Managing to End Groundwater Overdraft in California's Central Valley with Climate Change

By

IAN BUCK
B.S. (California Polytechnic State University, San Luis Obispo) 2010

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

Approved:

____
Jay R. Lund, Chair

____
Samuel Sandoval Solis

____
Jonathan Herman

Committee in Charge

2016

Abstract

Several water management cases with climate change are modeled to assess the effects of ending long-term groundwater overdraft in the Central Valley using the California Value Integrated Network (CALVIN) model, a hydro-economic optimization model of California's water system. CALVIN optimizes water management decision-making for the lowest net operating and water scarcity cost over an 82-year period of unimpaired inflows. Recent updates to the CALVIN model include, input hydrology, network representation, agricultural demand and shortage penalties, and hydropower improvements. Management cases evaluated include changes in outflow and inflow requirements for the Sacramento-San Joaquin Delta (Delta), and prohibiting long-term groundwater overdraft. Cases were analyzed over an 82-year modified historical record with a warmer, drier climate, and compared to historical hydrology results. A modelled warmer, drier climate reduces average inflows overall by about 28% and shifts stream flows towards winter and away from spring. Results show large water scarcities south of the Delta without Delta exports, especially for agriculture. Allowing for increased water transfers, Delta exports, conjunctive use, and water recycling and desalination reduces the water supply effects of groundwater overdraft and climate change.

Acknowledgements

I express my utmost appreciation to my adviser and committee chair, Professor Jay R. Lund, for his guidance and support, and commitment to my academic success and research. In addition, I thank all my committee members, Professor Samuel Sandoval-Solis and Professor Jonathan Herman, for their editorial reviews.

Special thanks to Mustafa Dogan for his invaluable assistance with CALVIN modelling and all my questions along the way. Also, special thanks to the students and staff at the UC Davis Center for Watershed Sciences. Thanks to my employer, MWH Americas, for their financial support and flexibility with my pursuits for higher education.

Lastly, I am so grateful to my family, for their constant encouragement and support.

Table of Contents

Figures

Tables

Acronyms and Abbreviations

AF	acre-feet
C2VSim	Central Valley Groundwater-Surface Water Simulation Model
CALVIN	California Value Integrated Network
CCWD	Contra Costa Water District
CDFW	California Department of Fish and Wildlife
CVP	Central Valley Project
CVPIA	Central Valley Project Improvement Act
Delta	Sacramento-San Joaquin Delta
DMC	Delta-Mendota Canal
DWR	California Department of Water Resources
EBMUD	East Bay Municipal Utility District
GSA	groundwater sustainability agency
GSP	groundwater sustainability plan
MAF	million acre-feet
MIF	minimum in-stream flow
MWD	Metropolitan Water District of Southern California
NMFS	U.S. Department of Commerce, National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
NOD	north-of-Delta
NWR	National Wildlife Refuge
Reclamation	U.S. Department of the Interior, Bureau of Reclamation
SFPUC	San Francisco Public Utility District
SOD	south-of-Delta
SWRCB	State Water Resources Control Board
SWAP	Statewide Agricultural Production Model
SWP	State Water Project
SWRCD	State Water Resources Control Board
TAF	thousand acre-feet
USACE	U.S. Army Corps of Engineers
USFWS	U.S. Department of the Interior, Fish and Wildlife Service
VAMP	Vernalis Adaptive Management Plan

Chapter 1. Introduction

Water management in California must balance scarce water supplies with municipal, industrial, agricultural and environmental objectives, so most of California's water management is multipurpose. California is the world's 8th largest economy with $2.3 trillion in goods and services in 2014. California is one of the world's most productive agricultural regions with its unique geography and Mediterranean climate, with more than 300 different crops and 80 commodities, such as almonds, artichokes, dates, figs, pistachios, and walnuts. On average, the water use proportion in California is 10 percent cities and communities, 40 percent agriculture, and 50 percent environment and other outflows, but varies depending on water year type. Total urban water use is approximately 9.5 million acre-feet (MAF) per year with roughly one-third going to residential landscaping, another third in homes and apartments. California agriculture irrigates more than 9 million acres on average with farms and ranches generating $46.6 billion in revenue in 2013. Agricultural water supply serves multiple purposes, such as flood-irrigated rice fields, which also serve as habitat to migratory birds on the Pacific Flyway. Applied water often is reused several times and recharges groundwater on the same farm or in the same region. Water reuse is prominent in California agriculture (DWR, 2015).

Water resources in California involves major floods and droughts (Lund et al., 2009). The Sierra Nevada Mountain range captures and stores winter precipitation due to its orographic effect and snowpack along the eastern edge of the state, and helps supply summer water demands. However, there is an imbalance in California's water supply and demand as more supply comes from northern California through winter precipitation and spring snow-melt; and larger demands in southern California during the dry summer. California's population is almost 40 million people, and could reach 50 million by 2060. Ninety percent of the state's population is served by nearly 400 urban water districts. Local aquifers and reservoirs supply most urban needs; however, one-fourth of urban water supply for Southern California and the San Francisco Bay Area comes directly from the Sacramento-San Joaquin Delta (Delta) via the State Water Project (SWP) (DWR, 2015). The Delta is the major thoroughfare for the California water system. A vulnerable Delta, population growth, and climate change pose challenges for California water management (Lund et al., 2009). In addition, water demands are exceeding supplies for urban, agricultural, and environmental water uses in California. Future statewide shortages are estimated to increase by 4.9 MAF per year by 2030. In dry years, surface water supplies for environmental and agricultural uses greatly diminish and requires heavy reliance on groundwater leading to overdraft (DWR, 2009).

Many activities can be explored to manage water supply demands. Such as operations, supply expansion, and policy tools, which is the intent of the California Value Integrated Network (CALVIN) model, a hydro-economic optimization model of California's water system (Lund et al., 2009). Data management, documentation, and reconciliation are key potential benefits from large-scale water resource models. Optimization models driven by economic objective functions can suggest a range of promising water management approaches such as water markets, conjunctive use, and expanding certain conveyance facilities (Draper et al., 2003).

Water from upstream reservoirs help control salinity in the Delta, which helps protect water supplies and threatened and endangered species, and maintains some river flows. In 1975, about 12% of California's freshwater fish species were extinct or highly vulnerable. Currently, about a quarter of the native freshwater fish species are listed as endangered or threatened. The current Biological Opinions (BOs) by the U.S. Department of Commerce, National Marine Fisheries Service (NMFS) and U.S. Department of the Interior, Fish and Wildlife Service (USFWS) have resulted in increased Delta pumping constraints and other operational restrictions. U.S. Department of the Interior, Bureau of Reclamation (Reclamation) has reinitiated ESA Section 7 consultation on the continued long-term operations of the Central Valley Project (CVP) and SWP with NMFS and USFWS, which is expected to be completed by 2018 (Reclamation, 2014b). The uncertainty of the consultation process, coupled with the recent drought, could lead to further restrictions on Delta exports, and water supply deliveries.

In the 2015 drought year, agricultural surface water deliveries were reduced by almost 8.7 million acre-feet (MAF), and groundwater pumping increased an estimated 6.2 MAF, a net loss of 2.5 MAF (Howitt et al., 2015). To make up the difference, farmers fallow land, deficit irrigate, and buy water from more fortunate growers. An estimated 564,000 acres were fallowed in 2015, resulting in a loss of $856 million in crop revenue (DWR, 2015). In addition, flow requirements for environmental purposes have been reduced by regulators struggling to balance the variety of demands. Since January 2014, 12 orders have been issued in the Delta alone for reducing flows required for environmental purposes, making over 400 thousand acre-feet (TAF) of water available to other uses. In addition to freshwater fish, controlling salinity in the Delta can ensure SWP and CVP south-of-Delta (SOD) deliveries for urban and agricultural users (DWR, 2015).

Conjunctive use of groundwater and surface water is a key to managing water sources. When surface water is abundant, reservoirs and streams can be used as the primary source for urban and agricultural uses, and also support groundwater recharge. During droughts, surface water is much scarcer, encouraging more groundwater pumping. In an average year, 30% of the state's water demand is supplied by groundwater, and 40% or more during dry years (DWR, 2003; Grabert and Narasimhan, 2006). Many cities in the Central Valley rely solely on groundwater (DWR, 2003). If balanced correctly, conjunctive use can efficiently manage water supply and reduce water scarcity. However, increasing economic development and water demand can overexploit groundwater and create conditions of groundwater overdraft; the amount of water withdrawn that exceeds basin recharged in the long term (DWR, 2003). Groundwater overdraft increases pumping costs, water scarcity costs, land subsidence, sea water intrusion; decreases water quality; and affects hydraulically connected rivers and streams (Konikow and Kendy, 2005). Numerous studies have assessed groundwater overdraft effects on California (Custodio, 2002; Dogan, 2015b; Gorelick and Zheng, 2015; Grabert and Narasimhan, 2006; Harou and Lund, 2008; Zektser et al., 2005)

On September 16, 2014, the Governor signed into law a three-bill legislative package: AB 1739 (Dickinson), SB 1168 (Pavley), and SB 1319 (Pavley), which collectively are known as the Sustainable Groundwater Management Act (SGMA). The legislation provides a framework for local authorities to improve groundwater management and significantly increases the roles and responsibilities of DWR and State Water Resources Control Board (SWRCB). SGMA provides local agencies the ability to "develop plans and implement strategies to sustainability manage groundwater resources," and "prioritizes basins with the greatest need." Local groundwater sustainability agencies (GSAs) must be formed for all basins by 2017, and can consist of joint power authorities, and/or other legal agreements. Groundwater sustainability plans (GSPs) must be completed by basins in critical overdraft by 2020 and all other high- and medium-priority basins by 2022 (except already adjudicated basins). After the adoption of GSPs, basins have 20 years to achieve sustainability (WEF, 2015). There will be complex issues of accounting and developing meaningful requirements towards sustainable groundwater management for regulatory agencies, and disputes over key definitions in the act, authorities, water rights, and data accounting.

