of storing in surface reservoirs to prevent losses, such as evaporation. The artificial recharge dramatically increases when overdraft is ended without Delta exports since the model tried to water as much as possible, especially south of the Delta where water scarcities are highest.

Table 15. Annual average artificial recharge at each basin

Case	Annual Average Artificial Recharge of Central Valley Basins (TAF/y)								
	GW-13	GW-15	GW-16	GW-17	GW-18	GW-19	GW-20	GW-21	Central Valley
Base Case	0	0	23	0	300	0	0	4	327
NoOD[a]	0	42	24	0	380	0	0	99	544
NoODRD	0	42	23	0	400	402	0	26	894
NoODAD	0	42	23	0	403	415	0	32	915
NoODDE	144	417	317	0	608	225	61	134	1,906

[a] Scenarios: *NoOD* no overdraft, *NoODRD* no overdraft & no reduction in Delta outflow, *NoODAD* no overdraft & no additional Delta exports, *NoODDE* no overdraft & no Delta exports

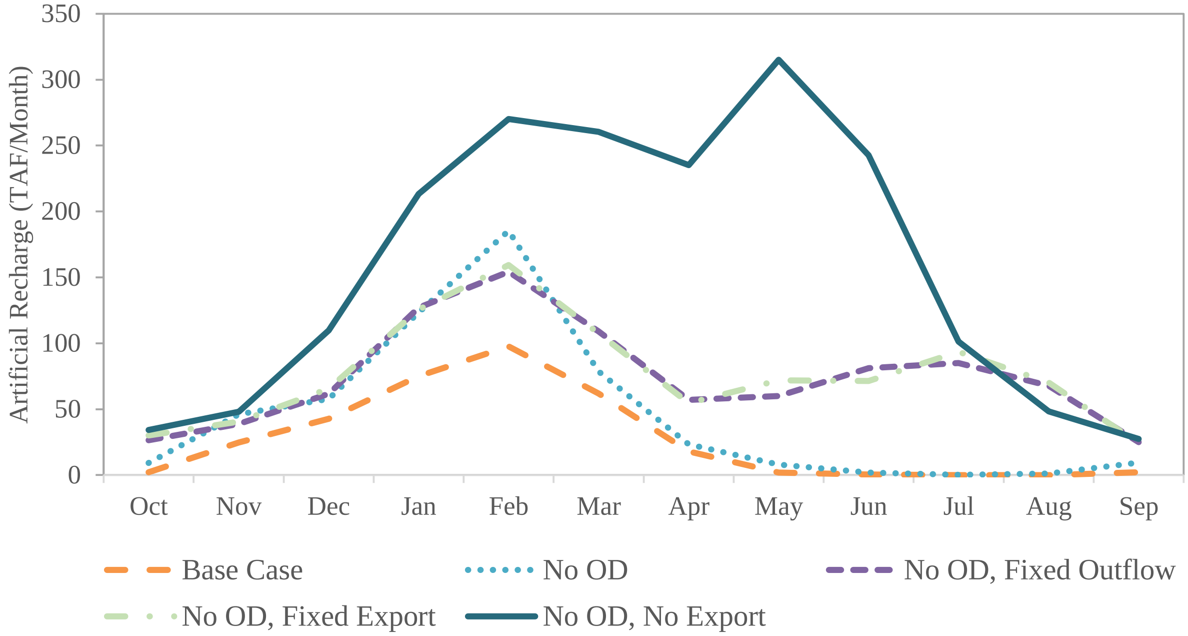

Figure 30. Monthly average artificial recharge into the Central Valley aquifer

Figure 31 shows the relationship between artificial recharge (AR) and surface water availability. Water is mostly recharged in wet years, such as 1938, 1969, 1983, and 1997. Peak and low AR rates match in base and no overdraft cases, but magnitudes of recharge vary. For instance, in January 1969, when AR is the highest in five cases, about 2 MAF is artificially recharged under no overdraft and no Delta export operations in the Central Valley, while it is about 1 MAF under base allocations. No overdraft and no Delta export case have the highest AR at any probability level.

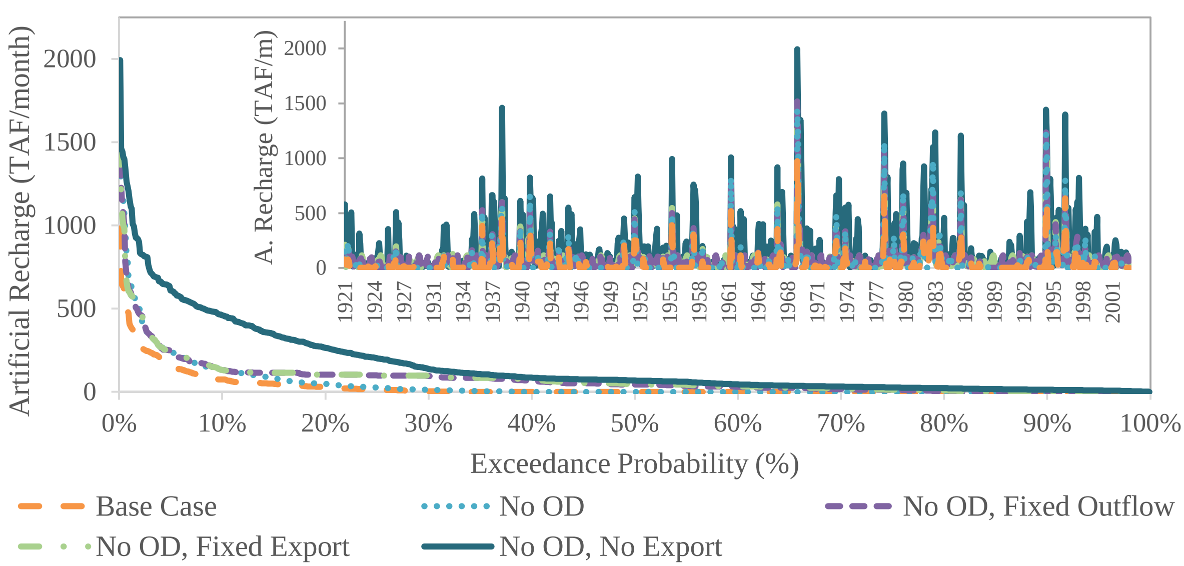

Figure 31. Exceedance probability and monthly time-series of artificial recharges

Delta Exports

Water transfers from the Delta increase when long-term groundwater overdraft ends in the Central Valley. Base case exports are about 6.6 MAF per year from the Delta. Annual average 667 TAF/y of additional water is exported from the Delta to reduce water scarcities south of the Delta under no overdraft operations (*Table 16*). When the reduction in the Delta outflow is not allowed (NoODRD), the increased Delta exports is 47 TAF/y, the amount that south of the Delta users buy from the north to reduce additional scarcities from ending overdraft. When Delta exports are limited to 5% of allowable pumping capacity, annual average 418 TAF is exported per year. Allowable pumping capacities for Tracy and Banks, incorporating environmental, physical and operational limitations, are gleaned from the CALSIM II model. Except for the no overdraft and no reduction in Delta outflow case, shadow prices on pumping capacities increase with a no overdraft policy in the Central Valley. Under no overdraft and no Delta export operations, marginal benefits of expanding exports dramatically increase due to vast water shortages from limited Delta exports.

Table 16. Annual average exports from Banks and Tracy pumping plants

Case		Base Case	NoOD[a]	NoODRD	NoODAD	NoODDE
Export (TAF/y)	Banks	4,108	4,657	4,158	4,108	251
	Tracy	2,478	2,597	2,475	2,478	167
	Total	6,587	7,254	6,634	6,587	418
Marginal Values on Upper Bound ($/AF)	Banks	14	16	13	65	1,761
	Tracy	8	14	8	58	1,756

[a] Scenarios: *NoOD* no overdraft, *NoODRD* no overdraft & no reduction in Delta outflow, *NoODAD* no overdraft & no additional Delta exports, *NoODDE* no overdraft & no Delta exports

Figure 32 shows the monthly average export patterns from the Delta. Exports are proportionate to the water demand, higher from March through October, and lower the rest of the year. Spring and summer exports are close the allowable pumping capacity, while almost half of the capacity remains unused in winter. Delta exports increase in every month when overdraft is ended. Marginal increase in Delta exports in winter is higher than other months under no overdraft operations.

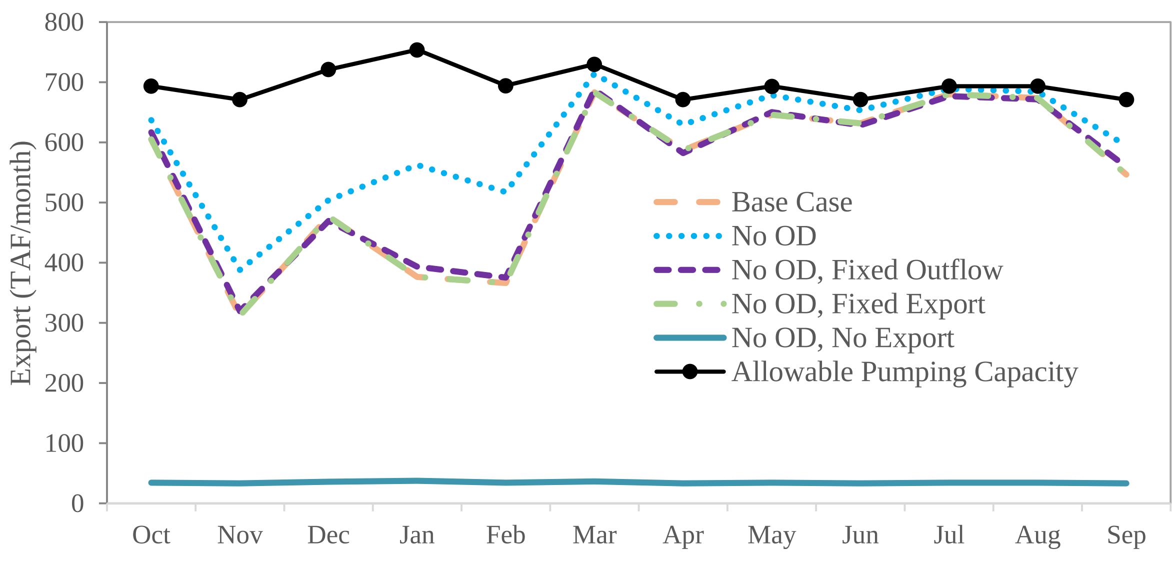

Figure 32. Monthly average Delta exports and allowable pumping capacity

Water exports are close to the allowed capacity at about 50% of time (*Figure 33*). Without overdraft, Delta exports have higher deliveries at any probability level, and differences increase after 50% probability. Delta export delivery-reliability for the base case and no overdraft cases without additional Delta exports and reduction in Delta outflow are quite close. All allowed capacity is used throughout the 82-year period when Delta exports are limited to 5% of allowable capacity.

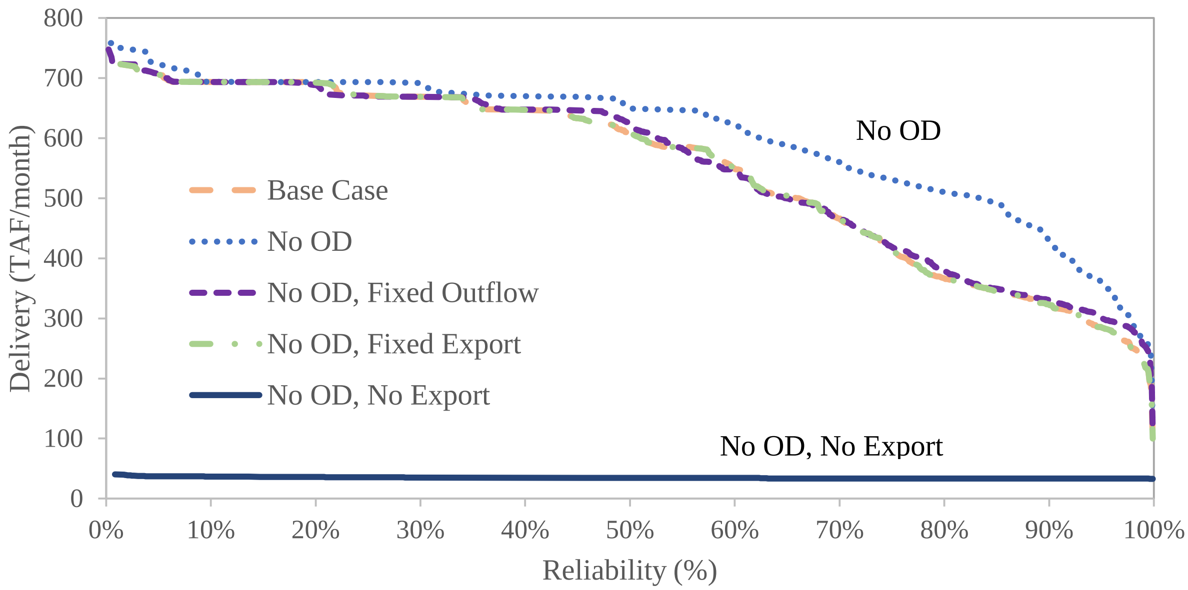

Figure 33. Delta exports delivery-reliability curves

Delta Outflow

Delta outflow is water flow from Central Valley into the San Francisco Bay, and is regulated by the State Water Resources Control Board (SWRCB, 2000). Total Delta outflow is the sum of required and surplus Delta outflows. Annual average total Delta outflow and marginal benefits of reducing the required Delta outflow are presented in *Table 17*. Annual average Delta outflow under no overdraft allocations, 13.6 MAF/y, is the lowest, showing that additional transfers are mostly made from the Delta outflow. When Delta exports are limited to 5% of capacity, annual average Delta outflow increases to 20.3 MAF/y. Shadow prices on the required Delta outflow increase when overdraft is ended in the Central Valley. The highest average marginal value of $64 per acre-foot is observed when the Delta outflow is constrained to the base case. The increased Delta outflow under no overdraft and no Delta export operations reduces marginal value of the required outflow.

Table 17. Annual average Delta outflows and average marginal values on the required Delta outflow

Case	Average Delta Outflow (MAF/y)	Average Marginal Value ($/AF)
Base Case	14.4	5.9
No Overdraft	13.6	7.9
No Overdraft & No Reduction in Delta Outflow	14.4	64.2
No Overdraft & No Additional Delta Outflow	14.2	6.7
No Outflow & No Delta Exports	20.3	0.4

Monthly average Delta outflow peaks in February in all cases. Higher water demands in summer and early fall reduce the outflow to the required levels in summer and early fall (*Figure 34*). In every month, the no Delta export policy creates higher Delta outflows. Monthly average peak outflows in February are 2.81 MAF/m and 3.43 MAF/m under base and higher outflow cases (last case), respectively. Flow fluctuations are higher between November and April. When overdraft is ended, the Delta outflow is exported mostly in the late fall and winter, when the outflow is abundant.

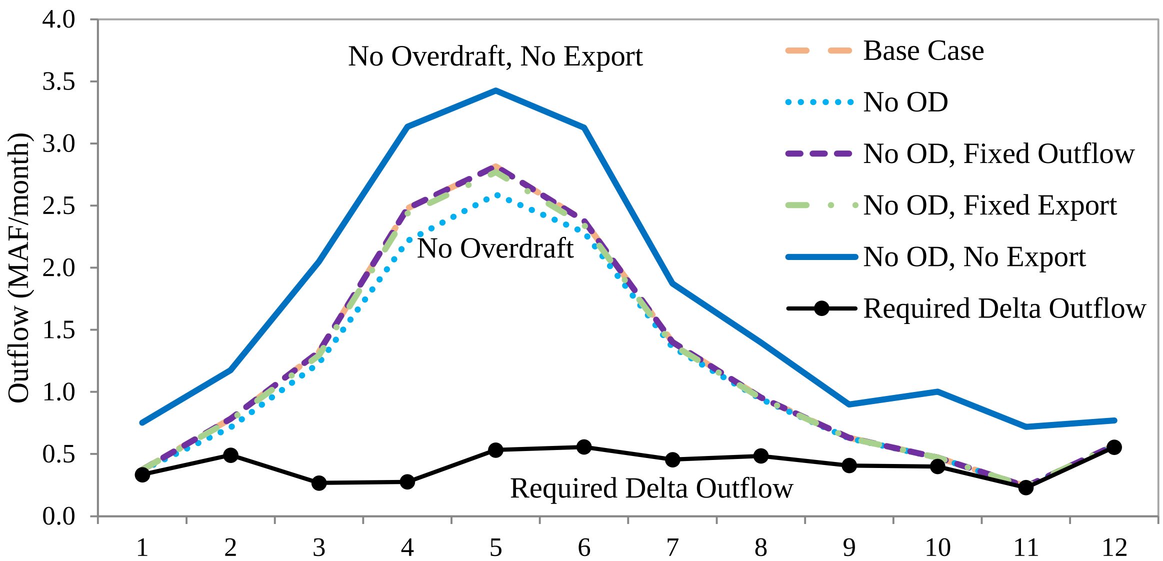

Figure 34. Monthly average and required Delta outflow

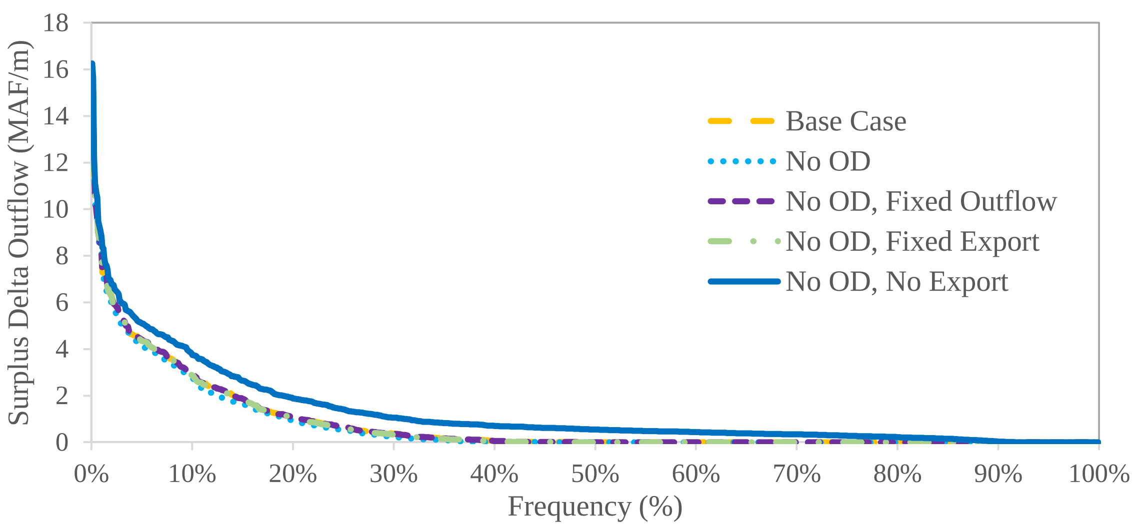

Figure 35. Frequency curves of monthly surplus Delta outflow

Surplus Delta outflow is highly variable across months and years (*Figure 36*). Standard deviations of the surplus outflow are 1.72 MAF and 1.65 MAF, and monthly mean outflows are 785 TAF/m and 718 TAF/m under base case and no overdraft operations, respectively. Variabilities are higher in winter and lower in summer. Surplus outflow increases in wet years, and the Sacramento River contributes to most surplus Delta outflow. Under historical operations, about 90% of total Delta outflow is from Sacramento River flows. Surplus Delta outflow can reduce additional water scarcities from overdraft, especially south of the Delta. However, exporting more surplus outflow requires more storage and pumping capacity since it is available when the water demand is lower.

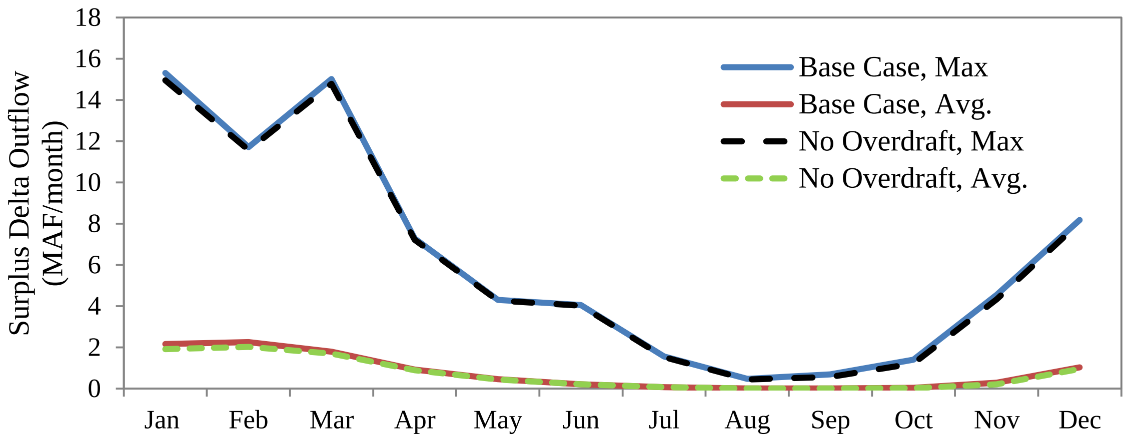

Figure 36. Monthly average and maximum surplus Delta outflow under base and no overdraft cases

Unconstrained Overdraft

The base CALVIN operations are based on historical overdraft in the Central Valley. About 84 MAF of total overdraft over 82 years is predefined to the model. However, this 84 MAF of overdraft is not economically optimal. Groundwater is pumped even though it is not needed. An economically optimal overdraft balances groundwater pumping, while maximizing agricultural production. When overdraft is higher than the optimal overdraft, pumping costs dominate total statewide cost, whereas below the optimal overdraft, scarcity costs become more prominent. Instead of predefining cumulative overdraft, end of period groundwater storage constraints are removed, and CALVIN is let to calculate the least cost overdraft for the 82-year period. Total least cost overdraft in the Central Valley is 62.8 MAF (*Figure 37*). Annual average groundwater pumping cost with the least cost overdraft is $957 million per year, which is less than the base case pumping cost, $1,051 million per year, and no overdraft case pumping cost, $976 million per year. Agricultural scarcity cost is also minimized with least cost overdraft. Annual average agricultural scarcity cost in the Central is $49 million per year with base operations and $69 million per year without overdraft, whereas it is $45 million per year with the least cost overdraft.

Figure 37. Change in monthly storage in the Central Valley aquifer with unconstrained overdraft over the 82-year period

Overall Summary

Agricultural scarcity costs from lost production increase when the long-term groundwater overdraft is ended in the Central Valley (*Table 18*). Tulare Basin is most affected. Urban scarcities do not significantly change within management scenarios, except when Delta exports are largely ended. However, urban scarcity costs are higher with no Delta outflow reduction (NoODRD) and no additional Delta exports (NoODAD) cases. When Delta exports are ended, annual average urban scarcity cost increases to $697 million per year. Annual average operating cost in no overdraft without Delta exports case (NoODDE) is also higher due to increased recycled water use. Small scarcities to urban users create enormous scarcity costs, although less use of Delta pumping plants reduce the total operating cost. Statewide annual average operating costs decrease with no overdraft cases because less groundwater is pumped. Average hydropower benefits slightly reduce with no overdraft cases. However, with less Delta exports, since power is not generated as water flows on the California Aqueduct, hydropower benefits decrease. Net statewide annual average costs show that operations without overdraft (NoOD) have the same cost as base historical operations. The most beneficial case is the unconstrained overdraft, with the lowest statewide annual average net cost, $4,140 million per year. Net statewide cost without Delta exports is higher than no overdraft cases because of large agricultural and urban water scarcity costs.

Table 18 shows annual average operating and net statewide costs with updated and old groundwater unit pumping costs. Without overdraft, net statewide costs are expected to increase. However, base case and no overdraft case operations have the same net statewide costs with updated unit pumping prices. With old unit pumping prices, the no overdraft case has higher annual average net statewide cost. The difference between old and updated unit pumping prices (*Table 35*) is so high that the state benefits from less groundwater pumping when overdraft is ended. This could be because updated unit groundwater pumping costs are overestimated, relative to surface water costs.

Table 18. Annual average statewide, including southern California, agricultural and urban scarcity costs, operating costs, and hydropower revenue under five management cases

Case	Agr. Scarcity Cost (M$/y)	Urban Scarcity Cost (M$/y)	Operating Cost[1] (M$/y)	Operating Cost[2] (Old Prices) (M$/y)	Hydropower Benefit (M$/y)	Net Statewide Cost[1] (M$/y)	Net Statewide Cost[2] (Old Prices) (M$/y)
Base Case	49	93	4,947	4,613	862	4,227	3,893
NoOD[a]	69	97	4,919	4,611	858	4,227	3,919
NoODRD	94	126	4,898	4,578	857	4,261	3,941
NoODAD	85	126	4,902	4,580	857	4,256	3,934
NoODDE	2,707	697	5,102	4,754	727	7,779	7,431
UnOD	45	104	4,846	4,545	855	4,140	3,839

[a] Scenarios: *NoOD* no overdraft, *NoODRD* no overdraft & no reduction in Delta outflow, *NoODAD* no overdraft & no additional Delta exports, *NoODDE* no overdraft & no Delta exports, *UnOD* unconstrained overdraft

[1] Operating and net statewide costs with updated groundwater pumping unit costs

[2] Operating and net statewide costs with old groundwater pumping unit costs

Water scarcities increase when overdraft is terminated. Even under base water operations, annual average water scarcity in the Central Valley is about 281 TAF/y (*Table 19*). Average scarcity increases to about 6 MAF/y without Delta Exports. Surplus Delta outflow can be an alternative supply source to reduce statewide water scarcities. Annual average surplus Delta outflow is much higher than water scarcities in the Central Valley. However, timing of surplus Delta outflow availability and water demand do not coincide. Surplus outflow is higher in wet years and winters. So, new or expanded water infrastructure would be needed to store excess Delta outflow.

Table 19. Annual average surplus Delta outflow and Central Valley water scarcities

Scarcity/Flow (TAF/y)	Base Case	NoOD[a]	NoODRD	NoODAD	NoODDE	UnOD
Scarcity in Central Valley	281	527	927	698	6,024	255
Surplus Delta Outflow	9,424	8,620	9,424	9,236	15,331	8,851

[a] Scenarios: *NoOD* no overdraft, *NoODRD* no overdraft & no reduction in Delta outflow, *NoODAD* no overdraft & no additional Delta exports, *NoODDE* no overdraft & no Delta exports, *UnOD* unconstrained overdraft

Conclusions

Hypothetical “no overdraft” scenarios evaluated with a hydro-economic optimization model provide insights into water management and planning decisions for the Central Valley. Although some temporary overdraft is useful, depending on duration and amount, all groundwater overdraft must be terminated for sustainable groundwater management. Ending overdraft also eliminates its adverse effects, such as land subsidence, increased pumping cost, and water quality degradation. No overdraft cases of this study show the system’s reaction to changes. Water scarcity, especially in agricultural areas, and its costs increase when overdraft is ended. Urban deliveries are unchanged, despite many cities in the Central Valley depending solely on groundwater for water supply. Increased Delta exports, water trading, and groundwater banking are useful adaptations when overdraft is ended. Delta exports are critical for south of Delta water supply. When Delta exports and overdraft are prohibited, dramatic agricultural and urban scarcity costs occur. Water trading reduces scarcity costs in San Joaquin Valley and Tulare Basin. If the Delta outflow cannot be decreased for environmental and operational reasons, Sacramento Valley users are willing to sell water to south of the Delta users. Artificial recharge increases groundwater reliability, especially in drought years. Although scarcity costs increase when overdraft is ended, groundwater pumping costs decrease. Thus, ending overdraft is more economical to the state than base historical operations with overdraft when indirect benefits, such as better water quality, less subsidence, and more storage, are considered. If overdraft cannot be completely eliminated, reducing it to the unconstrained amount, 63 MAF over the 82-year period, benefits the state about $87 million per year. Total average Delta outflow is higher than the required outflow in winter, creating excess outflow. So, with a new or improved infrastructure, more surplus Delta outflow can be captured, and water scarcities in the Central Valley can be eliminated. The study results are useful for regions where water trade, surface water export, and conjunctive use are parts of water resources system decisions.

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Chapter 5. Water Operations under Climate Warming

Introduction

Climate change effects vary for different regions. At high latitudes and wet tropics, river runoff and water availability are projected to increase, whereas arid and semi-arid areas are anticipated to experience serious water shortages (Bates et al., 2008). Located in the mid-latitude, California's water resources are prone to climate change effects although many of the specific changes are uncertain, such as overall precipitation. The California Sierra Nevada water system, driven largely by snowmelt runoff, is susceptible to changes in temperature and precipitation, which determine snowpack accumulation and the timing of snowmelt runoff. Increased temperatures can cause a timing-shift and more rapid recession in snowmelt. The changed runoff pattern will likely affect reservoir operations that regulate water for spring and summer irrigation and urban water, and electricity demands. (Miller et al., 2003; Vicuna et al., 2007)

The ecosystem is sensitive to climatic changes, especially changes in air and water temperature. A warm-dry climate scenario, employed here, represents an air temperature increase and precipitation decrease. Due to air-water temperature interaction, stream water temperature is expected to rise (Ficklin et al., 2013). Furthermore, faster snowmelt recession can raise stream water temperature, adversely affecting environmental water quality. Environmental water quality is beyond the scope of the CALVIN model. Environmental water requirements in CALVIN are represented as minimum in-stream flow (MIF) requirements and required wildlife refuge flows (Medellín-Azuara et al., 2008). Water is first allocated to environmental water users before any agricultural and urban deliveries. Nevertheless, all MIF requirements cannot be met with CALVIN operations due to less water availability with climate warming, resulting in reductions in MIF requirements.

High-elevation hydropower facilities with less storage capacities are most affected by increased temperature that leads to higher percentage of precipitation falling as rain and earlier spring snowmelt (Madani, 2009; Vicuna et al., 2008). However, low elevation hydropower plants with large storage capacities can accommodate seasonal changes and minimize power losses with adaptation (Hanak and Lund, 2012; Tanaka et al., 2006). With the warmer-only climate, hydropower benefits are unchanged, but with this warmer-drier climate, generation losses increase (Connell-Buck et al., 2011). Increased energy demands and prices with climate warming are likely to put more stress upon hydropower generation.

Under climate warming, water management in California becomes more complicated. New management, planning, and adaptation strategies have to be considered. CALVIN, which represents the entire inter-tied water supply system of California, including ground and surface water, agricultural, urban, and environmental water demands, and hydropower, is employed to evaluate climate change effects on water management in California. Groundwater and surface water hydrology is perturbed based on NOAA GFDL CM 2.1 A2 scenario (Delworth et al., 2006). This climate scenario projects a 2°C average increase in temperature, 3.5% decrease in precipitation, and 27% decrease in streamflow runoff by the end of 21st century in the Central Valley of California (Medellín-Azuara et al., 2008). Therefore, it is called a "warm-dry" hydrologic scenario. Several previous CALVIN studies have examined climate change effects with various climates (Connell-Buck et al., 2011; Connell, 2009; Harou et al., 2010; Medellín-Azuara et al., 2006, 2008, 2009; Tanaka et al., 2006; Zhu et al., 2005). This study uses the updated CALVIN model with better California water infrastructure and hydrology representations and explores adaptive water management and policy decisions under population, land use, and climatic changes.