Climate change modeling shows a shift of precipitation from snow to rain in the Sierra Nevada mountain range, leading to more winter runoff (Hancock et al., 2004). River runoff and water availability are anticipated to decrease for the western United States, a semi-arid to arid region. Much of California's water system is driven by snowmelt, and climate warming will have major impacts on hydropower and water supply (Dracup and Vicuna, 2005; Bates et al., 2008). Many studies have assessed the effects of climate change on the state's water resource (Cayan et al., 2008; Dogan, 2015b; 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)

Seasonal shifts from climate warming could change hydropower management, which typically manages for high, summer energy demands (Dogan, 2015b; Madani and Lund, 2009). Increased winter runoff would increase winter generation; however, it would reduce hydropower potential and increase energy scarcity during the summer (Phinney et al., 2005). Impacts from climate warming will require integrated operations for water supply, flood control, hydropower, and recreation to maximize statewide benefits.

This study explores effects of ending groundwater overdraft in the Central Valley with a warmer, drier climate, and using several water management cases related to uncertainty in future Delta operational constraints. The management cases are compared against two baselines; historical hydrology and a warm-dry climate hydrology. The first case assumes no long-term overdraft in the Central Valley groundwater basins with warm-dry climate conditions. The second case explores water operations without overdraft and reduction in Delta outflow with warm-dry climate conditions. The third case explores water operations without overdraft, restricts Delta exports from Tracy and Banks pumping plants to historical rates, and with warm-dry climate conditions. The last case explores water operations without overdraft, and no Delta exports (Banks and Tracy pumping plants are limited to 5% of average exports for CVPIA refuge deliveries), and with warm-dry climate conditions.

The objective of this thesis is to study California's complex water system with different climate and overdraft conditions with various Delta management cases to contribute insights for future management solutions.

The organization of this thesis is as follows:

- Chapter 2 describes the CALVIN model and presents recent updates to the model, including discussion of perturbed hydrology development for a warm-dry climate scenario.
- Chapter 3 discusses effects of ending the long-term groundwater overdraft on California's water supply system with warm-dry climate scenario, explores adaptations to mitigate water supply impacts; and presents concluding remarks and potential next steps for future research.

Chapter 2. CALVIN Model

Introduction

The California Value Integrated Network (CALVIN) is a system-wide, hydro-economic optimization model of California's water supply system which includes a broad range of water management options and economic objectives for a wide range of policy, operations, and planning problems. CALVIN operates surface and groundwater supplies, and allocates water using a monthly time series of hydrology over 82 years (1922-2003) to represent system variability, and 2050 levels of development for agricultural and urban water demands. The U.S. Army Corps of Engineers (USACE), Hydrologic Engineering Center (HEC) developed HEC-PRM, a network-flow optimization solver, which is utilized by CALVIN. The model minimizes net scarcity and operating costs statewide by managing water infrastructure and demands to maximize the economic value of water use, considering physical, environmental, and policy constraints. Such constraints include environmental flow requirements, facility capacities, and flood control operations (Draper et al., 2003; Lund et al., 2009).

California's water system is represented in CALVIN by 49 surface reservoirs, 38 groundwater reservoirs, 600+ conveyance links, 1250+ nodes; and 36 agricultural, 41 urban, and 8 wildlife refuge water demand areas, covering about 88% the state's irrigated acreage and 92% of the urban population (Draper et al., 2003). Figure 1 shows the five main regions represented in CALVIN: Upper Sacramento Valley, Lower Sacramento Valley and Bay Delta, San Joaquin Valley and South Bay, Tulare Basin, and Southern California (Lund et al., 2009). This chapter discusses the CALVIN model sequence and network representation; recent modeling updates, including historical hydrology, climate change hydrology, network representation, agricultural demand and shortage penalties, hydropower improvements; and limitations.

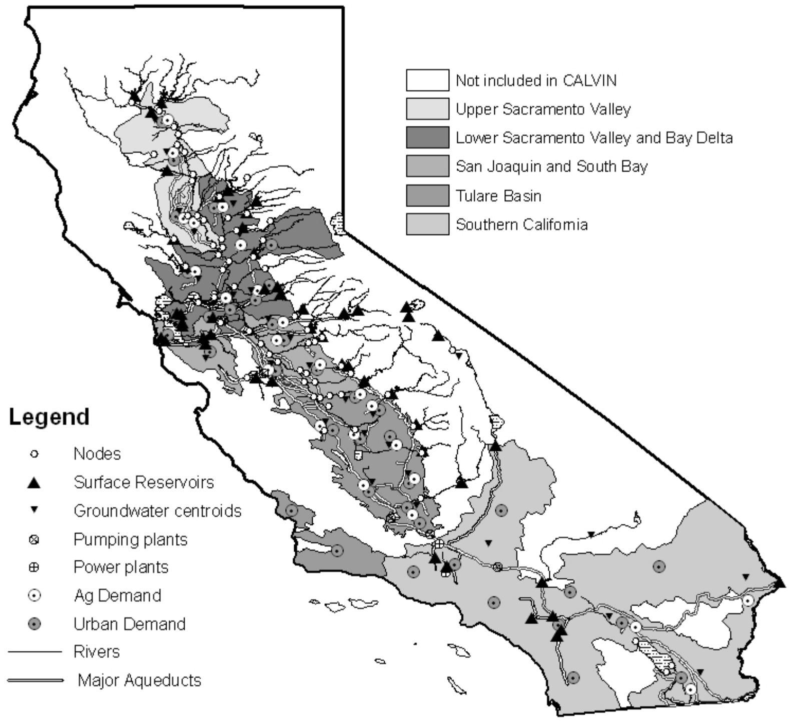


Figure 1. CALVIN Representation of California's Water System (Lund et al., 2009)

Model Sequence and Network Representation

As an economic optimization model, CALVIN's objective function (Equation 1) is to minimize system-wide operating and scarcity costs over the entire network and modeled time period. The generalized network flow optimization with gains and losses is the fundamental optimization framework for CALVIN.

The general mathematical form is:

Minimize,

$$\boldsymbol{Z = \sum_i \sum_j \sum_k c_{ijk} X_{ijk}} \qquad \text{Equation 1}$$

Subject to,

$$\boldsymbol{\sum_i \sum_k X_{jik} = \sum_i \sum_k a_{ijk} X_{ijk} + b_j} \quad \text{for all nodes j} \qquad \text{Equation 2}$$

$$\boldsymbol{X_{ikj} \le u_{ijk}} \qquad \text{for all arcs} \qquad \text{Equation 3}$$

$$\boldsymbol{X_{ijk} \ge l_{ijk}} \qquad \text{for all arcs} \qquad \text{Equation 4}$$

where Z = total cost of flows throughout the network; X_{ijk} = flow on the kth arc leaving node i toward node j; c_{ijk} = economic costs or loss of benefits (agricultural, urban, and operating); b_j = external inflows to node j; a_{ijk} = gains/losses on flows in arc ijk; u_{ijk} = upper bound on arc ijk; and l_{ijk} = lower bound on arc ijk.

The objective function seeks the minimum net cost of all network flows. Each flow arc is weighted by a unit cost, which include piece-wise convex economic loss functions to agricultural and urban regions, and operating costs such as water treatment and pumping. The agricultural and urban water values and target demands are central inputs to the model as the primary purpose is to operate and allocate water for the least cost system-wide. Figure 2 represents the economic value of water, which is the area under the economic water demand curve between the target and actual delivery, known as the scarcity cost. The difference between the target and actual delivery is water scarcity. Scarcity cost is the amount of water a user is willing to pay for, but did not receive because the demand target exceeded the available supply. Each demand area in CALVIN is assigned a penalty function for the water scarcity cost to users. The water target demands for agricultural and urban users are based on a 2050 level of development, considering agricultural land use, population growth, and urban per-capital use. Operating costs are simply defined as a unit cost or monthly varying, piece-wise linear cost curve by flow (Connell-Buck et al., 2011; Dogan, 2015b).

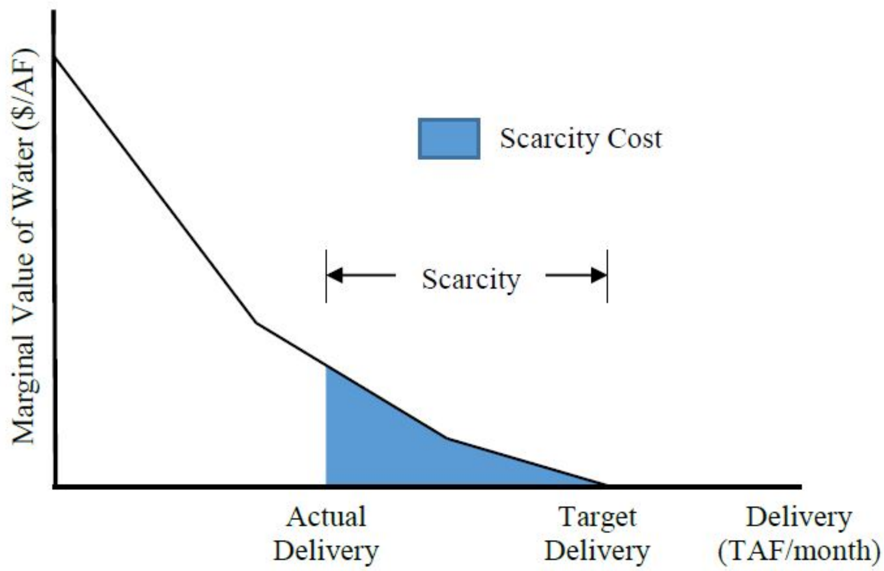


Figure 2. Economic Value of Water (Dogan, 2015b)

Each node represents a conservation of mass location in the flow network. Each node outflow leaving for node j is weighted by a loss or gain factor (e.g., a_{ijk}=1 represents no loss or gain) (Draper et al., 2003, Dogan, 2015b). The data flow schematic, including inputs and outputs for CALVIN is shown in Figure 3. Hydrology-related inputs include surface and groundwater hydrology, environmental flow constrains, and wildlife refuge deliveries. Environmental flows constraints for minimum in-stream flow requirements are represented as a lower bound in the model. Wildlife refuge deliveries are fixed, allocating water to environmental uses first. Another model input includes the physical facilities and capacities of the system, such as reservoirs, water conveyance (i.e., aqueducts, pumping and hydropower plants), and treatment (Dogan, 2015b).