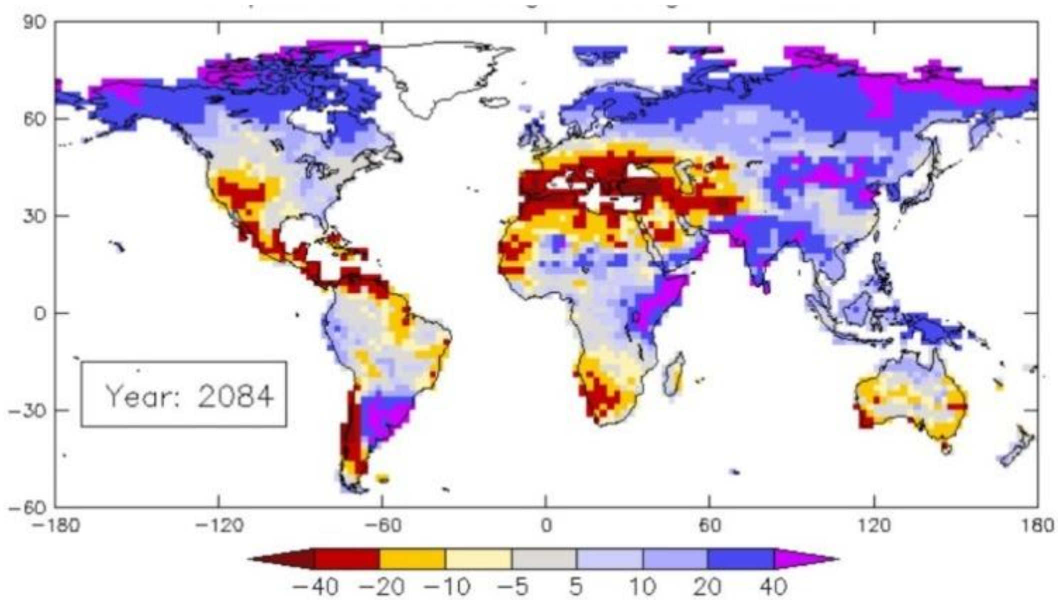


Figure 38. Expected percentage change in global runoff by the end of the century under climate warming (Source: http://www.gfdl.noaa.gov/visualizations-climate-prediction)

Perturbed Hydrology

The downscaled results of this warm-dry climate scenario are used to perturb the 82 years of monthly CALVIN hydrology. Perturbed hydrologic components are rim inflows, groundwater inflows, local runoff, and reservoir evaporation (Zhu et al., 2005). Perturbation methods preserve the hydrologic variability while incorporating climatic changes (Medellín-Azuara et al., 2008). Perturbation ratios obtained from other studies (Miller et al., 2001, 2003; Zhu et al., 2005) used for stream flows to reflect earlier snowmelt and overall reduction in magnitude (*Figure 39*). CALVIN rim inflows are mapped to 18 index basins by considering watershed characteristics (Connell, 2009). Monthly perturbation ratios that incorporate warm-dry climate changes calculated for 18 index basins are applied to corresponding CALVIN rim inflows.

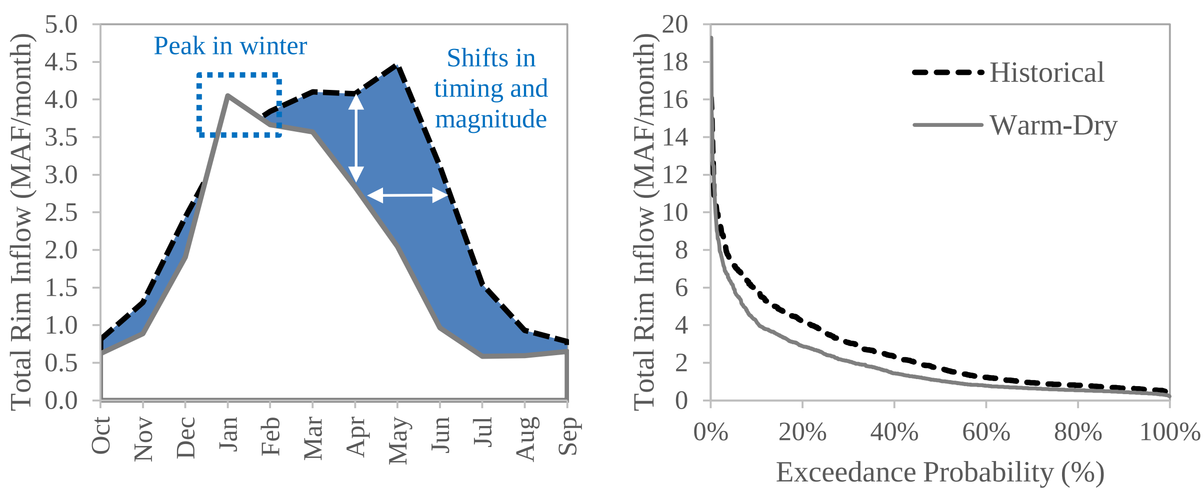


Figure 39. Total monthly average stream flow runoff and exceedance probabilities

Groundwater inflows are assumed to be only affected by changes in deep percolation. Deep percolation is amount of precipitation that infiltrates to underlying groundwater basin. An empirical cubic relationship between precipitation and groundwater recharge is employed to calculate change in deep percolation (*Equation 8*) for each groundwater basin in the Central Valley (Medellín-Azuara et al., 2008; Zhu et al., 2005). Change in deep percolation, the first order derivative of cubic relationship with respect to precipitation, is added to historical groundwater inflows (*Equation 9*). Precipitation and deep percolation from precipitation data are gathered from C2VSim model's groundwater budget. Deep percolation is lagged by a month, assuming that it takes a month for precipitation to deep percolate underlying groundwater basin. A good fit is obtained from relationship between deep percolation and precipitation. Peak plateau on the trend line represents infiltration capacity.

$$DP = a \cdot P + b \cdot P^2 + c \cdot P^3 \quad \textit{Equation 7}$$

$$\Delta DP = (a + 2b \cdot P + 3c \cdot P^2) \cdot \Delta P \quad \textit{Equation 8}$$

$$I_{perturbed} = I_{historical} + \Delta DP \quad \textit{Equation 9}$$

where *DP* is deep percolation, *P* is precipitation, I is groundwater inflow, *a*, *b*, and *c* denote regression parameters, and Δ*DP* and Δ*P* represent change in deep percolation and precipitation, respectively.

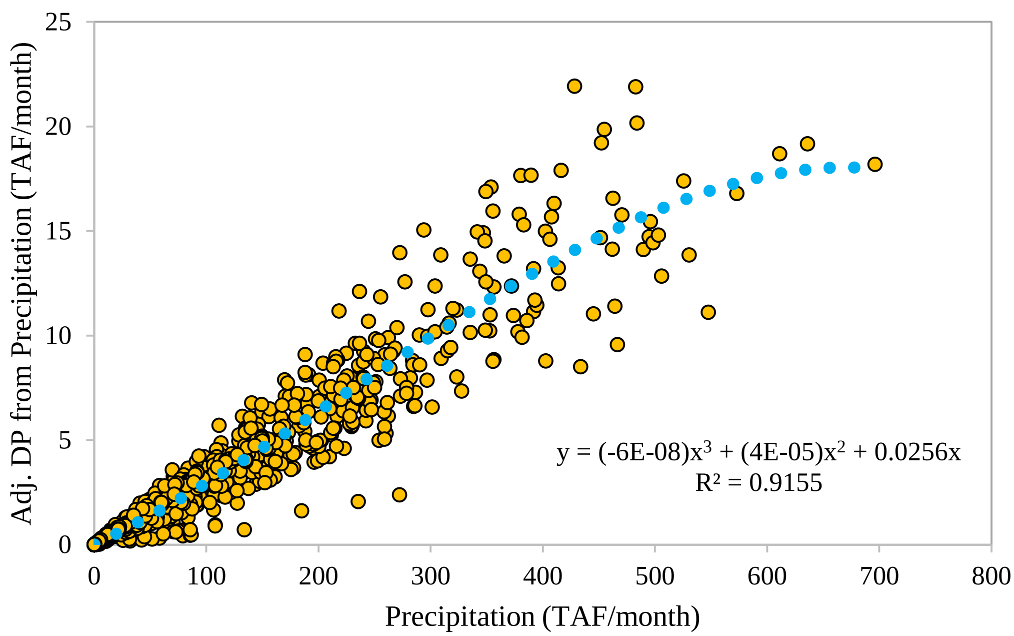


Figure 40. Deep percolation to groundwater from precipitation for sub-basin GW-05

Each groundwater basin has a local runoff (surface accretion and depletion) that conceptually represents interaction between stream flow and groundwater. Local runoff increases with precipitation, and decreases as deep percolation increases. Therefore, perturbed local runoff can be found as historical local runoff plus incremental change in precipitation minus incremental change in deep percolation (*Equation 10*). Precipitation and deep percolation changes are specific to each groundwater basin.

$$LR_{perturbed} = LR_{historical} + \Delta P - \Delta DP \qquad \textit{Equation 10}$$

where LR represents local runoff, ΔP and ΔDP are changes in precipitation and deep percolation, respectively.

Reservoir evaporation is controlled by temperature and precipitation. Net reservoir evaporation rate decreases with precipitation, and increases with temperature. Changes in net reservoir evaporation rates are calculated with linear regression based on incremental changes in precipitation and temperature, and added to historical net evaporation rates to calculate perturbed net evaporation rates. Monthly reservoir evaporation volume depends on reservoir surface area and is obtained from CALVIN operations (Zhu et al., 2005).

$$\Delta RE = a \cdot \Delta T + b \cdot \Delta P \qquad \textit{Equation 11}$$

$$RE_{perturbed} = RE_{historical} + \Delta RE \qquad \textit{Equation 12}$$

where ΔRE represents change in net reservoir evaporation, a and b are regression coefficients, ΔT and ΔP denote changes in temperature and precipitation, respectively, and RE represents net reservoir evaporation.

Table 20 compares annual average rim and groundwater inflows, and local runoff for historical and warm-dry climate cases. Under climate warming, total annual reduction in stream flow is about 8.6 MAF/year. Local runoff considerably decreases from 1675 to 542 TAF/y. Although local runoff is about 4.3% of historical total annual flow, reduction in local runoff reaches 67%. However, this warm-dry climate scenario decreases groundwater inflow by only 6% of historical flows. Overall, system inflows are reduced by about 10.1 MAF per year, a 26% overall reduction, excluding changes in reservoir evaporation, which also increase with climate warming.

Table 20. Historical and warm-dry hydrology comparison

Hydrology	Historical (TAF/year)	Warm-Dry (TAF/year)	Difference (TAF/year)	Change (%)
Rim Inflow	30,884	22,282	8,602	-28%
Groundwater Inflow (GW)	6,100	5,734	366	-6%
Local Runoff	1,675	542	1,133	-68%
Total	38,659	28,558	10,101	-26%

Overall monthly water quantity, including rim inflows, groundwater inflows, and local runoff, are shown in *Figure 41*. Climate warming would result in significant shifts in timing and magnitude of water quantity, especially in spring months, from March to July. Water quantity is less in this warm-dry climate than historical case, with an exception of January. The peak flows occur in winter rather than spring with climate warming, potentially causing floods in winter. The decrease in overall water quantity is higher in spring mostly by snowmelt recession. Serious water shortages are expected in spring months. Change in water quantity and timing also affect hydropower generation and environmental water deliveries. Less hydropower revenue is expected with the warm-dry climate. Minimum in-stream flow requirements may not be met under climate warming.

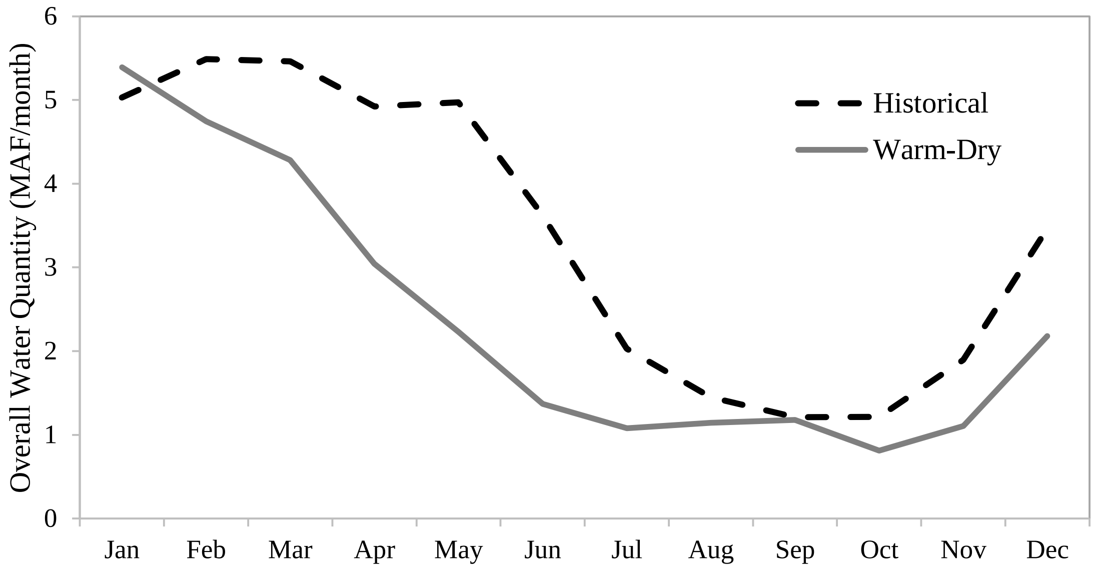


Figure 41. Average monthly overall water inflow quantity for warm-dry and historical climate cases

Results

Environment Flows and Shadow Prices

Environmental flows and wildlife refuge demands are represented as minimum in-stream flow requirements (MIF) and fixed-water deliveries in CALVIN. Environmental allocations are made before any other diversions. However, with climate warming, some requirements are not met due to water shortage. MIF requirements that are not met had to be reduced to allow mass balance to be feasible. *Table 21* shows MIF constraints under historical and warm-dry climates, and shadow prices (marginal value) of environmental water. Support rate represents how much of historical requirement can be met on average with warm-dry climate. The largest MIF requirement reduction occurs on Cosumnes River, a rare undammed river in California. MIF requirements to maintain Mono Lake levels were also reduced by 6.8 TAF per year, about 10% of the annual average requirement. Other MIF reductions are relatively small. Shadow prices indicate economic benefits to the state if environmental flow requirements were reduced by one unit of water. Shadow prices of environmental and wetland flows substantially increase with climate warming. Water scarcity and hydropower losses are mostly responsible for the significant increase in shadow prices. The state could benefit about $545 if MIF on Sacramento River at Rio Vista were reduced by one acre-foot with this warm-dry climate. Marginal value of Mokelumne River MIF downstream of Camanche Reservoir increases from $14 to $1,036 per acre-foot. Mono Basin, Trinity River, and Delta Outflow MIFs are much higher because of consumptive use environmental requirements, requiring water to leave the system. The average marginal value of minimum Delta outflow increases from $6 to $371 per acre-feet with climate warming. Shadow prices only show economic aspects of environmental water, which could be important in water trading. Ecologic and water quality losses are not economically valued.

Table 21. Annual average minimum in-stream flow requirements and average shadow prices

River	Annual Avg. MIF (TAF/y)		Climate Change	Shadow Price ($/AF)	
	Historical	**Warm-Dry**	**Reliability (%)**	**Historical**	**Warm-Dry**
Trinity R.	607	604	99.5%	48	538
Clear Cr.	122	121	99.7%	8	62
Sacramento R. below Keswick	2,646	2,646	100%	8	177
Sacramento R. below Ord Ferry	3,272	3,272	100%	3	28
Sacramento R. at Red Bluff	2,392	2,392	100%	2	10
Sacramento R. at Hood	3,540	3,540	100%	10	139
Sacramento R. at Rio Vista	941	941	100%	10	545
Stony Cr.	6	6	100%	11	48
Stony Cr. below Black Butte	16	16	100%	6	71
Feather R. at Thermalito Div.	547	547	100%	5	8
Feather R. at Yuba Confluence	866	866	100%	5	168
Feather R. at Confluence	1,222	1,222	100%	3	52
Yuba R. at Marysville	438	436	99.6%	3	7
Yuba R. at Smartville	317	316	99.7%	3	61
Bear R. at Wheatland	10	10	100%	6	31
Bear R. above Rollins	1	1	100%	0	0
Bear R. below Rollins	33	32	97.7%	6	10
Bear R. below Camp Far West	23	23	100%	9	75
American R. at Confluence	228	228	100%	0	130
American R. below Nimbus	1,088	1,088	100%	3	60
Cosumnes R.	361	247	68.3%	47	95
Mokelumne R.	157	154	98.5%	13	1,036
Calaveras R.	102	101	98.9%	20	269
Minimum Delta Outflow	4,994	4,994	100%	6	371
Stanislaus R. at Ripon	309	309	100%	8	118
Stanislaus R. at Confluence	309	309	100%	0	0
Tuolumne R. below La Grange	220	220	100%	7	128
Tuolumne R. below Don Pedro	6	6	100%	0	0
Fresno R.	2	2	98.4%	10	195
Merced R. (Upper)	170	167	98.6%	9	93
Merced R. (Lower)	82	80	96.9%	4	141
San Joaquin R. (Upper)	117	117	100%	10	212
San Joaquin R. at Vernalis	3,068	3,068	100%	37	208
Mono Basin	74	67	90.7%	716	1,503
Owens Lake	40	40	100%	562	1,049

CALVIN aggregates California's wildlife refuges at eight demand locations. Wildlife refuges are managed by U.S. Fish and Wildlife Service (USFWS) and California Department of Fish and Wildlife (CDFW), and target deliveries are mostly authorized by Central Valley Project Improvement Act (CVPIA). Flow targets vary by month and year, depending on year type (wet to critically dry) (Ferreira and Tanaka, 2002). These refuge areas are ecologically important because they provide food and resting places for migratory birds in the Pacific Flyway. They are also home to several endangered aquatic and wildlife species. The highest refuge water demands are at refuges in the west of San Joaquin River (*Table 22*). All refuge deliveries, except San Joaquin East (SJE), are met under warm-dry climate conditions. SJE refuge deliveries are reduced by small amount. Average marginal values of refuge deliveries roughly increase from north to south. However, with climate warming, price variations among refuges decrease. All refuge deliveries become more valuable and other economic water users want to buy them. The largest monetary increase occurs in Pixley National Wildlife Refuge (NWR) deliveries, whose average marginal value increases from $141 to $926 per acre-foot due to vast water shortages in Tulare Basin.

Table 22. Annual average wildlife refuge deliveries and average shadow prices

Wildlife Refuge	**Annual Avg. Refuge Demand (TAF/y)**		**Climate Change Reliability (%)**	**Shadow Price ($/AF)**	
	Historical	**Warm-Dry**		**Historical**	**Warm-Dry**
Sacramento West Refuges	102	102	100%	11	524
Gray Lodge	43	43	100%	7	393
Sutter	29	29	100%	6	368
San Joaquin East Refuges	29	29	99.7%	47	756
San Joaquin West Refuges	281	281	100%	39	485
Mendota Pool	29	29	100%	43	569
Kern	25	25	100%	68	648
Pixley	6	6	100%	141	926

Water Supply and Scarcity

Agricultural water users in the Central Valley experience significant water shortages with drier climate warming (*Figure 42*). Annual average water scarcities increase from 0.27 to 7.07 MAF/y in the Central Valley, an important agricultural production area. The highest agricultural water scarcity of 3 MAF/y is in the Tulare Basin (Region 4). Agricultural deliveries from groundwater fall in the Sacramento and San Joaquin Regions, mostly because many urban users depend solely on groundwater in these regions. Surface water's proportion decreases in the agricultural supply portfolio with drier climate warming. Most agricultural target demand is met under historical conditions, with the lowest delivery-target met rate of 80% in Ventura (*Table 23*). However, with drier climate warming, delivery-target satisfaction falls as low as 20%. Central Valley agricultural users see more shortages than southern California users. This is because agricultural demand in the southern California is mostly met by Colorado River diversions, assuming California's share of 4.4 MAF per year does not change with climate warming due to California's water right priorities.

Southern California urban water users have more water scarcity with a warm-dry climate, about 472 TAF/y (*Figure 43*). Antelope, Municipal Water District of Southern California (MWDSC), Mojave, and San Bernardino Valley urban users have the highest water shortages. Urban users in the Lower Sacramento, San Joaquin Valley, and Tulare Basin use more surface water and less groundwater with a warm-dry climate, while residents and industry in the southern California use less surface water and explore other supply options, such as wastewater reuse. Annual average wastewater reuse increase from 118 to 735 TAF/y with a warm-dry climate. Desalinated water is used only in San Luis Obispo-Santa Barbara urban area, and does not change with drier climate warming. Annual average desalinated water supply is 97 TAF/y. Overall, urban users have less shortage because they are willing to pay more for water and purchase from agricultural users.

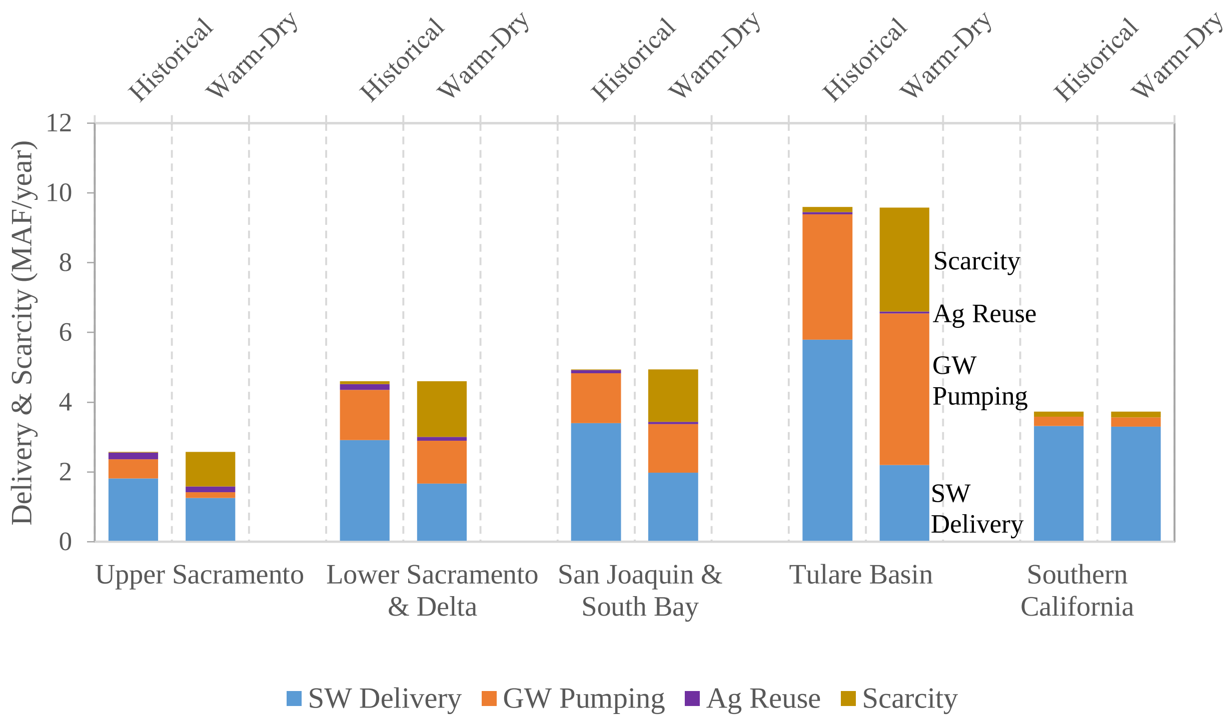


Figure 42. Agricultural water supply portfolio and water scarcity

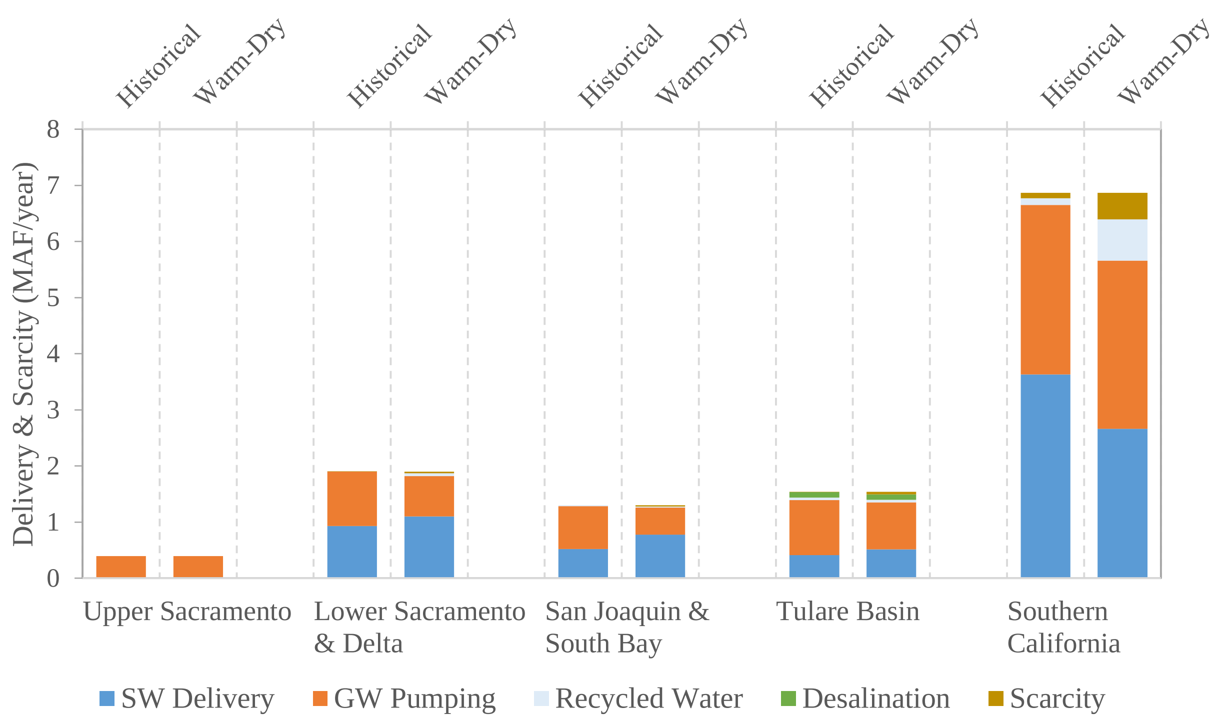


Figure 43. Urban water supply portfolio and scarcity

Table 23. Annual average agricultural target demand, scarcity, scarcity cost, and average willingness-to-pay (WTP)

	Demand Area	**Target (TAF/y)**	**Scarcity (TAF/y)**		**Scarcity Cost (K$/y)**		**Average WTP ($/AF)**	
			Hist.	**Warm-Dry**	**Hist.**	**Warm-Dry**	**Hist.**	**Warm-Dry**
	CVPM01	49	0	37	3	12,516	0.9	293
	CVPM02	410	18	119	346	20,341	9	267
	CVPM03A	962	0	167	0	24,964	0	178
	CVPM03B	293	0.1	51	52	8,022	9	206
	CVPM04	863	1	619	40	200,881	0.2	273
	CVPM05	1,305	26	310	451	45,765	4	241
	CVPM06	801	0	289	36	77,733	9	302
	CVPM07	442	0	357	0	93,755	0	235
	CVPM08	1,290	62	454	5,588	100,983	0	276
Delta	CVPM09	767	0	184	0	45,258	16	305
	CVPM10	843	0	231	9	60,916	0	458
	CVPM11	1,568	0	374	0	119,075	0.1	418
	CVPM12	875	18	321	1,117	116,074	12	598
	CVPM13	1,654	2	577	142	213,922	1	540
	CVPM14A	390	23	97	723	18,150	0	438
	CVPM14B	1,075	0	90	0	29,999	0	374
	CVPM15A	116	0	6	0	1,481	0	263
	CVPM15B	819	5	164	297	30,862	2	426
	CVPM16	1,911	0	523	0	155,586	27	534
	CVPM17	75	0	11	1	3,062	13	422
	CVPM18	2,454	118	1,565	11,640	744,718	32	307
	CVPM19A	752	0	113	1	36,805	0	428
	CVPM19B	302	0	15	0	3,430	0	117
	CVPM20	642	0	150	0	58,942	1	475
	CVPM21A	669	0	211	0	90,600	0	482
	CVPM21B	289	0	30	0	8,686	0	343
	CVPM21C	77	0	5	0	1,266	0	134
	Ventura	234	47	47	22,835	22,835	658	658
	Antelope Valley	79	0	0	0	0	549	549
	Coachella	229	0	0	0	0	0	0
	Palo Verde	440	0	0	0	0	0	0
	East & West MWD	292	0	15	0	6,495	138	360
	Imperial Valley	2,199	105	105	5,343	5,343	46	46
	San Diego	35	0	1	1	856	3	307
	Bard WD	98	0	0	0	0	0	0
	Statewide	25,298	426	7,235	48,627	2,359,320	45	325

Table 24. Annual average urban target demand, scarcity, scarcity cost, average willingness-to-pay (WTP)

Demand Area	**Target (TAF/y)**	**Scarcity (TAF/y)**		**Scarcity Cost (K$/y)**		**Average WTP ($/AF)**	
		Hist.	**Warm-Dry**	**Hist.**	**Warm-Dry**	**Hist.**	**Warm-Dry**
Redding	90	0	0	0	0	0	0
CVPM02	209	0	0	0	0	0	0
CVPM03	52	0	0	0	0	0	0
CVPM04	44	0	0	0	0	0	0
Yuba	91	0	3	0	1,459	0	154
Sacramento	677	0	14	0	8,415	0	209
Napa-Solano	176	1	5	1,181	8,473	143	357
CVPM08	83	0	2	0	1,584	0	324
Contra Costa	114	0	0	0	0	0	0
EBMUD	260	0	5	0	6,166	0	307
Stockton	118	0	0	0	0	0	0
CVPM05	94	0	0	0	0	0	0
CVPM06	117	0	0	0	0	0	0
CVPM09	170	0	0	0	0	0	0
Delta							
CVPM10	131	0	0	0	0	0	0
SFPUC	219	0	0	0	0	0	0
CVPM11	236	0	0	0	0	0	0
Santa Clara V.	715	0	18	0	20,130	0	607
CVPM12	177	0	0	0	0	0	0
CVPM13	224	0	6	0	4,259	0	377
CVPM14	36	0	0	0	0	0	0
CVPM15	103	0	0	0	0	0	0
Fresno	168	0	16	0	10,576	0	382
CVPM17	144	0	0	0	6	0	24
CVPM18	207	0	5	0	2,841	0	276
SB-SLO	202	6	6	12,343	12,343	1,387	1,387
CVPM19	58	0	0	0	0	0	0
CVPM20	137	0	0	0	0	0	0
CVPM21	60	0	0	0	0	0	0
Bakersfield	128	0	0	0	0	0	0
Ventura	153	20	20	20,874	20,874	832	832
Antelope Valley	350	30	57	22,186	49,228	813	1,049
Castaic Lake	159	0	11	117	13,760	41	1,296
Central MWD	3,280	0	206	0	254,571	0	877
Mojave	221	0	6	0	5,505	0	463
San Bernardino	547	42	88	30,871	77,740	525	723
Coachella	321	0	0	0	0	0	0
Blythe	16	0	0	6	6	13	13
E&W MWD	886	5	80	5,211	85,652	156	784
El Centro	70	0	0	0	0	0	0
San Diego	837	0	3	0	4,392	0	207
Statewide	12,081	105	552	92,790	587,978	95	260

Scarcity and Operating Costs

Water scarcity costs increase as the climate becomes warmer and drier, while operating costs, including surface and ground water pumping, water and wastewater (potable, non-potable, and desalination) treatment, decrease overall since less water is transferred across the State, and facilities are operated less with less water availability. Average annual statewide agricultural and urban scarcity costs increase from $141 million to $3 billion per year. Agricultural regions have dramatic increases in total scarcity costs from lost agricultural production (*Table 25*), although some agricultural loss is compensated by water sales to urban users. The estimated average agricultural scarcity cost in Tulare Basin rises from $12 million to $1.2 billion per year. Annual average cost of climate change to the Central Valley agricultural users is $2.3 billion per year. Total annual average scarcity and operating costs increase from $5 to $7.3 billion per year under warm-dry climate operations, excluding hydropower benefits.