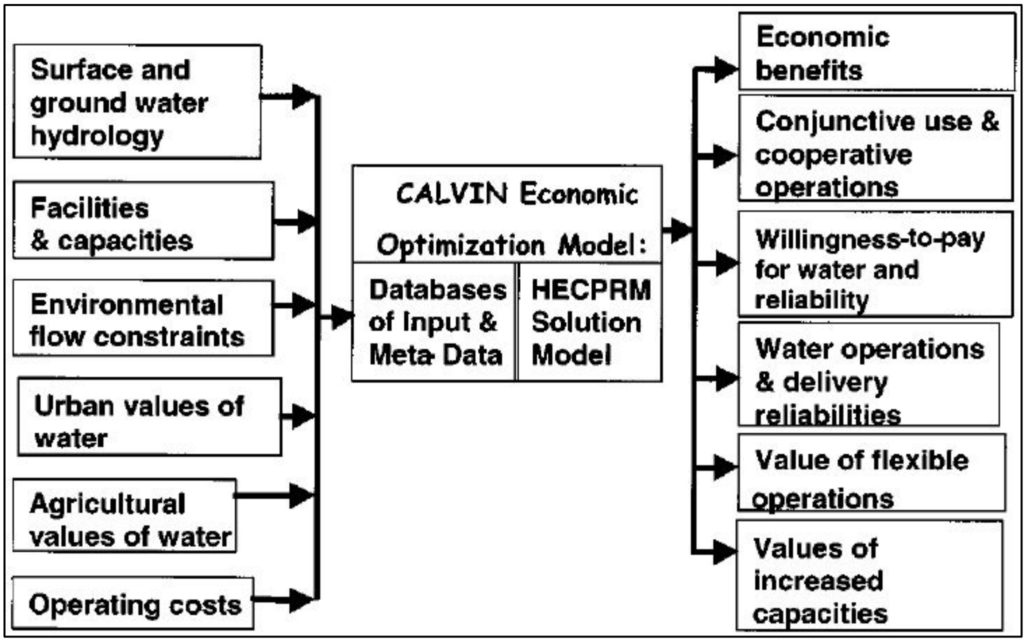


Figure 3. Data flow schematic for CALVIN (Draper et al., 2003)

CALVIN hydrologic outputs include water delivery, channel flow, surface and groundwater storage, and reservoir evaporation time-series. Water supply portfolios are shown for urban and agricultural users, and include deliveries from surface water, groundwater, desalination, water reuse, and water conservation. Economic outputs include marginal values of increased facility capacity, opportunity cost of water for urban and agricultural users, and shortage costs (Dogan, 2015b).

Recent Model Updates

Updating water resources models helps adapt to changing planning and policy conditions, and keep the model relevant and accurate. Modeling performed in this study used the recently updated CALVIN model, which has gone through many updates since its development in early 2000s (Bartolomeo, 2011; Chou, 2012; Connell, 2009; Dogan, 2015b; Nelson, 2014; Zikalala, 2013). Some key model updates include, adding more years of hydrologic data; improvements to network-flow representation, and agricultural and urban demand areas; minimum in-stream flow requirements (MIF), agricultural demand and shortage penalties using the updated Statewide Agricultural Production Model (SWAP), and updates to groundwater and regional flow estimates.

Historical Hydrology

Hydrologic components of CALVIN include surface water, groundwater, and local inflows. Return flows are calculated during system operations for agricultural, urban, and environmental users. Local inflows are mostly attributable to surface water accretions and depletions from interaction with local groundwater and precipitation. In CALVIN, surface water inflows are represented by rim flows, which are rivers and streams that cross the boundary of the physically modelled system. CALVIN also includes net evaporation rates for reservoir and losses from canals. CALVIN was recently updated with 10 more years of monthly surface and groundwater historical hydrology data, spanning 82 years from October 1921 through September 2003, and using surface hydrology from the CALSIM II model, California Data Exchange Center (CDEC), DWR; and groundwater hydrology from the Central Valley Groundwater-Surface Water Simulation Model (C2VSim) model (Chou, 2012; Dogan, 2015b; Draper, 2000a; Draper et al., 2004; Zikalala, 2013).

Climate Change Hydrology

Global warming due to climate change will significantly affect some hydrologic processes and ultimately affect water availability and quality. Most climate change studies show that California will have more winter runoff and less summer runoff through the next century (Zhu 2003). Several studies have used the CALVIN model with climate changed hydrologies. In 2003, a study used a perturbation process on CALVIN rim inflows, reservoir evaporation rates, local surface water accretions, and groundwater inflows 72-year historical monthly hydrological time-series. The perturbations were broken into six index river basins with 12 climate change scenarios (Zhu 2003). In 2009, a study assessed the effects of warmer, drier climate conditions and potential water management adaptations. The warm-dry hydrology was developed from downscaled effects of the NOAA GFDL CM2.1 (A2 emissions scenario) global climate model for a 30-year period centered at 2085. The model predicted earlier snowmelt, peak storage, increased water scarcity, and significant management adaptation for the warm-dry climate. Management adaptation strategies included increased conjunctive use and changes to surface water operations (Connell, 2009; Delworth et al., 2006).

The downscaled results from the A2 emissions scenario (warm-dry climate) are used in this study to perturb the 82 years of monthly CALVIN hydrology, a warm-dry climate scenario. Perturbation methods incorporate climate changes while preserving hydrologic variability (Dogan, 2015b; Medellín-Azuara et al., 2008). To update CALVIN with climate change hydrology, the CALVIN rim inflows, reservoir evaporation, groundwater inflows, and local accretions and depletions were updated using a perturbation process. The CALVIN rim inflows were updated using perturbation coefficients, incorporating a warm-dry climate (Equation 5). These coefficients were calculated for 18 index river basins, which cover northern Central Valley to southern California and were broken into two groups: wet and dry season (Connell, 2009; Dogan, 2015a; Zhu, 2003; Zhu et al., 2005).

$$\boldsymbol{I_{perturbed,i} = c_i * I_{historical,i}} \qquad \text{Equation 5}$$

where; $I_{perturbed}$ is the perturbed inflow, c is the perturbation coefficient, and $I_{historical}$ is the original river flow.

The CALVIN reservoirs and lakes net evaporation time-series were perturbed by adding the change in net reservoir evaporation rates (Equation 6). This is calculated using a regression analysis, dependent on the change in temperature and precipitation (Equation 7) (Dogan, 2015a; Zhu, 2003).

$$\boldsymbol{RE_{perturbed,i} = RE_{historical,i} + \Delta RE_i} \qquad \text{Equation 6}$$

$$\boldsymbol{\Delta RE_i = \alpha * \Delta T_i + b * \Delta P_i} \qquad \text{Equation 7}$$

where; a and b are regression coefficients for the change in net evaporation rate (ΔRE_i), and ΔT_i and ΔP_i are change in temperature and precipitation, respectively.

The CALVIN groundwater perturbation process is simplified by assuming the perturbed groundwater inflows depend only on the change in deep percolation, which is added to the historical groundwater inflows (Equation 8). The change in deep percolation is calculated using a regression analysis, dependent on the precipitation (Equation 9) (Dogan, 2015a; Zhu, 2003).

$$GW_{perturbed,i} = GW_{historical,i} + \Delta DP_i \qquad \text{Equation 8}$$

$$\Delta DP_i = (3c_i * P_i^2 + 2b_i * P_i + a) * (P_i * \Delta P_i) \qquad \text{Equation 9}$$

where; a, b, and c are regression coefficients for the change in deep percolation (ΔDP_i).

The CALVIN local accretion (LA) and depletion (LD) perturbation process is similar to the groundwater perturbation process, utilizing the change in precipitation and deep percolation (Equations 10 and 11) (Dogan, 2015a; Zhu, 2003).

If (ΔP_i - ΔDP_i) > 0, then

$$LA_{perturbed,i} = LA_{historical,i} + (\Delta P_i - \Delta DP_i) \qquad \text{Equation 10}$$

Else, (ΔP_i - ΔDP_i) < 0, then

$$LD_{perturbed,i} = LD_{historical,i} + (\Delta P_i - \Delta DP_i) \qquad \text{Equation 11}$$

Network Representation

The CALVIN network was recently updated to standardize the representation of agricultural and urban demand areas (Dogan, 2015b). Agricultural demands areas were updated with new naming convention and divided into two parts based on return flows either to underlying groundwater or downstream surface water (Figure 4). The returns flows from agricultural and urban uses to underlying groundwater basins were aggregated into one node for each basin. Groundwater pumping costs and consumptive use estimates were updated using the SWAP model for Central Valley agricultural demand areas (Dogan, 2015b; Howitt et al., 2012).

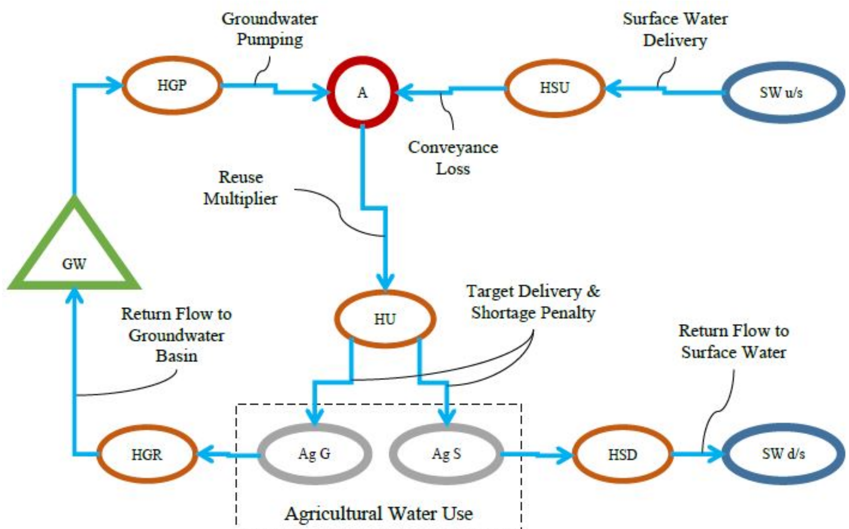


Figure 4. CALVIN Updated Agricultural Demand Area Representation (Dogan, 2015b)

Recent updates to the CALVIN urban demand areas include adding, removing, and modifying the network to include standardized representation and naming convention. The urban demand areas now have more distinct potable and non-potable use, and water and wastewater treatment. Groundwater pumping, conveyance, and water and wastewater treatment costs were updated. In addition water treatment and distribution costs were separated. Urban demand areas in CALVIN are sub-divided into three uses: exterior residential, interior residential, and industrial (Figure 5). Interior residential and industrial return flows are first treated and then reused or discharged into the system, whereas, exterior residential return flows are recharged directly into the underlying groundwater (Dogan, 2015b).

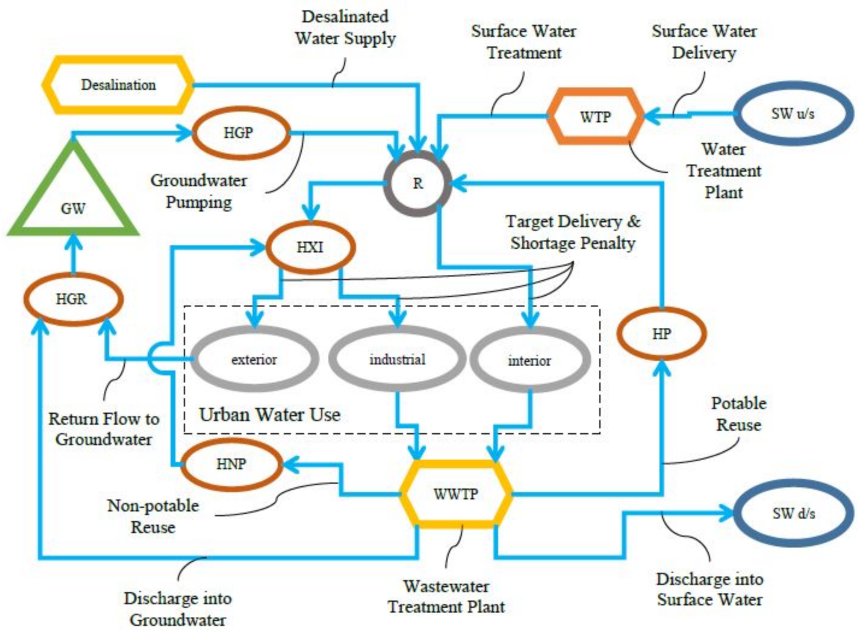


Figure 5. CALVIN Updated Urban Demand Area Representation (Dogan, 2015b)

Recent updates to the CALVIN wildlife refuge demand areas include separating water sources into surface water, groundwater and agricultural return flows (Figure 6). In addition, all supplies were aggregated into one node before delivering to the demand area. Groundwater pumping costs, seepage, and evaporation loss are the same as surrounding agricultural areas (Dogan, 2015b).

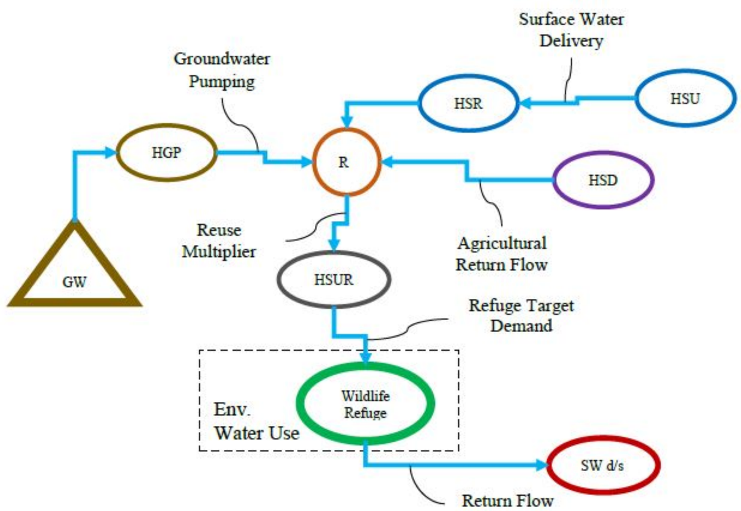


Figure 6. Calvin Updated Wildlife Refuge Demand Area Representation (Dogan, 2015b)

In addition to the recent updates for CALVIN agricultural, urban, and wildlife refuge demand areas, other CALVIN network components were updated. The upper Bear River watershed was recently updated to include more consolidated upstream diversion and reservoir representation, and new MIF requirements. The Delta-Mendota Canal (DMC)/California Aqueduct intertie and Vernalis Adaptive Management Plan (VAMP) were added to the CALVIN network. The required Delta outflow time-series, and other MIF requirements were updated, including locations along American River, Bear River, Calaveras River, Clear Creek, Feather River, Mokelumne River, Mono Basin, Sacramento River, San Joaquin River, Stony Creek, Tuolumne River, Trinity River, and Yuba River. All MIF time-series data were developed from the CALSIM II model except for Yuba and Mokelumne rivers, which were based on SWRCB flow requirement orders (Dogan, 2015b; Draper et al., 2004).

Agricultural Demand and Shortage Penalties

Recent updates were made to the CALVIN agricultural target demand time-series and shortage penalties. The 36 CALVIN agricultural demand areas are based on the 2012 SWAP model, which calculates the net cost of lost production (i.e., opportunity cost) for various water supply deliveries and is represented as a penalty function, adjusted for 2050 land use. This penalty function data establishes the agricultural target demand at the point where the marginal product of water has zero value (Dogan, 2015b; Draper, 2000b). Figure 7 compares the old and new annual average agricultural target demands by CALVIN region. In addition to the target demand and shortage penalties, five demand areas within the Central Valley were disaggregated into eleven demand areas, and new demand area for Bard Water District for improved representation (Dogan, 2015b).

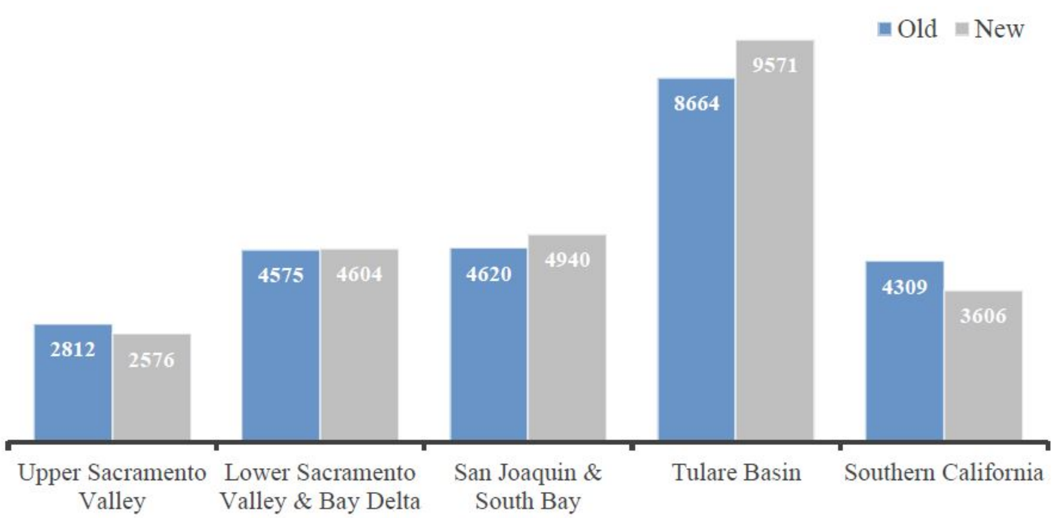


Figure 7. Old and New Annual Average Agricultural Target Demands (TAF/year) (Dogan, 2015b)

Hydropower Improvements

Hydropower generation is modeled within CALVIN using penalty curves. Methods for determining hydropower facility shortage penalties vary in CAVLIN depending on the facility type. Piece-wise linear penalty curves are used for hydropower facilities, assuming constant head and efficiencies for varying flow rates. Recent updates to CALVIN include a new hydropower post-processing tool, which retrieves storage and release time-series data, and provides power capacity, monthly generation, and revenue. In addition, the hydropower penalty curves were updated with non-linear, convex functions to incorporate peaking energy operations. Other recent CALVIN hydropower improvements include updated hydropower facilities penalty curves, new energy prices, and hydropower post-processor. The monthly average electricity prices were updated from 2008 to 2009 dollars (Figure 8), using the LongTermGen model, a hydropower post-processor for CALSIM II model (Bartolomeo, 2011; Dogan, 2015b).

Figure 8. Updated Average Monthly Electricity Prices ($/MWh, 2009 dollars) (Dogan, 2015b)

Limitations

As with most models, CALVIN has limitations. It is a large, system-wide model that requires continual upkeep and improvements to maintain functionality and applicability. The quality of the output depends on the quality of inputs. CALVIN model inputs include surface and groundwater hydrology, facilities and capacities, agricultural and urban water values, and operating costs, all of which are limited by the quality of the data sets. Environmental regulations, water quality requirements, and surface-groundwater interactions are simplified due to CALVIN's solver and data availability (Draper et al., 2003). This is particularly important for representing environmental and water quality flow regulations affecting Delta operations. Old and Middle River reverse flows, export/inflow ratios, carriage water, and several other Delta requirements must be represented more simply in terms of export pumping capacities and required Delta outflows, due to limitations of the generalized network flow solver.

CALVIN operates the system and allocates water using deterministic linear optimization with perfect foresight over the 82 years of hydrologic data, which has some shortcomings (Draper, 2001; Ilich, 2008). In addition, using piece-wise linear functions for non-linear functions losses some accuracy for temporal uncertainty in hydrology and water demands (Draper et al., 2003). CALVIN uses fixed groundwater inflows from C2VSim (Brush and Dogrul, 2012). In addition, CALVIN also uses fixed-unit pumping costs from SWAP (Howitt et al., 2012). CALVIN neglects recreation operations, only uses seasonal flood storage pools for its flood control operations, and simplifies Delta operations (Tanaka et al., 2006).

Although this study looks at future water demand and hydrologic impacts from a warm-dry climate, there is still uncertainty related to both of these projections. CALVIN has some limitations, but it provides useful results for managing California water as it can run various management cases and provide insights into state and regional water policy, planning, and operations. The recent updates to CALVIN will improve its representations and accuracy. Extending the hydrology data, updating to a 2050 level of development, and refined demand areas all improve quality of results (Dogan, 2015b).