Table 25. Regional and statewide annual average agricultural and urban water scarcity costs

Region	Scarcity Cost (M$/y)			
	Historical		Warm-Dry	
	Agricultural	Urban	Agricultural	Urban
Upper Sac. Valley	0.4	0	267	0
Lower Sac. Valley and Delta	6	1	363	26
San Joaquin and South Bay	1	0	510	24
Tulare Basin	13	12	1,184	36
Southern California	28	79	36	512
Statewide	49	93	2,359	599
	Historical		Warm-Dry	
Average Scarcity Cost (M$/y)	141		2,958	
Average Operating Cost (M$/y)	4,947		4,939	
Total	5,088		7,897	

Annual average statewide operating costs decrease by $10 million per year overall with this warm-dry climate, although wastewater recycling costs increase (*Figure 44*). Recycled water supplies have high initial costs. However, CALVIN only incorporates operating costs (capital and fixed costs are beyond the scope of CALVIN). Surface water diversion, treatment, and pumping costs, and groundwater pumping costs decrease with this climate change. Artificial groundwater recharge costs are slight in the cost portfolio in both cases, which are $13 and $21 million per year, respectively. CALVIN does not employ additional seawater desalination as a climate change adaptation due to its high costs.

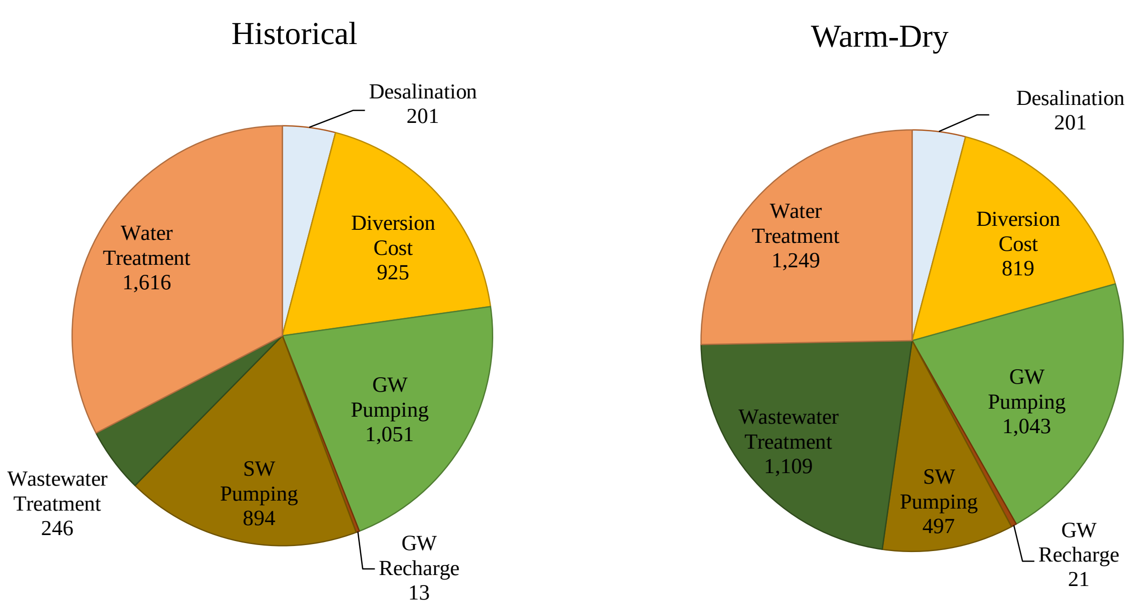


Figure 44. Statewide annual operating cost portfolio (M$/year)

Hydropower

Most CALVIN hydropower facilities are at lower foothill elevations and have large storage capacities. With climate warming, annual average hydropower generation and revenue decrease (*Table 26*). Statewide annual average hydropower generations are 15,857 and 10,285 GWh per year, with hydropower benefits of $862 and $564 million per year, for historical and warm-dry climate cases, respectively. Reduction in annual average hydropower production is about 35%, corresponding to approximately $300 million per year revenue loss. This 5,572 GWh per year reduction represents about 2.5% of California's total average energy generation. The biggest decrease in hydropower generation is in Tulare Basin. This is partly because Pine Flat reservoir in Tulare Basin is operated only for flood control and water supply, and hydropower is not a decision variable, so there is no penalty for lost hydropower revenue in Pine Flat operations. Climate change has fewer effects on the Upper Sacramento region, with Trinity, Whiskeytown, and Shasta power plants. Hydropower production in this region is about 22% less, with annual average revenue losses of $47 million per year. In southern California, generation reduction is about 1,640 GWh/y under warm-dry climate water operations.

Table 26. Regional and statewide hydropower revenues

Region	**Generation (GWh/year)**		**Difference (%)**	**Revenue (M$/year)**		**Difference (%)**
	Hist.	**Warm-Dry**		**Hist.**	**Warm-Dry**	
Upper Sacramento Valley	3,893	3,022	-22%	215	168	-22%
Lower Sacramento Valley and Bay Delta	4,844	3,234	-33%	267	182	-32%
San Joaquin Valley and South Bay	2,586	1,449	-44%	138	78	-44%
Tulare Basin	444	130	-71%	22	6	-71%
Southern California	4,090	2,450	-40%	219	130	-41%
Statewide	15,857	10,285	-35%	862	564	-35%

CALVIN reservoirs store water in the winter and spring, and release in the summer when it is most needed and profitable since the price of electricity is the highest in the summer in California due to air conditioning. Statewide monthly average power generation is high in the summer (also coinciding with water supply releases), peaking in July with a modelled generation of 2.2 TWh/m under historical climate conditions. Although the peak generation occurs in July, it reduces to 1.4 TWh/m with climate warming. As generation increases, discrepancies between historical and warm-dry climates increase. The highest generation reduction of 41% occurs in August, while the smallest reduction is in November.

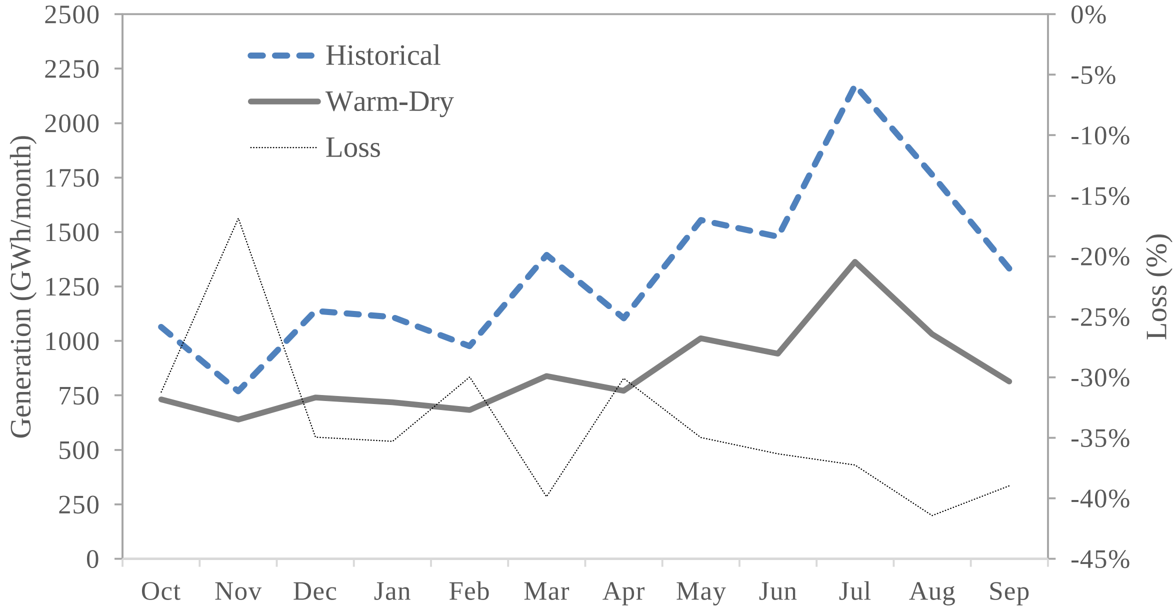


Figure 45. Statewide average monthly hydropower generation and reduction rates

Less water availability reduces hydropower generation with drier climate warming. *Figure 46* shows generation reliabilities under historical and warm-dry hydrologic conditions. Average monthly hydropower generation with a warm-dry climate is less at any probability level. Discrepancies increase as hydropower generation increases, except for peak generations. This warmer and drier climate reduces statewide average turbine capacity uses by 11%, and reductions increase from north to south (*Figure 47*). Only 31% of total statewide turbine capacity is used in warm-dry climate water operations. Southern California region has the highest capacity use rate, about 49%.

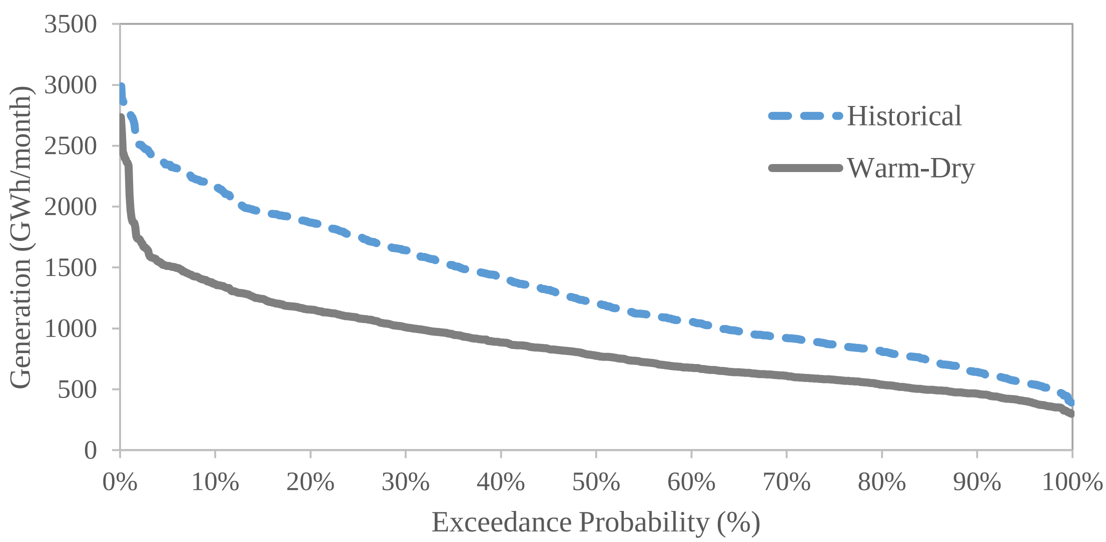


Figure 46. Statewide monthly hydropower generation-exceedance probability curve

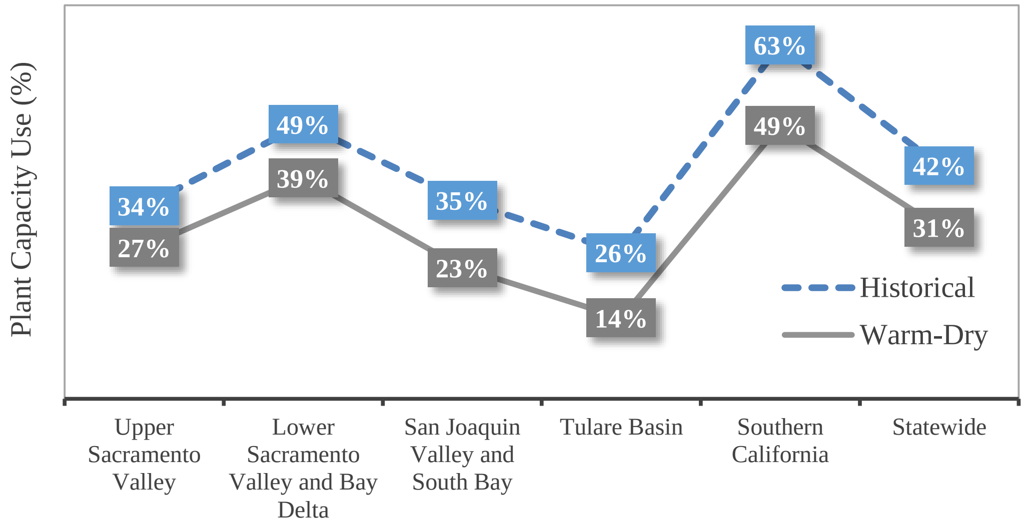


Figure 47. Regional average turbine capacity use with historical and warm-dry climates

Reservoir Operations

Reservoirs are important in water management, storing water when it is more abundant and releasing when the demand is high and water is scarce. With the timing shift in peak flows and earlier spring snowmelt under warmer conditions, peak storage occurs in April, rather than May (*Figure 48*). Peak storage is about 21 MAF with historical hydrology and 15 MAF with this warm-dry hydrology. In all months, average monthly surface water storage with perturbed hydrology is less than historical surface storages. Surface storage reliabilities also decrease with climate change, reducing system-wide hydropower capacities and increasing water scarcities. Exceedance probability of surface water storage with warm-dry climate is lower at any probability level.

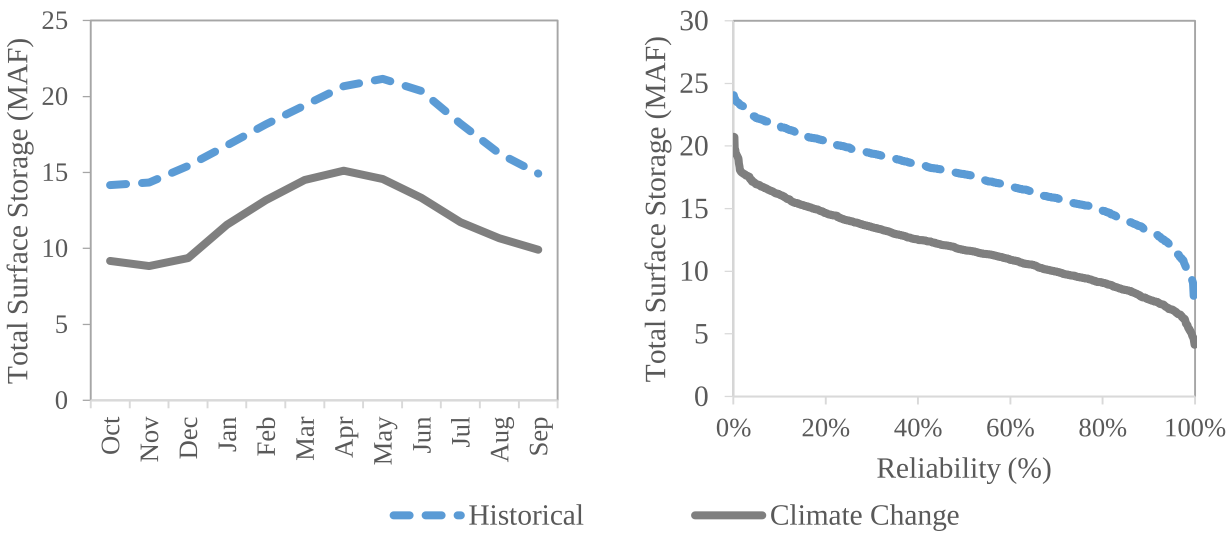


Figure 48. Average monthly pattern of surface storage and exceedance probabilities

Climate change effects are unevenly distributed in California. Climate warming has more severe impacts on San Joaquin, Tulare Basin, and southern California regions. Water availability roughly decreases from north to south in California under historical hydrology, so most large reservoirs are north of the Delta. With dry climate warming, average marginal values of expanding storage capacity increase in the north and decrease south of the Delta. *Table 27* show marginal values that the state would benefit if storage capacities were expanded by one acre-foot. With larger storage capacities, reservoirs can store more peak flows, reducing water scarcities in dry months. Black Butte Lake, Camanche Reservoir, Folsom Lake, and Pardee Reservoir would most benefit from capacity expansion. There is no or little benefit of expanded storages in the southern regions since capacities can rarely be filled with drier climate warming, despite the higher marginal value of water when it is stored.