Chapter 3. Groundwater Overdraft Management in the Central Valley with Climate Change

Introduction

Groundwater overdraft is when groundwater pumping exceeds recharge over an extended period of time and is often the result of unsustainable management. Sustainable groundwater management is important because groundwater is often cheaper, more easily accessible, and typically better water quality compared to surface water. On average, groundwater is 30% of California's water supply, and can be more than 40% in some regions during dry years when water users cannot meet their demands with surface water (DWR, 2003; Chou, 2012; Dogan, 2015b; Knapp and Vaux, 1982). Unfortunately, few statewide regulations for groundwater exist in California and accounting is inaccurate or incomplete. SGMA increases the roles and responsibilities of DWR, SWRCB, and local authorities to improve groundwater management. Overdraft is estimated to average one to two MAF per year, leading to increased pumping costs, land subsidence, decreases in water quality; and depletions in hydraulically connected streams and wetlands (DWR, 2003; WEF, 2015; Harou and Lund, 2008; Konikow and Kendy, 2005). The San Joaquin Valley and Tulare Basin have severe land subsidence due to groundwater overdraft, and eastside California rivers are impacted so much by overdraft that streamflows are inadequate for salmon migration during the dry season.

Pumping less groundwater is an obvious solution; however, recent droughts and reductions in surface water deliveries have led to consistent aquifer over-pumping. Recent studies have shown that short periods of over pumping are economical beneficial; however, in the long-term, overdraft is not sustainable. These studies also showed that increased canal capacities, pumping, and groundwater recharge lead to improved conjunctive use and reduced water scarcity costs without overdraft (Harou and Lund, 2008; Zektser et al., 2005). Specifically, increased Delta exports accompanied with artificial recharge are principal management solutions to ending Central Valley overdraft; however, increased Delta water quality and pumping restrictions constrain this solution (Chou, 2012). This chapter studies groundwater overdraft in California's Central Valley with a warm-dry climate scenario. Various management cases are modelled in CALVIN to examine solutions for ending long-term groundwater overdraft in the Central Valley and potential impacts.

Study Area

California is broken into five regions in CALVIN: Upper Sacramento Valley, Lower Sacramento Valley and Bay-Delta, San Joaquin and South Bay, Tulare Basin, and Southern California (Figure 9). The Central Valley is encompassed by all of the CALVIN regions except Southern California. It is bounded by Tehachapi Mountains in the south, Cascade Range in the north, Sierra Nevada Mountains to the east, and Coastal Range to the west (Dogan, 2015b; Faunt, 2009; Vasconcelos, 1987). California has an arid to semi-arid Mediterranean climate with hot and dry summers, cool and damp winters, and most precipitation in the winter and spring months (Faunt, 2009).

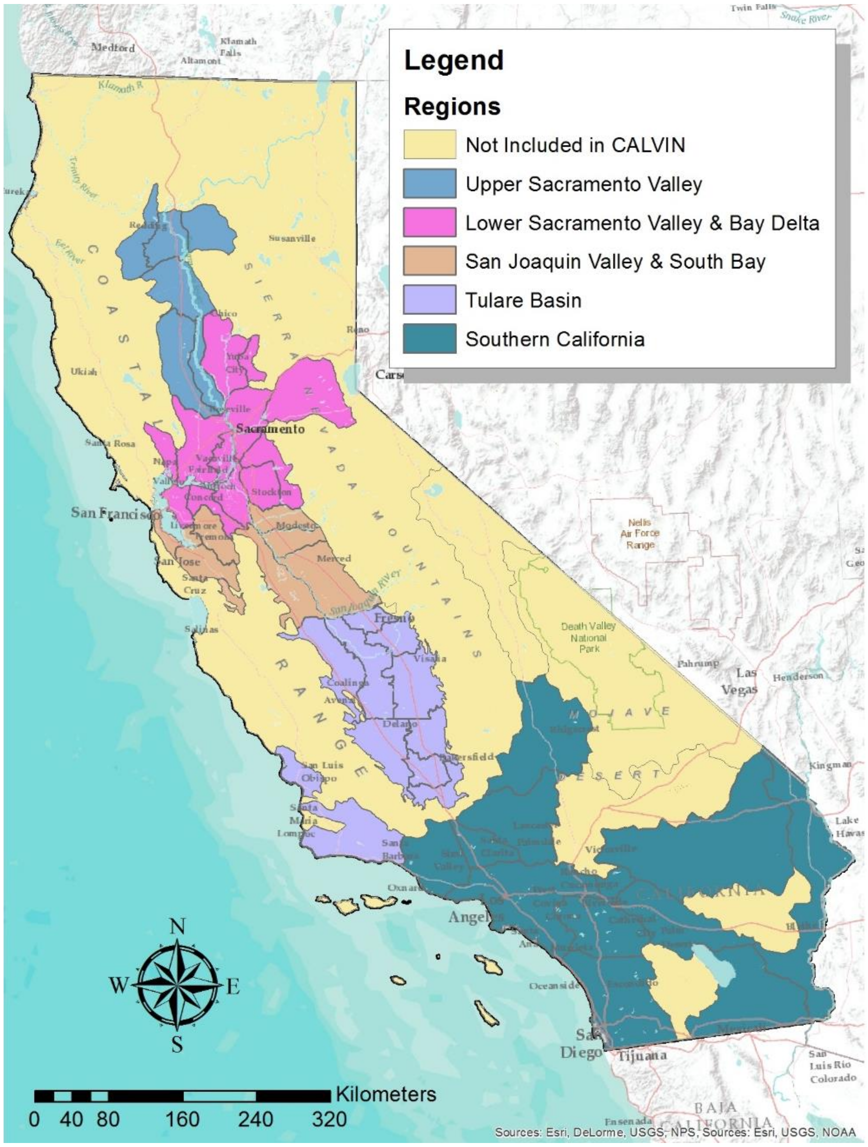


Figure 9. Agricultural and Urban Regions Represented in CALVIN (Dogan, 2015b)

The CVP and SWP are large, multi-purpose projects that deliver water throughout the state in addition to providing hydropower, flood control, and recreation (Dogan, 2015b; Hanak et al., 2011; Lefkoff and Kendall, 1996). The CVP is operated by Reclamation and serves more than 250 long-term water contractors, consisting of 20 reservoirs, 11 power plants, and 500 miles of major canals and aqueducts, and managing 9 MAF of water. On average, the CVP supplies 7 MAF annually for agricultural, urban, and environmental uses (Reclamation 2016). The SWP supplies 4.2 MAF per year with 2.5 MAF going to southern California on average (Reclamation 2014a).

Compaction of aquifer sediments from groundwater overdraft has been one of the primary causes of land subsidence in the Central Valley. Land subsidence began to occur as a result of increased groundwater pumping for agriculture in the mid-1920s (Ireland, 1986). By the mid-1970s, the maximum land subsidence exceeded 28 feet with the most seriously affected location in the western and southern areas of the valley (Poland et al., 1975). Figure 10 shows the land subsidence in the San Joaquin River and Tulare Lake hydrologic regions from 1926 to 1970.

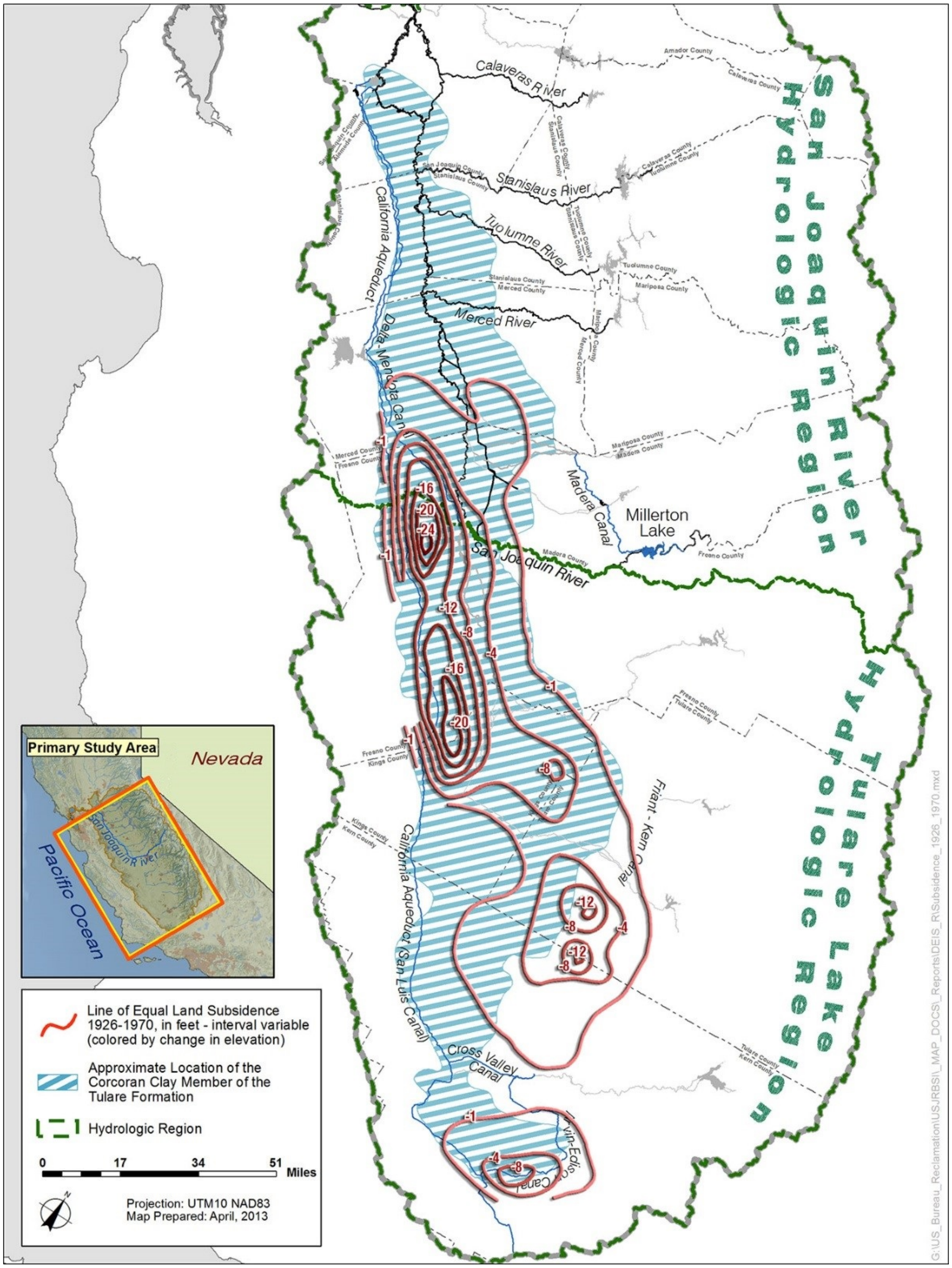


Figure 10. Land Subsidence in the San Joaquin River and Tulare Lake Hydrologic Regions from 1926 to 1970 (Reclamation, 2014b; Williamson et al., 1989)

Ending groundwater overdraft was one of the primary objectives for the CVP and SWP during the 1930s; however, economic growth and increased water demands have led to consistent overdraft (DWR, 2003; Dogan, 2015b). Figure 11 shows cumulative change in Central Valley groundwater storage from 1961 through 2003 (Faunt, 2009).