Table 27. Marginal values of capacity expansion for selected surface reservoirs

Region	**Reservoir**	**Marginal Value of Expanding Storage Capacity ($/AF)**	
		Historical	**Warm-Dry**
1	Clair Engle Lake	3	61
1	Shasta Lake	4	55
1	Whiskeytown Lake	3	67
1	Black Butte Lake	5	115
2	Lake Oroville	5	40
2	New Bullard’s Bar Res.	6	64
2	Camp Far West Res.	3	75
2	Englebright Lake	4	77
2	Folsom Lake	4	107
2	Lake Berryessa	0.2	0*
2	Los Vaqueros Res.	3	58
2	Camanche Res.	2	106
2	Pardee Res.	1	186
Delta			
3	Eastman Lake	0.5	0*
3	New Don Pedro Res.	3	0.1*
3	Hensley Lake	2	0*
3	Hetch Hetchy Res.	2	4
3	Lake McClure	4	0*
3	Millerton Lake	10	0*
3	New Melones Res.	4	0.02*
3	San Luis Res.	0	0
4	Lake Isabella	5	0.8*
4	Pine Flat Res.	1	0*
4	Lake Success	14	0*
4	Lake Kaweah	12	0*
5	Grant Lake	119	2*
5	Pyramid Lake	2	0.2*
5	Lake Skinner	12	27
5	Silverwood Lake	0.9	1.5

* Incremental storage value decreases with warmer-drier climate

Conjunctive Use

Conjunctive use of surface and ground water supplies reduces total water scarcities and adds flexibility to water operations. CALVIN conjunctively operates surface and ground water resources of California. *Figure 49* shows total groundwater storage with filling and drawdown periods over 82 years with historical and climate change operations. Historical CALVIN operations suggest conjunctive use as an adaptive strategy. Groundwater storage decreases during drought years, such as 1976-1977, and 1987-1992 due to groundwater pumping, and increases during wet years with aquifer recharge (*Figure 50*). However, Groundwater is already highly stressed under historical operations. With increased temperatures and decreased precipitation under drier climate warming, less water is projected to deep percolate to groundwater. Reduced groundwater inflows reduce groundwater storage available for agricultural and urban water demands. Groundwater overdraft is limited to historical levels. Thus, groundwater storage in most years is slightly greater than historical storage levels. Less availability of groundwater increases agricultural and urban water shortages. Although less groundwater storage is available, agricultural supply percentages of groundwater increase with drier climate warming (*Table 28*). Groundwater inflows are less with climate change, but surface water inflows are even less. So, the percentage of groundwater deliveries increases with drier climate warming. Approximately 30% and 42% of total agricultural water is supplied from groundwater under historical and warm-dry climates, respectively. More than half urban water use is pumped from groundwater in both climate cases. Depending on the water year type, from 15% to 67% of historical water deliveries are from groundwater (*Figure 50*). With climate warming, percent deliveries from groundwater vary from 20% to 72%.

Table 28. Percent deliveries from groundwater

Delivery	Deliveries from Groundwater (% of Total)	
	Historical	**Warm-Dry**
Agricultural	29.7%	41.5%
Urban	52.7%	51.6%

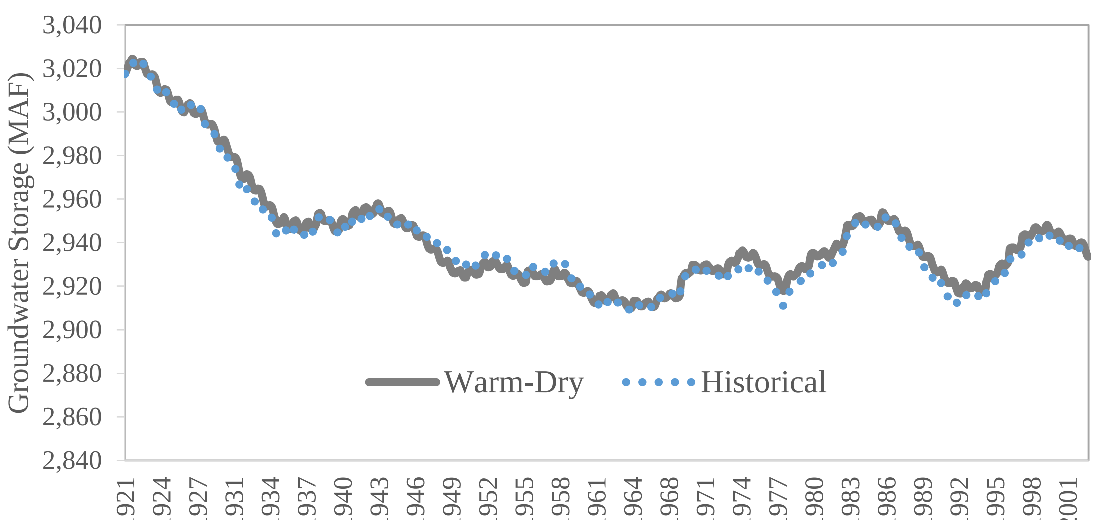


Figure 49. Statewide average groundwater storage time-series over the 82-year period

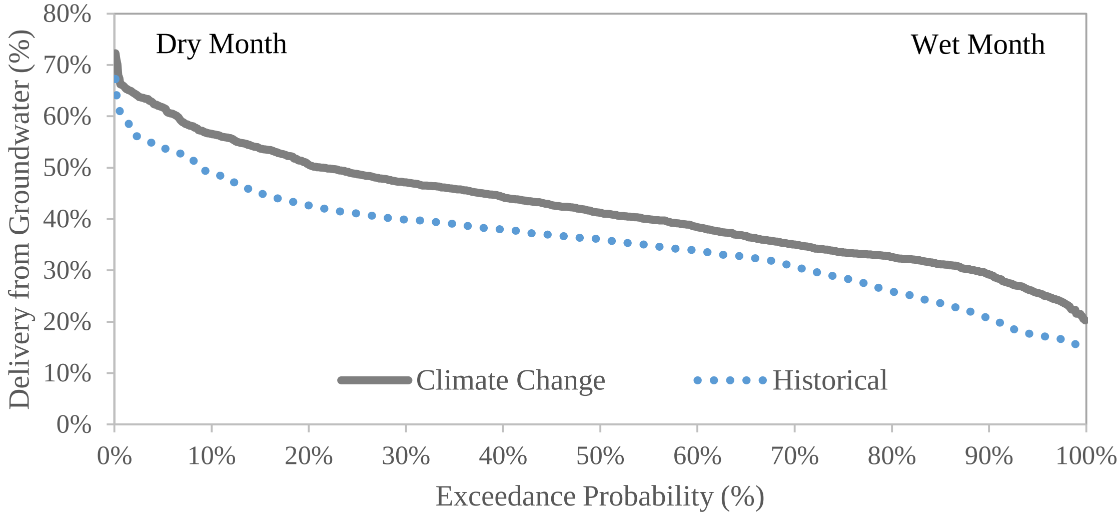


Figure 50. Percent deliveries from groundwater with historical and warm-dry climates

Water Transfers

California's inter-tied water system allows water managers to transfer water across the state within physical and environmental limits. In California, water availability is higher in the north, where demand is low, and low in the south, where demand is higher. Banks and Tracy pumping plants export water from the Delta south through the Delta-Mendota Canal (DMC) and California Aqueduct CAA). Colorado River Aqueduct and All American Canal transfer water from the Colorado River. The Los Angeles Aqueduct carries water to southern California from the eastern Sierra. Friant-Kern Canal system delivers water to Tulare Basin users from Millerton Lake. Trinity River's water is exported to the Central Valley through Clear Creek Tunnel. Hetch Hetchy Aqueduct delivers water from Sierra Nevada Mountains to San Francisco's urban users.

Table 29. Average water transfers from selected conveyances and capacity shadow prices

Conveyance	**Annual Transfer (TAF/y)**		**Difference**	**Shadow Price ($/AF)**	
	Historical	**Warm-Dry**	**(%)**	**Historical**	**Warm-Dry**
Trinity River Exports	641	455	-29%	0.29	0.08
Delta-Mendota Canal	2,478	2,617	6%	5.90	137.20
California Aqueduct[1]	4,108	3,543	-14%	0.02	0.08
Hetch Hetchy Aqueduct	336	231	-31%	12.26	0.21
Friant-Kern Canal	1,496	922	-38%	0.98	0
SWP Transfers to So. Cal.[2]	2,170	1,379	-36%	0	0
Los Angeles Aqueduct	368	189	-49%	6.86	1.36
Colorado River Aqueduct	1,301	1,301	0%	4.52	56.37
All American Canal	2,687	2,687	0%	0	0

[1] Transfers through California Aqueduct pumped from Banks PP.

[2] SWP Transfers to southern California over Tehachapi Mountains.

Climate warming has considerable effects on California's water transfers (*Table 29*). With climate warming, intra- and inter-regional water transfers are reduced. Annual average flow reduction in the Los

Angeles Aqueduct (LAA) is about 49% due to water scarcities and Mono Basin flow requirements. LAA runs almost dry from November through May with drier climate warming (*Figure 51*). Annual average water transfers from Friant-Kern Canal decreases from about 1.5 MAF/y to 0.9 MAF/y, contributing to water scarcities in Tulare Basin. Also, Friant-Kern's delivery pattern significantly changes with climate warming. More water is transferred in the winter, peaking in January, and spring and summer deliveries are significantly less. Of the selected water conveyances, only Delta-Mendota Canal transfers increase with climate warming from 2.5 MAF/y to 2.6 MAF/y. Hetch Hetchy water exports fall by 31% with climate change. However, San Francisco water users can compensate with other water supplies (Null and Lund, 2004, 2006). Transfers from the Colorado River do not change because California's share of 4.4 MAF/y remains the same. Shadow prices show marginal benefit of expanding conveyance capacities. DMC and Colorado River Aqueduct deliveries would most benefit from capacity expansion. There is more scarcity of water than scarcity of conveyance capacity.

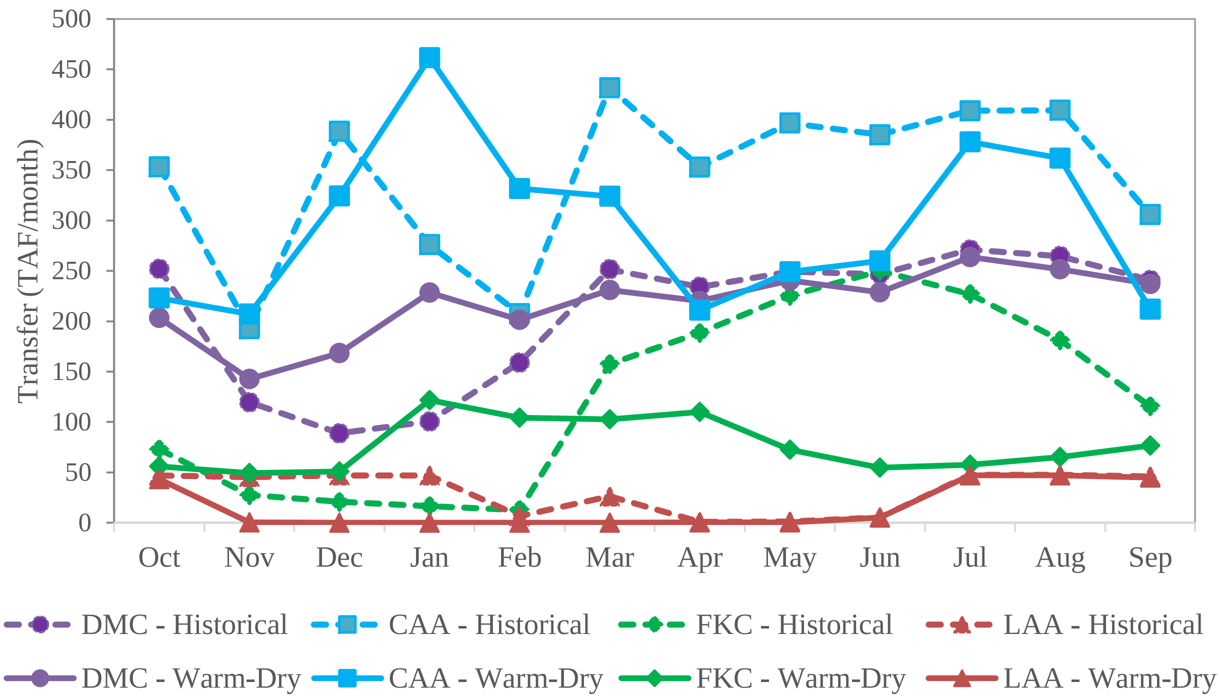


Figure 51. Monthly average water transfers from Delta-Mendota Canal, California Aqueduct, Friant-Kern Canal, and Los Angeles Aqueduct under historical and warm-dry conditions

Overall delivery reliability decreases as the climate becomes warmer and drier. Because of minimum in-stream flow requirements on Trinity River, limited amount of water can be transferred to the Sacramento River. *Figure 52* shows that exports from Trinity River in 16% of months are made at full capacity with the historical climate. However, the probability of reaching Trinity's transfer capacity reduces to 7% with climate warming, making Trinity exports less reliable. Delta exports are water transfers from DMC and CAA pumped from plants in south of the Delta. Although water exports increase in the DMC system with climate warming, total water transferred from the Delta decreases about 426 TAF per year. The reduction in Delta exports increases water scarcities in the south of the Delta.