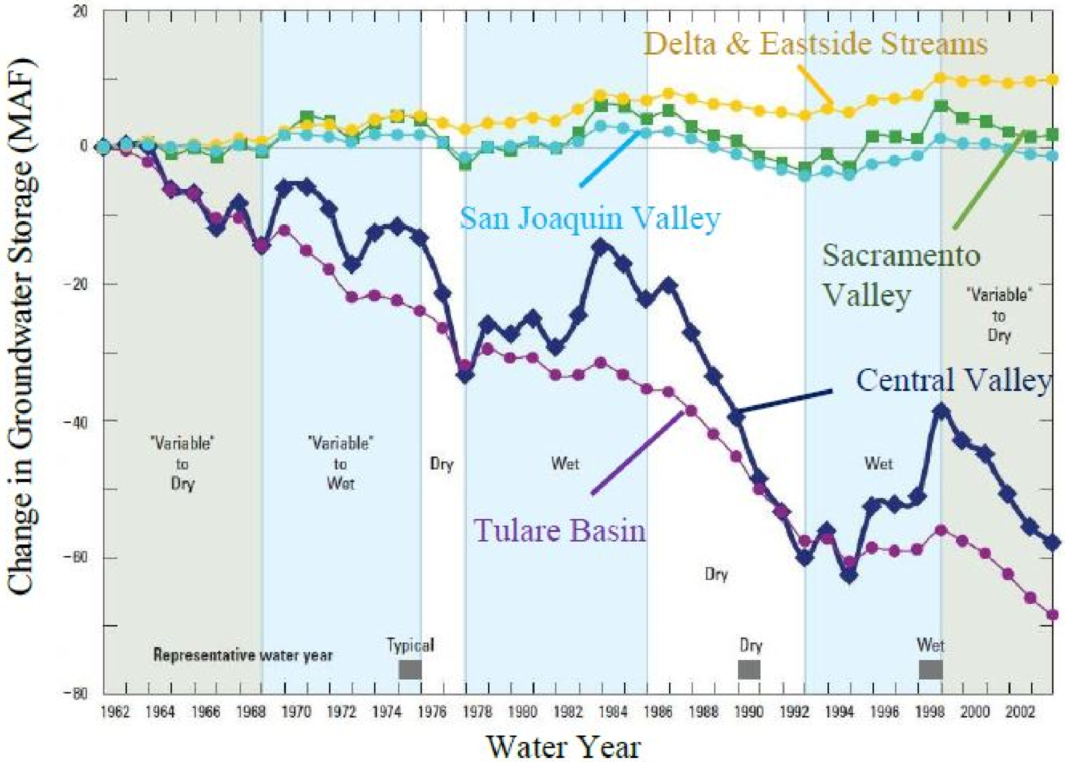


Figure 11. Cumulative Change in Central Valley Groundwater Storage (Faunt, 2009)

Figure 12 shows the Central Valley groundwater sub-basins that are used in CALVIN. Table 1 lists the initial and ending storages for the Central Valley groundwater sub-basins modelled historically in CALVIN. Over the 82 year period, groundwater overdraft in the Central Valley is approximately 84 MAF with the highest in the Tulare region (GW-19, GW-20, and GW-21 sub-basins) (Chou, 2012; Dogan, 2015b).

Figure 12. Central Valley Groundwater Sub-basins in CALVIN (Dogan, 2015b)

Table 1. CALVIN Central Valley Groundwater Sub-basins Change in Storage (Chou, 2012; Dogan, 2015b)

CALVIN Region	CALVIN Sub-basin	Initial Storage (MAF)	Ending Storage (MAF)	Overdraft (MAF)[1]	Change in Storage
Upper Sacramento Valley	GW-01	38	39	1	2.6%
	GW-02	136	136	0	0.0%
	GW-03	133	132	-0.9	-0.7%
	GW-04	61	61	-0.2	-0.4%
Lower Sacramento Valley and Delta	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%
San Joaquin and South Bay	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%
Tulare Basin	GW-14	179	172	-6.8	-3.8%
	GW-15	310	307	-3	-1.0%
	GW-16	65	64	-0.3	-0.4%
	GW-17	97	94	-3.6	-3.7%
	GW-18	321	321	0	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		**2943**	**2858**	**-84**	**-2.9%**

Notes: Central Valley excludes the Southern California region.
[1] Some sub-basins show a positive overdraft, signifying a net increase in storage.
Key:
MAF = million acre-feet

The Delta is the major hub for the CVP and SWP systems, transporting water from the northern to southern California. In addition, the Delta has large outflow requirements for water quality and aquatic species. CALVIN represents this as required Delta outflow in the model, and also includes surplus Delta outflow, which is the difference of total versus required outflow. A simplified Sankey representation of the Delta is shown in Figure 13. On average, there is about 14.4 MAF per year in Delta outflow, of which only 5 MAF per year is required (Dogan, 2015b).

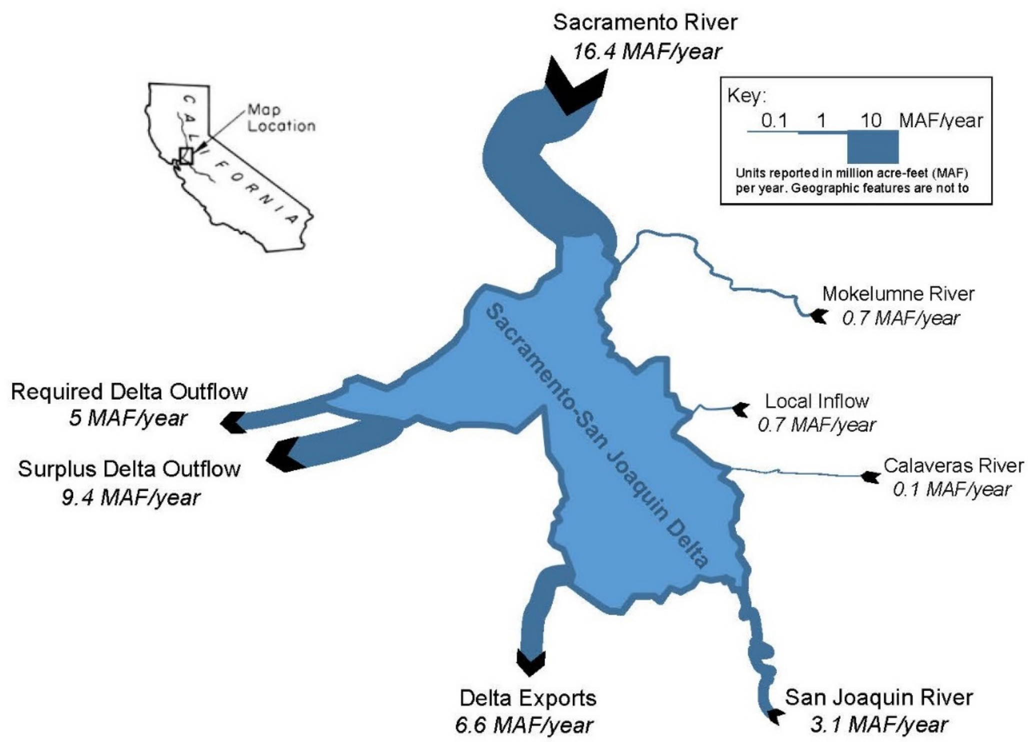


Figure 13. Sankey Representation of the Delta and average Delta flows (CDFW, 1970; Dogan, 2015b)

Water Operations with Climate Warming

The effects of climate warming can vary by region. High altitude and tropic climates are expected to have increases in runoff and water availability. However, arid and semi-arid regions will experience water shortages (Bates et al., 2008). For California, climate change modeling has revealed decreases in Sierra Nevada snowpack and runoff due to changes in temperature and timing of precipitation, which will impact reservoir operations that rely on spring runoff and manage for summer demands (Miller et al., 2003; Vicuna et al., 2007).

As discussed in the previous chapter, the downscaled results from the A2 emissions scenario (warm-dry climate) are used in this study to perturb the CALVIN surface and groundwater hydrology as a representative climate change hydrology. A warmer, drier climate represents an increase in air temperature and decrease in precipitation. It leads to warmer lake and river water temperatures, decreases in spring snowmelt, and increases in winter flows; an ultimate shift in timing and magnitude of flows. The warm-dry climate scenario reduces CALVIN precipitation by 3.5%, rim inflows by almost 30%, and 2°C (35.6°F), leading to increases in water scarcity (Connell 2009; Dogan, 2015b; Ficklin et al., 2013; Medellín-Azuara et al., 2008). Figure 14 displays the change in mean annual precipitation for the A2 emissions scenario by 2100. Hydropower facilities are impacted by the reduction in precipitation and timing shift, especially higher elevation facilities with less storage. Lower elevation facilities with large storage can adjust to the timing shift; however, a warmer-drier climate still shows increased generation losses due to the overall loss in precipitation (Connell-Buck et al., 2011; Dogan, 2015b; Hanak and Lund, 2012; Madani, 2009; Tanaka et al., 2006; Vicuna et al., 2008).

New water management strategies need to be considered in order to adapt to climate change. Recent CALVIN studies have shown that climate change impacts can be reduced through increased water transfers, Delta exports, conjunctive use, and water recycling and desalination (Dogan, 2015b; 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 examines the warm-dry climate scenario with no long-term groundwater overdraft in the Central Valley, and potential management strategies.

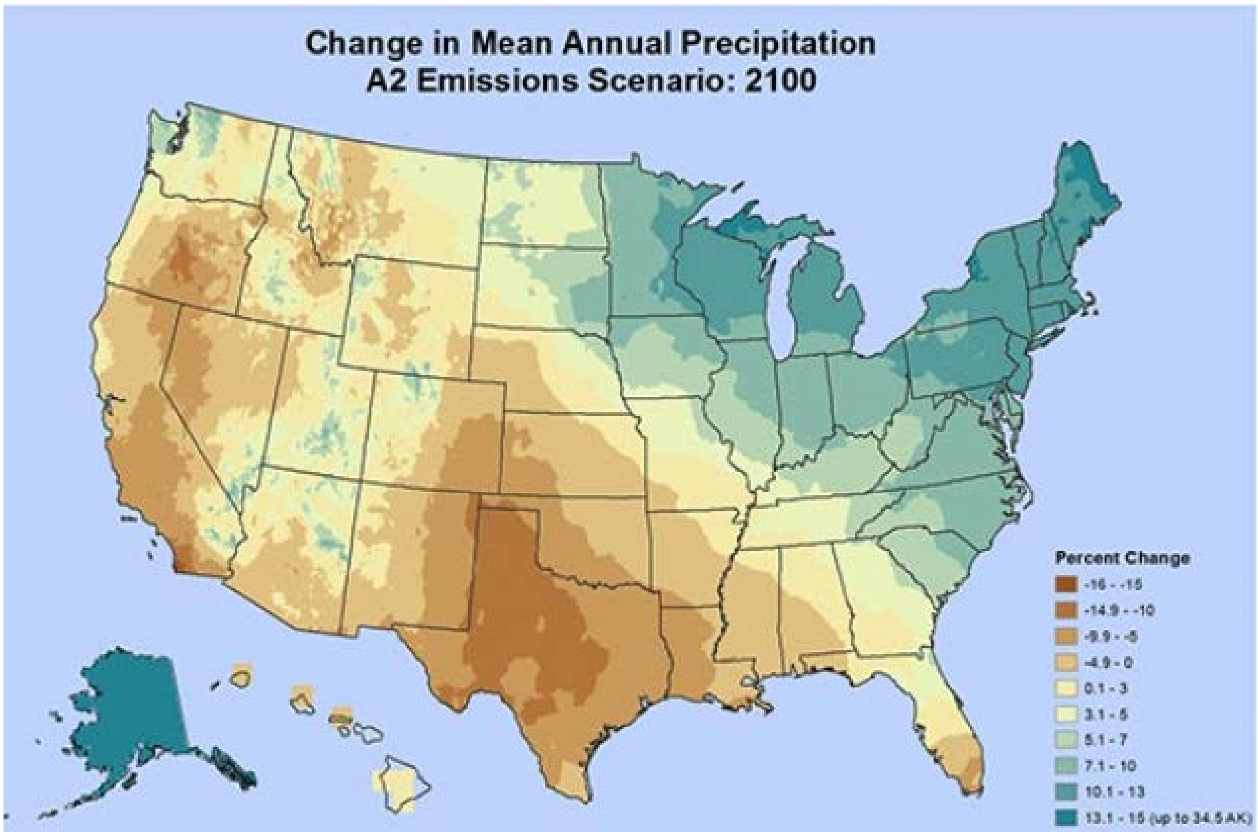


Figure 14. Change in Mean Annual Precipitation for A2 Emissions Scenario by 2100 (Hazen and Sawyer; 2016)

Management Cases and Evaluation Method

For this study, two base cases were considered, comparing historical and warm-dry climate hydrology for the 82 month period and with groundwater overdraft. Four hypothetical “no overdraft” cases also were evaluated with climate change hydrology, grouped as the “no overdraft with climate change” cases. No overdraft is modeled by setting the initial and ending storages as the same for each Central Valley groundwater sub-basin, making the net long-term overdraft zero. All cases were evaluated using the recently updated 2050 level of development water demands. Table 2 lists the six cases evaluated in this study.

Table 2. Evaluated Water Management Cases

Case		Description[1]
Base Cases	Base Case	Base CALVIN operations with overdraft and historical hydrology
	Base Case with Climate Change Hydrology	Base CALVIN operations with overdraft and climate change hydrology (warm-dry climate)
No Overdraft with Climate Change	No Overdraft with Climate Change Hydrology	No Central Valley overdraft with climate change hydrology.
	+No Reduction in Delta Outflow	No Central Valley overdraft with climate change hydrology and no reduction in Delta outflow. Delta outflow lower bound is fixed to historical surplus Delta outflow.
	+No Additional Delta Exports	No Central Valley overdraft with climate change hydrology and no additional Delta exports. Banks and Tracy pumping plants are limited to upper bound of historical time series.
	+No Delta Exports	No Central Valley overdraft with climate change hydrology and no Delta exports. Delta exports from Banks and Tracy pumping plants are limited to 5% of the total allowable capacity to account for CVPIA refuge water supply.

Notes:
[1] All cases use 2050 level of development water demands.
Key:
CVPIA = Central Valley Project Improvement Act

The first case assumes no long-term overdraft in the Central Valley groundwater basins with warm-dry climate conditions. The second case explores water operations without overdraft and prohibits reduction in Delta outflows with warm-dry climate conditions. The third case explores water operations without overdraft, restricts Delta exports from Tracy and Banks pumping plants up to historical rates, and with warm-dry climate conditions. The last case explores water operations without overdraft, and no Delta exports (Banks and Tracy pumping plants are limited to 5% of average exports for CVPIA refuge deliveries), and with warm-dry climate conditions. The last three cases help examine the effects of an uncertain future Delta operations with no overdraft and climate change.

CALVIN, California's statewide hydro-economic model, was used to assess overdraft and climate change impacts for various management cases. The CALVIN model network represents California's water system, managing surface and groundwater supplies to maximize statewide economic benefits with physical, environmental, and policy constraints. CALVIN is a large-scale model, employing a network-flow optimization solver (HEC-PRM) for the 82-year, monthly operations to manage for the represented agricultural, urban, and environmental demands. CALVIN has limitations related to data simplification, linear optimization, and fixed flow and unit costs. CALVIN does model optimal water supply operations, including use of alternative water sources such as water reuse, desalination, water transfers, and artificial recharge (Draper et al., 2003; Dogan, 2015b; Lund et al., 2009).

Results

In this section, the water management cases are analyzed based on their effects to Delta exports and outflow, water delivery and scarcity, groundwater storage, and artificial recharge.

Delta Exports and Outflow

Delta exports and outflows were assessed for each water management case. Table 3 lists the annual average exports from Banks and Tracy Pumping Plants. Overall Delta exports decrease with climate change compared to the base case from 6.6 to 6.2 MAF per year. With no long-term Central Valley groundwater overdraft and climate change Delta exports increase by 237 TAF to 6.4 MAF per year compared to the base case with climate change. However, Delta exports decrease for no overdraft cases with climate change and Delta constraints. With no reduction in Delta outflow, exports decrease to 3.3 MAF per year, whereas no additional Delta exports are limited to 6 MAF, demonstrating that Delta outflow requirements constrain more in these conditions. When Delta exports are limited to 5% of allowable pumping capacity, only 445 TAF per year is exported on average. Table 3 also lists the marginal value (average of the upper bound) for Delta exports. All cases with climate change have increases in marginal value of water. All no overdraft with climate change cases increase marginal export economic value compared to the base case with climate change except for no reduction in Delta outflow as the supply has diminished. When Delta exports are limited to 5%, marginal value to increase exports increases dramatically due to large SOD scarcities.

Table 3. Annual Average Exports from Banks and Tracy Pumping Plants

Item		Base Case	Base Case with CC	No OD with CC	+No Reduction in Delta Outflow	+No Additional Delta Exports	+No Delta Exports
Export (TAF/yr)	Banks	4,108	3,543	3,770	1,897	3,698	278
	Tracy	2,478	2,617	2,627	1,392	2,304	167
	Total	**6,587**	**6,160**	**6,397**	**3,289**	**6,002**	**445**
Marginal Value on Upper Bound ($/AF)	Banks	14	322	337	308	346	2,083
	Tracy	8	409	454	234	331	2,081

Key: $/AF = dollars per acre-feet CC = climate change OD = overdraft TAF/yr = thousand acre-feet per year

Figure 15 shows the monthly average Delta exports by management case. Under the base case, exports follow the water demand pattern with higher exports in spring and summer. Only about half of the allowable pumping capacity is used during the winter months. With climate change, exports increase during winter months and almost all capacity is used in January to capture the surplus Delta outflow, whereas exports decrease during spring and summer compared to the base case. With no overdraft and climate change, exports increase during spring and summer months compared to the base case with climate change; however, are still less than the base case.