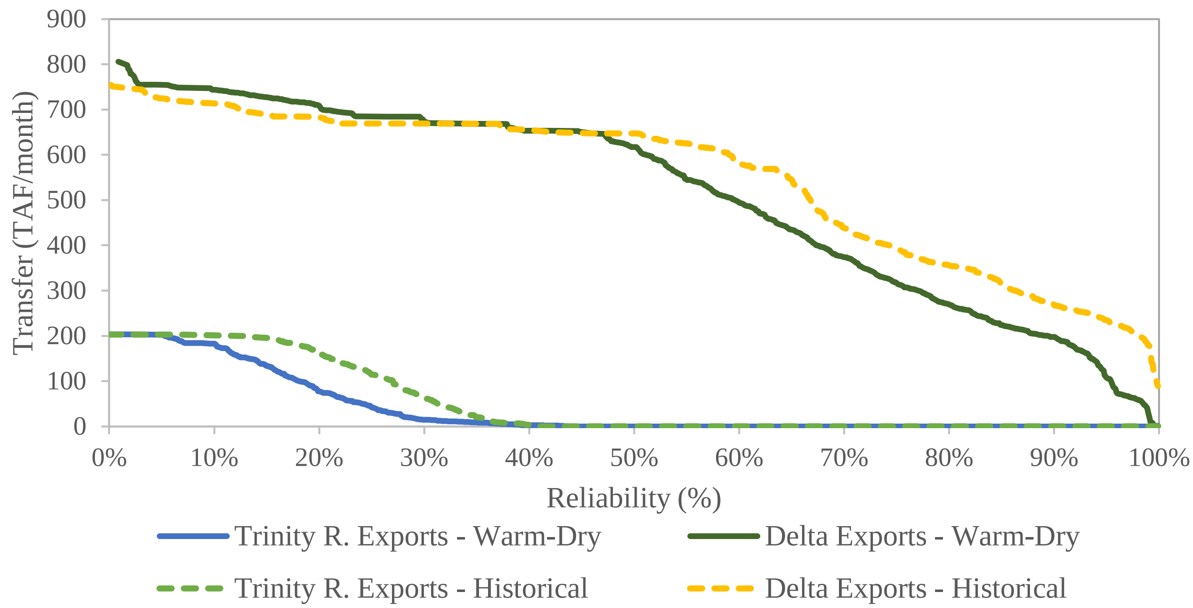


Figure 52. Delivery reliabilities of Trinity River and Delta exports over 82 years with a drier-warmer climate

Water Marketing

CALVIN assumes an ideal decentralized water market in California. Users can purchase and sell their water within physical and policy constraints and without substantial transaction costs. Water is always allocated to users who are willing to pay more (Ragatz, 2013). Urban users generally have higher willingness to pay for water than agricultural users (*Table 30*). Therefore, agricultural water scarcities are much greater than urban water scarcities. With climate warming, urban areas increase water market purchases. When water is scarce, agricultural users sell water to farmers growing more valuable crops and urban water users, and reducing actual financial costs to farmers. Environmental uses do not have an option to sell water. However, marginal values can indicate the market price of environmental water. Environmental water becomes more economically valuable with drier climate warming. Shadow prices in *Table 21* and *Table 22* present the modelled market value of environmental water. Environmental managers could use water trading as a management tool to improve infrastructure, increase habitat acreage, conduct more research, etc. to benefit the environment.

Table 30. Average and maximum willingness-to-pay of users for additional unit of water

Region	**Average WTP ($/AF)**				**Max WTP ($/AF)**			
	Historical		**Warm-Dry**		**Historical**		**Warm-Dry**	
	Agr.	**Urban**	**Agr.**	**Urban**	**Agr.**	**Urban**	**Agr.**	**Urban**
Upper Sac. Valley	4	0	244	0	18	0	295	0
Lower Sac. Valley and Delta	6	19	272	146	18	312	343	648
San Joaquin and South Bay	3	0	503	184	23	0	620	914
Tulare Basin	6	139	365	207	64	1,985	624	1,985
Southern CA	187	232	262	589	790	1,285	790	1,326
Statewide	41	78	329	225	790	1,985	790	1,985

Overall Summary

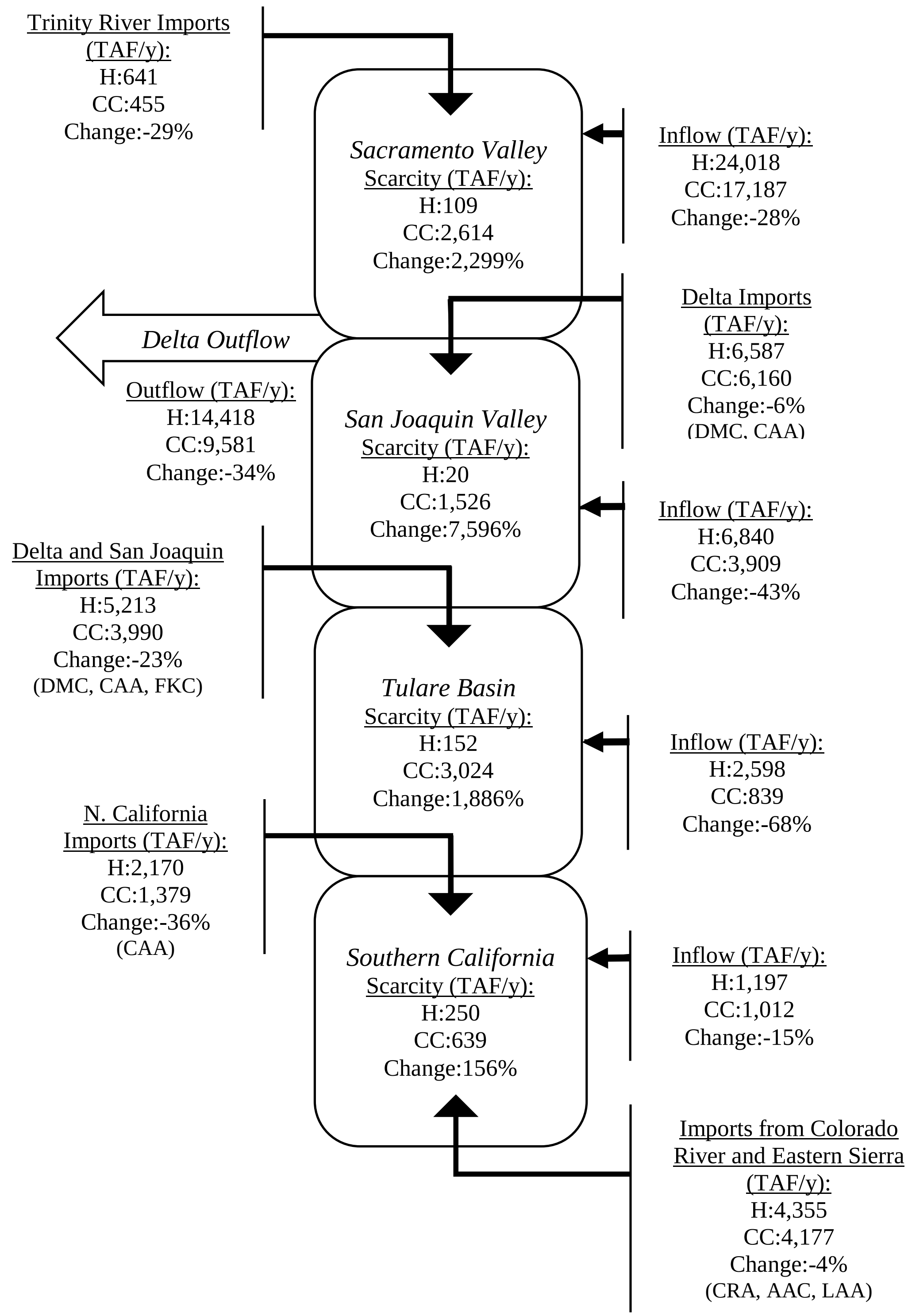
Annual average total surface and groundwater inflow decreases by 26% due to less precipitation and higher temperature with drier climate warming (*Table 31*). Shifts in timing and magnitude of water availability alter deliveries and increase water scarcities. This warm-dry climate has larger effects on agricultural users. Agricultural deliveries decrease by 27%, and thus scarcity and scarcity cost increase. Agricultural production lost due to warmer and drier climate costs about $2.3 billion per year. Historical wildlife refuge deliveries and in-stream flows are mostly supported under warmer and drier climate except for some areas. Hydropower revenue lost averages $298 million per year. Although operating costs slightly decrease with drier climate warming, dramatic increase in scarcity costs and decrease in hydropower revenue increase statewide net cost.

Climate change effects are not evenly distributed in California. Reduction in annual average inflow increases from north to south in the Central Valley. *Figure 53* shows regional annual average inflow, water scarcity, and major interregional water transfers. Drier climate warming reduces water transfers across the state. Northern California imports to southern California fall by 36%. Annual average water transfers to Tulare Basin through Delta-Mendota Canal, California Aqueduct, and Friant-Kern Canal decrease from 5.2 MAF to 4 MAF per year. Annual average Delta outflow decreases by 34% with warmer and drier climate due to less water availability.

Table 31. Statewide annual average summary

	Historical	Warm-Dry	Difference	Change (%)
Inflow/Delivery (TAF/y)				
Inflow	38,659	28,558	-10,101	-26%
Agricultural Delivery	24,872	18,063	-6,809	-27%
Urban Delivery	12,273	11,809	-464	-4%
Environmental Delivery*	544	544	0	0%
Scarcity (TAF/y)				
Agricultural	426	7,235	6,809	1,598%
Urban	105	569	464	442%
Scarcity Cost (M$/y)				
Agricultural	$49	$2,359	$2,310	4,752%
Urban	$93	$599	$506	545%
Total Economic Cost (M$/y)				
Scarcity Cost	$141	$2,958	$2,817	1,992%
Operating Cost	$4,947	$4,939	-$8	0%
Hydropower Revenue	$862	$564	-$298	-35%
Net Total	$4,226	$7,333	$3,107	74%

* Wildlife refuge delivery



Conveyances: *DMC* Delta-Mendota Canal, *CAA* California Aqueduct, *FKC* Friant-Kern Canal, *CRA* Colorado River Aqueduct, *AAC* All American Canal, and *LAA* Los Angeles Aqueduct.

Figure 53. Regional total annual average surface water inflows (rim + local runoff), water transfers, and scarcities with historical (H) and a warm-dry climate (CC)

Conclusions

Climate change effects on California's hydrology are presented. Then, California's water operations from hydro-economic optimization model, CALVIN, are shown for historical and climate change conditions. With a warm-dry climate, severe surface and groundwater shortages are expected. Overall average annual water delivery scarcities reach 10 MAF. Rim inflows, entering the system, reduce about 8.6 MAF per year on average, about 28% of annual average total rim inflow. Shifts in timing and magnitude in stream flows are projected. Spring snowmelt decreases, and winter flows increase with drier climate warming. Climate changes most threaten agricultural users in the Central Valley. Surface water and groundwater agricultural deliveries dramatically fall. Increased scarcity costs are somewhat reduced by water market trading to urban and agricultural users with high willingness to pay. Climate change has little impact on Central Valley urban water deliveries. Southern California urban users see shortages and seek new water supply alternatives. Wastewater reuse increases with climate change. Agricultural users in southern California, especially in the Imperial Valley, have unchanged water scarcity since they are reliably supplied from the Colorado River. Although climate warming restricts groundwater supplies with less aquifer recharge, conjunctive use is still essential to meet water demand and reduce scarcities. More groundwater could be available with higher overdraft rates in the Central Valley, but it would not be sustainable. Storage capacity expansion to capture more peak flows is more beneficial in the Sacramento Valley. Annual average net cost of climate change to the state with current conveyance and water management can be calculated as the difference in scarcity costs plus operating costs minus hydropower benefits under historical and warm-dry climate operations, which is $3.1 billion per year. Evaluation of climate change impacts provides system insights to water managers, decision and policy makers. Adaptations are needed to lessen climate change impacts. But overall, California's inter-tied water is adaptable to changing population, demand, and climate trends.

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Chapter 6. Conclusions

Hydro-economic models can provide engineering solutions to large-scale water management and policy problems. Models simulate and optimize various scenarios to help decision makers and stakeholders. CALVIN provides advantages, shortcomings, and insights for changes to California's inter-tied water supply system.

Data availability and quality are important for models. As better data become available, models should be revisited. Periodic updates preserve a model's representativeness and applicability to real problems. Chapter 2 presented major updates to CALVIN model. In this effort, all hydrology datasets are updated and extended from 1993 to 2003, covering the 82-year period. Calibration flows from previous CALVIN runs are eliminated, improving mass balance of the model, and accuracy and reliability of results. Network-flow representation of CALVIN is also updated. Agricultural, urban, and wildlife refuge demand representations are standardized. Water and wastewater treatments become more explicit in urban areas. Treatment costs are updated. Agricultural groundwater pumping costs are updated. Groundwater and agricultural return flows are added to wildlife refuge areas as a new supply source besides to surface water. Allowable pumping capacities of Banks and Tracy pumping plants are updated. The resolution of the upper Bear River watershed is improved in CALVIN's water network. Based on new land use and crop type estimates, the projected 2050 agricultural target demands and shortage penalties of all demand areas are updated. Hydropower representation in the model is improved. Energy prices are updated, and a new post-processor is created, adding new features, such as average spilled amount, turbine capacity use, water year type statistics, and reliability curves.

A better energy price representation for hydropower operations of hydro-economic models was presented in Chapter 3. Hydropower benefits are underestimated when constant monthly average prices are used. The proposed method reflects hourly price variations in long-term, large-scale model operations, and can be applied to hydropower plants with an after-bay. The method uses price-duration curves and estimates hourly-varying prices as a function of hours of generation at turbine capacity. The new representation resulted in higher hydropower revenue, while keeping agricultural and urban scarcity costs the same. Reservoir storage also increased with hourly-varying prices.

Using the updated CALVIN model, effects of ending the long-term groundwater overdraft in the Central Valley were studied. Several management cases, including base historical operations with total overdraft of 84 MAF, no overdraft, no overdraft and no reduction in the Delta outflow, no overdraft and no additional Delta exports, and no overdraft and no Delta exports. When overdraft is terminated, urban deliveries were unchanged, even though some areas depend solely on groundwater for drinking water supply. However, agricultural water scarcities significantly increased. Adaptations, such as higher Delta exports and groundwater banking decreased additional scarcities from ending overdraft. Prohibiting Delta exports resulted in catastrophic water scarcity and scarcity costs, especially south of the Delta. Water trading reduced scarcity costs when reduction in the Delta outflow is not allowed. Although scarcity costs increased when overdraft is ended, groundwater pumping costs decreased. Thus, operations without overdraft had the same cost as historical operations with overdraft. Agricultural scarcity cost in CALVIN represents production loss. However, there are indirect costs, such as job losses from less agricultural activity, which are not included in this study, which would increase when overdraft is ended. Unconstrained overdraft in the Central Valley minimized scarcity and operating costs, especially groundwater pumping costs.

Chapter 5 discussed drier climate warming effects on California's water resources. Annual average water scarcities reached 10 MAF. Total reduction on rim inflows was about 28%. Climate change causes shifts in timing and magnitude in stream flows, decreasing spring snowmelt and increasing winter flows. Given these effects, annual average agricultural and urban water scarcities increase from 531 TAF/y to 7,787 TAF/y. Agricultural users see most of the shortages. Drier climate warming also slightly reduces the reliability of environmental deliveries. Potable and non-potable reuses of wastewater increased in southern California urban areas. High initial cost of implementing wastewater recycling, waste disposal cost, and public acceptance of wastewater reuses are not included in this study. Hydropower generation falls with drier climate warming. Statewide average turbine capacity use with historical operations was 42%, while capacity use reduces to 31% with drier climate warming, resulting in annual average hydropower revenue loss of $298 million per year.

Limitations and Further Research

Developing statewide models, such as CALVIN, requires many simplifications; nonetheless, results of CALVIN study provide insights into California's water management and planning decisions. Deterministic linear programming has some disadvantages. For instance, CALVIN knows every hydrologic event in 82 years. Operations with perfect future knowledge are likely to underestimate water scarcity and scarcity costs. Environmental water is represented as minimum in-stream flow requirements and fixed wildlife refuge deliveries. CALVIN's hydropower representation is also fairly simple.

Almost all hydrology and network-flow components of CALVIN are revised and datasets are updated in this effort. However, data quality affects the virtue of results. So, keeping periodic updates in the future would be useful for maintaining and improving the model's functionality. Agricultural and environmental target demands are updated, but older urban demands are used. Updating the projected 2050 urban water demand with new population and water use estimates is recommended. Revisiting operating costs, especially treatment and surface water pumping would improve results. Using hourly-varying energy prices increase hydropower revenue. The inverse of the method presented in Chapter 3 can be applied to pumping plants with a forebay or after-bay. These pumping plants can store water in the forebay or after-bay, and operate when prices are the lowest. Price-duration curves with non-exceedance probabilities can be related to hours of operation at pumping capacity, and pumping costs can be minimized with hourly-varying prices. Several management scenarios are evaluated in Chapter 4 for ending overdraft in the Central Valley. However, more policy, management, and hydrology cases would be useful to study the effects of ending overdraft. For example, hypothetical no overdraft cases can be studied under climate change effects. Artificial recharge unexpectedly increases when Delta exports are reduced. The highest recharge is from Tule and Kaweah Rivers and Friant-Kern Canal into sub-basin 18. A detailed research on artificial recharge would provide more insights. Base case and no overdraft case operations have the same annual average net statewide costs, although total cost is expected to increase when overdraft is ended. The reduction in total operating cost due to less groundwater pumping is close the increase in scarcity costs. This could be because updated groundwater unit prices are overestimated, relative to surface water costs. A detailed study on estimating unit pumping costs would be useful. CALVIN operations are based on good future knowledge of hydrologic events. Exploring drier climate warming effects with limited foresight or stochastic approach could provide more certain results.

Appendix A

Table 32. Index and corresponding years for water year type extension

CALVIN Extension Period Year Types & Indices					Mapped Year to extend CALVIN Time-series					
	Sacramento Valley		San Joaquin Valley		Sacramento Valley			San Joaquin Valley		
Year	Index	Water Year*	Index	Water Year	Year	Index	Water Year	Year	Index	Water Year
1993	8.54	AN	4.20	W	1978	8.65	AN	1941	4.43	W
1994	5.02	C	2.05	C	1929	5.22	C	1929	2.00	C
1995	12.89	W	5.95	W	1982	12.76	W	1969	6.09	W
1996	10.26	W	4.12	W	1971	10.37	W	1974	3.90	W
1997	10.82	W	4.13	W	1970	10.40	W	1986	4.31	W
1998	13.31	W	5.65	W	1982	12.76	W	1967	5.25	W
1999	9.80	W	3.59	AN	1943	9.77	W	1979	3.67	AN
2000	8.94	AN	3.38	AN	1940	8.88	AN	1946	3.30	AN
2001	5.76	D	2.20	D	1926	5.75	D	1964	2.19	D
2002	6.35	D	2.34	D	1925	6.39	D	1981	2.44	D
2003	8.21	AN	2.81	BN	1928	8.27	AN	1950	2.85	BN

*Water Years: W wet, AN above normal, BN below normal, D dry, C critical

Table 33. Rim inflows, data source, and extension methods

Region+	River	CALVIN Link	Source	Extension Method*
1	Cottonwood Creek	Source_C2	Calsim - I10802	FR
1	Antelope, Mill, and Deer Creeks	Source_D75	Calsim - I11307+8+9	FR
1	Big Chico Creek	Source_D76b	Calsim - I11501	FR
1	Trinity River	Source_SR-CLE	Calsim - I1	FR
1	Clear Creek	Source_SR-WHI	Calsim - I3	FR
1	Sacramento River	Source_SR-SHA	Calsim - I4	FR
1	Stony Creek	Source_SR-BLB	Calsim - I40+I41+I42	FR
1	Paynes & Seven Miles Creeks	Source_C87	Calsim - I11001	FR
1	Thomas & Elder Creeks	Source_C86	Calsim - I11303+304	FR
1	Red Bank Creek	Source_D77	Calsim - I112	FR
1	Lewiston Lake Inflow	Source_D94	Calsim - I100	FR
1	Cow & Battle Creeks	Source_D74	Calsim - I10801+803	FR
2	Dry Creek	Source_C38	Reg-Calsim - I501	REG
2	Feather River	Source_C77	Calsim - I6	FR
2	Calaveras River	Source_SR-NHG	Calsim - I92	FR
2	Cosumnes River	Source_C37	Calsim - I501	FR
2	Kelly Ridge	Source_C23	Calsim - I200	FR
2	Cache Creek	Source_SR-CLK-INV	DWR Study	FR
2	Putah Creek	Source_SR-BER	DWR Study	FR
2	Bear River	Source_SR-RLL-CMB	Calsim - I291+I293	FR
2	Mokelumne River	Source_SR-PAR	CDEC – MKM	FR
2	North Fork Yuba River	Source_SR-BUL	Reg-Cdec – YRS	REG
2	Middle & South Forks Yuba River	Source_C27	Reg-CDEC - YRS	REG
2	North and Middle Forks American R.	Source_D17	Reg-CDEC – AMF	REG

2	South Fork American River	Source_SR-FOL	Reg-CDEC - AMF	REG
2	Deer Creek	Source_C28	Reg-USGS 11418500	REG
2	French Dry Creek	Source_C29	Reg-USGS 11418500	REG
2	Butte & Little Chico Creeks	Source_D43a	Calsim - I217	FR
3	Stanislaus River	Source_SR-NML	Calsim - I10	FR
3	San Joaquin River	Source_SR-MIL	Calsim - I18	FR
3	Merced River	Source_SR-MCR	Calsim - I20	FR
3	Fresno River	Source_SR-HID	Calsim - I52	FR
3	Chowchilla River	Source_SR-BUC	Calsim - I53	FR
3	Local Inflow to New Don Pedro Res.	Source_SR-DNP	Ferc Tuolumne	PR
3	Tuolumne River	Source_SR-HTH	Ferc Tuolumne	PR
3	Cherry & Eleanor Creeks	Source_SR-LL-ENR	Ferc Tuolumne	PR
3	Santa Clara Valley Inflow	Source_SR-SCAGG	SCV Inflow	WYT
4	Kaweah River	Source_SR-TRM	CDEC - Kwt	FR
4	Kings River	Source_SR-PNF	CDEC - KWF	FR
4	Tule River	Source_SR-SCC	Ext-CDEC – SCC	PR
4	Kern River	Source_SR-ISB	CDEC - KRI	PR
5	Owens River	Source_SR-CRW	CDEC - OWL	FR
5	Colorado River Aqueduct	Source_SR-CR3	Colorado Aqueduct	PB
5	White River	Source_C146	Whitewater	PB
5	New & Alamo River	Source_C148	New & Alamo River	PB
5	Mono Basin	Source_SR-GNT	Reg-CDEC - WWR	REG
5	Long Valley to Haiwee	Source_C116	Reg-CDEC - OWL	REG

[+] Regions: *1* upper Sacramento Valley, *2* lower Sacramento Valley and Bay Delta, *3* San Joaquin Valley and South Bay, *4* Tulare Basin, *5* Southern California

* Extension Methods: FR full replacement, REG regression analysis, PR partial replacement, WYT water year type extension, PB pattern based extension

Appendix B

Table 34. Old and updated non-consumptive use ratios for the Central Valley agricultural demands

Demand Area	Area	AW[a]	ETAW[b]	Consumption Ratio	Updated CALVIN Return Ratio	Old CALVIN Return Ratio
CVPM 01	19	54	38	0.70	0.30	0.47
CVPM 02	174	415	309	0.74	0.26	0.26
CVPM 03A & 03B	375	1,176	754	0.64	0.36	0.20
CVPM 04	264	888	543	0.61	0.39	0.14
CVPM 05	353	1,324	819	0.62	0.38	0.21
CVPM 06	254	789	524	0.66	0.34	0.10
CVPM 07	99	440	260	0.59	0.41	0.25
CVPM 08	308	778	541	0.69	0.31	0.12
CVPM 09	398	1,278	868	0.68	0.32	0.10
CVPM 10	499	1,521	1,059	0.70	0.30	0.20
CVPM 11	258	844	584	0.69	0.31	0.22
CVPM 12	304	886	637	0.72	0.28	0.18
CVPM 13	559	1,663	1,187	0.71	0.29	0.13
CVPM 14A	430	1,067	805	0.75	0.25	0.18
CVPM 14B	48	117	85	0.72	0.28	0.18
CVPM 15A	612	1,875	1,352	0.72	0.28	0.12
CVPM 15B	22	75	57	0.76	0.24	0.12
CVPM 16	138	387	284	0.73	0.27	0.28
CVPM 17	264	823	593	0.72	0.28	0.13
CVPM 18	732	2,443	1,734	0.71	0.29	0.18
CVPM 19A	106	413	311	0.75	0.25	0.03
CVPM 19B	160	644	475	0.74	0.26	0.03
CVPM 20	206	790	588	0.74	0.26	0.10
CVPM 21A	188	675	487	0.72	0.28	0.10
CVPM 21B	105	290	216	0.74	0.26	0.10
CVPM 21C	62	192	149	0.77	0.23	0.10

[a] Applied Water

[b] Evapotranspiration of Applied Water

Table 35. CALVIN updated unit pumping costs for the Central Valley demand units

Demand Area	Old Unit Pumping Cost ($/AF)	Updated Unit Pumping Cost ($/AF)
CVPM 01	23.49	39.41
CVPM 02	15.82	43.52
CVPM 03A	11.93	57.13
CVPM 03B	11.93	79.97
CVPM 04	9.33	39.18
CVPM 05	11.93	40.09
CVPM 06	11.93	42.27
CVPM 07	23.07	47.98
CVPM 08	31.89	74.71
CVPM 09	11.93	39.06
CVPM 10	9.07	62.94
CVPM 11	19.45	61.00
CVPM 12	24.89	59.40
CVPM 13	25.93	61.91
CVPM 14A	69.22	176.99
CVPM 14B	69.22	176.99
CVPM 15A	30.08	74.37
CVPM 15B	30.08	74.37
CVPM 16	19.07	62.37
CVPM 17	16.07	55.28
CVPM 18	24.48	76.09
CVPM 19A	44.85	136.20
CVPM 19B	44.85	136.20
CVPM 20	84.00	142.14
CVPM 21A	59.37	119.51
CVPM 21B	59.37	119.51
CVPM 21C	59.37	159.96

Table 36. Old and updated water and wastewater unit treatment costs for urban demand areas

Demand Area	Old Unit Cost ($/AF)		Updated Unit Cost ($/AF)					
					WWTP			
	WTP[a]	WWTP[b]	Dist.[c]	WTP	Potable	Non-Potable	Discharge	
							GW[d]	SW[e]
Redding	0	1480	45	30	1800	1480	50	50
CVPM 02	-	-	No WTP		No WWTP			
CVPM 03	-	-	No WTP		No WWTP			
CVPM 04	-	-	No WTP		No WWTP			
Yuba	74	1480	45	30	1800	1480	-	50
CVPM 05	-	-	No WTP		No WWTP			
CVPM 06	-	-	45	30	1800	1480	50	-
Sacramento	84.4-103.6[f]	518	45	30	1480	518	50	50
Napa-Solano	96.2-111.0[f]	1480	45	30	1800	1480	50	-
CVPM 09	-	-	No WTP		No WWTP			
CVPM 08	74	1480	45	30	1800	1480	50	-
Contra Costa	442.52	518	45	375.92	1480	518	-	-
EBMUD	51.8	518	45	30	1480	518	-	-
Stockton	37-59.2[f]	1480	45	30	1800	1480	50	50
SF PUC	185	1480	177.6	30	1800	1480	-	-
CVPM 11	74	1480	45	30	1800	1480	50	-
CVPM 10	-	-	No WTP		No WWTP			
Santa Clara	148-516.52[f]	518	140.6	375.92	1480	518	50	-
CVPM 12	74	1480	45	30	1800	1480	50	-
CVPM 13	-	1480	No WTP		1800	1480	50	-
Fresno	74	1480	45	30	1800	1480	50	50
CVPM 14	-	-	45	30	1800	1480	50	-
CVPM 17	-	1480	No WTP		1800	1480	50	-
CVPM 15	-	-	No WTP		No WWTP			
CVPM 18	74	1480	45	30	1800	1480	50	50
SB-SLO	479.52	1480	140.6	375.92	1800	1480	-	-
CVPM 20	74	1480	45	30	1800	1480	50	50
CVPM 19	-	-	No WTP		No WWTP			
CVPM 21	-	-	No WTP		No WWTP			
Bakersfield	0	1480	45	30	1800	1480	50	50
Ventura	516.52	518	140.6	375.92	1480	518	-	-
Antelope	516.52	518	140.6	375.92	1480	518	50	-
Castaic Lake	516.52	1480	140.6	375.92	1800	1480	-	-
Centr. MWD	516.12	1258	140.6	375.92	1480	1258	-	-
Mojave	-	518	45	375.92	1480	518	50	-
San Bernard.	59.2	518	45	375.92	1480	518	-	-
Coachella	550.56	518	140.6	409.96	1480	518	50	50
Blythe	275.28	1480	45	230.88	1800	1480	-	-
E & W MWD	516.12	1258	140.6	375.92	1480	1258	-	-
El Centro	275.28	1480	45	230.88	1800	1480	-	50
San Diego	1124.8	1258	140.6	460	1480	1258	-	-

[a] Water Treatment Plant, [b] Wastewater Treatment Plant, [c] Distribution cost, [d] Groundwater, [e] Surface Water, [f] varies for sources.

Table 37. Updated Minimum in-stream flow requirements and locations

Region*	River	CALVIN Link	Source	Annual Average (TAF/year)
1	Clear Creek	SR-WHI_D73	Calsim - C3_MIF	122
1	Sacramento River	D5_D73	Calsim - C5_MIF	2,646
1	Sacramento River	D77_D75	Calsim - C112_MIF	2,392
1	Sacramento River	D61_C301	Calsim - C129_MIF	3,272
1	Stony Creek	SR-BLB_C9	Calsim - C17301_MIF	16
1	Stony Creek	C9_C12	Calsim - C173A_MIF	6
1	Trinity River	D94_Sink D94	Calsim - C100_MIF	607
2	Bear River	C35_SR-RLL-CMB	Calsim - C294_MIF	1
2	Bear River	N201_N202	Calsim - C292_MIF	33
2	Bear River	SR-CFW_C33	Calsim - C286_MIF	23
2	Bear River	C33_C308	Calsim - C283_MIF	10
2	American River	D64_C8	Calsim - C303_MIF	228
2	American River	D9_D85	Calsim - C9_MIF	1,088
2	Calaveras River	C41_C42	Calsim - C508_VAMPDO	102
2	Feather River	C23_C25	Calsim - C200A_MIF	547
2	Feather River	C25_C31	Calsim - C203_MIF	866
2	Feather River	D42_D43	Calsim - C223_MIF	1,222
2	Cosumnes River	C37_C38	Calsim - C501_VAMPDO	361
2	Sacramento River	D503_D511	Calsim - C400_MIF	3,540
2	Sacramento River	D507_D509	Calsim - C405_MIF	941
2	Yuba River	SR-ENG_C28	SWRCB D-1644	317
2	Yuba River	C83_C31	SWRCB D-1644	438
3	San Joaquin River	D616_C42	Calsim - C639_VAMPDO	3,068
3	San Joaquin River	D609_D608	Calsim -C605A_VAMPDO	117
3	Fresno River	D624_C48	Calsim - C588_MIF	2
3	Merced River	D645_D646	Calsim - C561_MIF	170
3	Merced River	D649_D695	Calsim - C562_MIF	82
3	Stanislaus River	D672_D675	Calsim - C520_MIF	309
3	Stanislaus River	D675_D676	Calsim - C528_MIF	309
2	Mokelumne River	SR-CMN_C38	SWRCB D-1641	157
3	Tuolumne River	SR-DNP_D662	Calsim - C81VAMP	7
3	Tuolumne River	D662_D663	Calsim - C540_MIF	221
5	Mono Basin	SR-GNT_SR-ML	MONO BASIN	74

* Regions: *1* upper Sacramento Valley, *2* lower Sacramento Valley and Bay Delta, *3* San Joaquin Valley and South Bay, *4* Tulare Basin, *5* Southern California