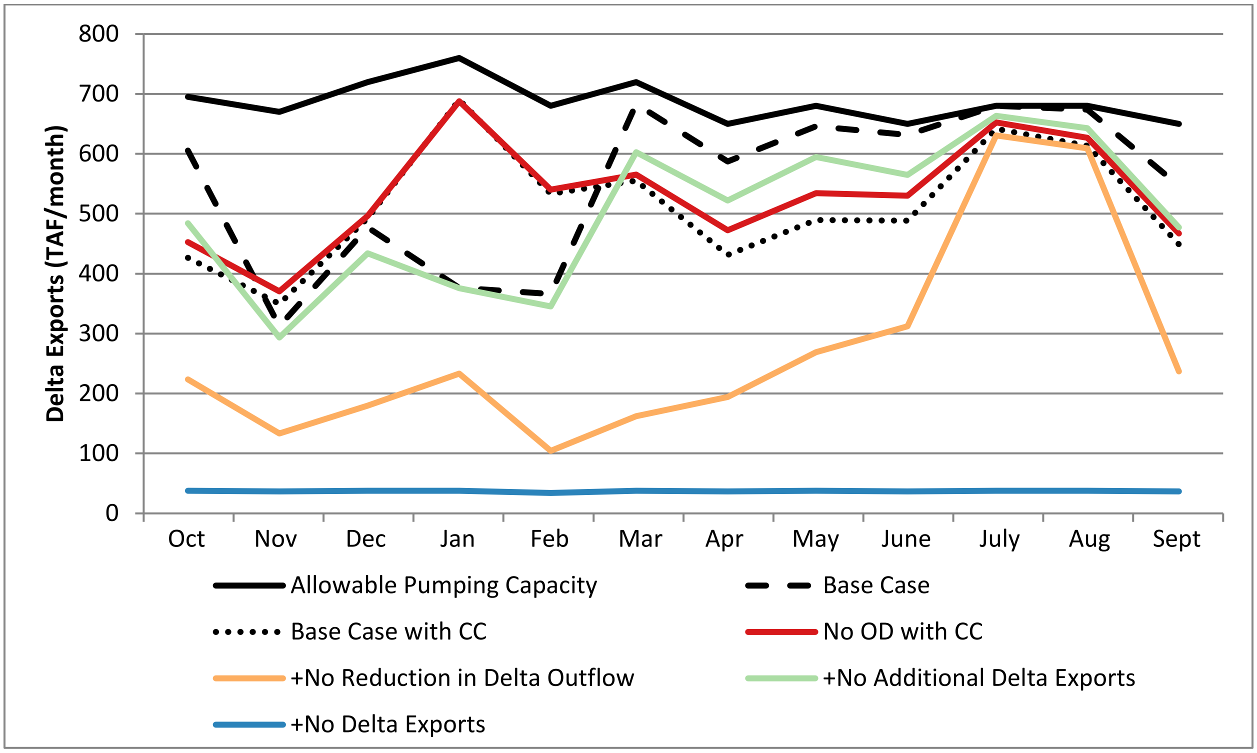


Figure 15. Monthly Average Delta Exports and Allowable Pumping Capacity

Figure 16 shows the Delta exports delivery-reliability curves for the cases. Delta exports for all cases besides no Delta exports and no reduction in Delta outflow are near the allowable capacity roughly 30% to 40% of the time. With climate change, exports decrease compared to the base case after 40% probability. With no overdraft and climate change, exports increase compared to both base cases below 15% probability, and then in between both beyond 50% probability. With Delta constraints and climate change, exports decrease compared to the base cases past the 10% to 20% probabilities. When Delta exports are limited to 5% of allowable pumping capacity, the maximum allowable capacity is utilized constantly.

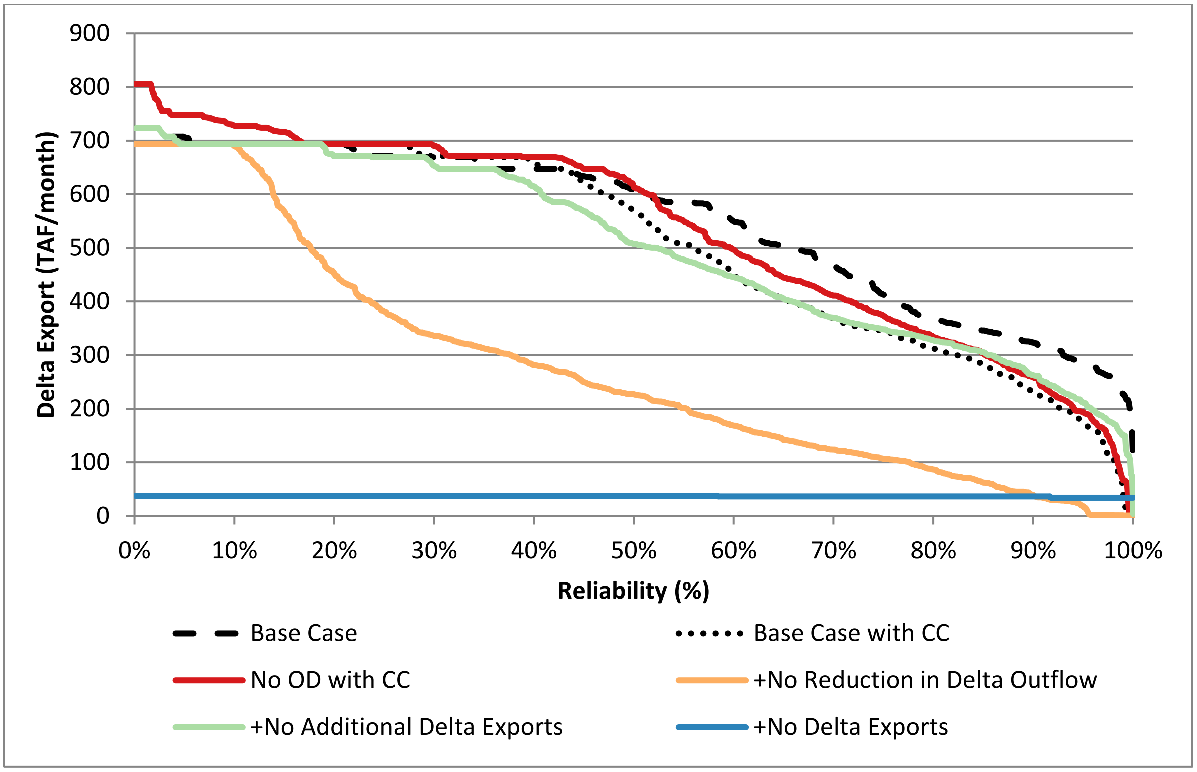


Figure 16. Delta Exports Delivery-Reliability Curves for all Months

Delta exports are often limited by Delta outflow requirements, which are regulated by the SWRCB and heavily consist of required flows from the Sacramento and San Joaquin rivers out the San Francisco Bay (SWRCB, 2000). Delta outflow is vital to the estuary and salinity control. In CALVIN, Delta outflow is represented as two arcs, required and surplus (Dogan, 2015b). Table 4 lists the annual average Delta outflows and marginal values of reducing the required Delta outflow by management case. The annual average Delta outflow under the base case is 14.4 MAF per year, whereas with climate change it is 9.6 MAF per year. With no overdraft and climate change, Delta outflow is unchanged compared to the base case with climate change. When adding Delta constraints the outflow increases. The marginal value on the required Delta outflow increases with climate change and more so with ending groundwater overdraft. Ending groundwater overdraft in the Central Valley will increase demands for Delta exports. The highest marginal value ($1,164 per acre-foot) is when there is no reduction in Delta outflow with climate change and no groundwater overdraft, demonstrating the high expense to retain current levels of Delta outflows under these conditions.

Table 4. Annual Average Delta Outflows and Average Marginal Values on the Required Delta Outflow

Item	Base Case	Base Case with CC	No OD with CC	+No Reduction in Delta Outflow	+No Additional Delta Exports	+No Delta Exports
Average Delta Outflow (MAF/year)	14.4	9.6	9.6	14.4	10.3	13.9
Average Marginal Value ($/AF)	5.9	370.8	415.8	1164.2	391.2	21.6

Figure 17 shows the monthly average and required Delta outflow, which illustrates that all cases peak in January and February, ranging from 1.8 to 2.8 MAF per month. Cases with climate change show peaks in January due to the shift in precipitation timing. Summer demands reduce the surplus Delta outflow, and overall total outflow to the required levels from July to September. The base case and no reduction in Delta outflow cases mimic similar outflows, and are almost always the highest outflow in every month except for when Delta exports are reduced to 5% of allowable capacities, which sees greater outflow in summer compared to the other cases.

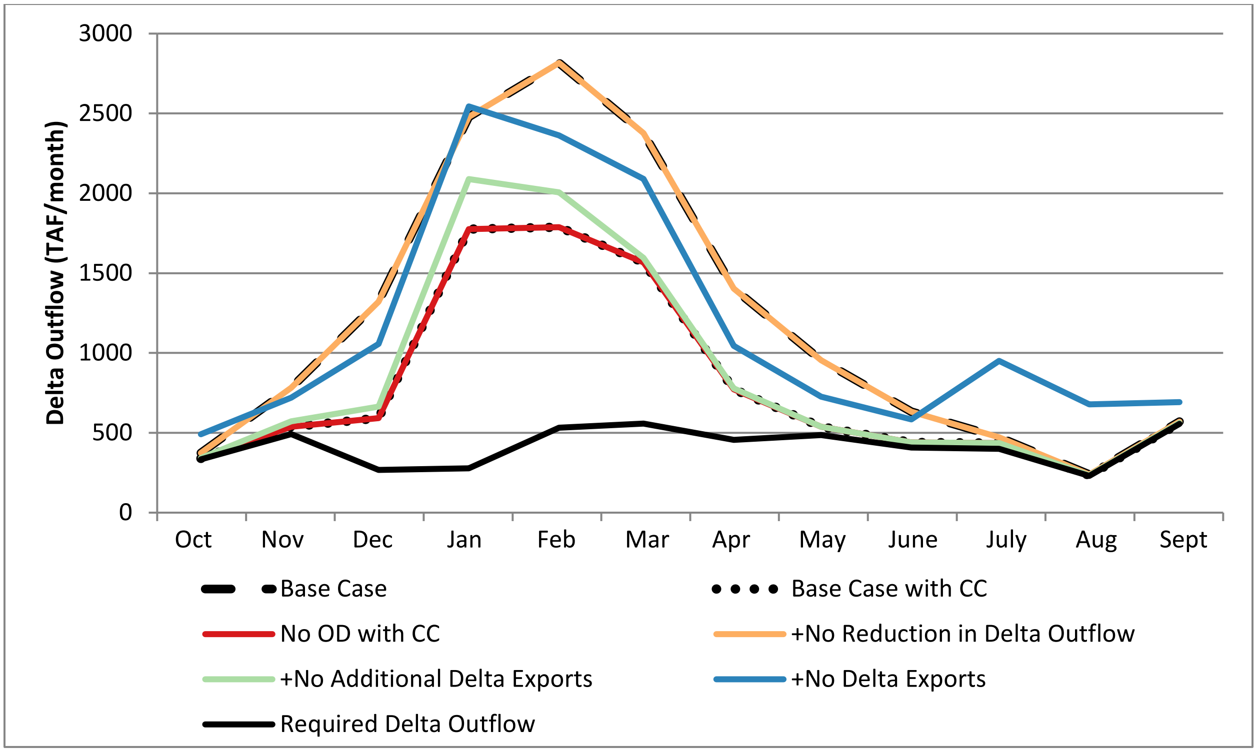


Figure 17. Monthly Average and Required Delta Outflow

In the base case, 90% of the total Delta outflow is from the Sacramento River, and surplus flows increase during wet years (Dogan, 2015b). Monthly surplus Delta outflow is reliably the lowest and the same for both the base case with climate change and no overdraft with climate change (Figure 18). With climate change, some surplus Delta outflow can assist with limiting groundwater overdraft; however, this requires more SOD storage and Delta pumping capacity especially during winter months when there is less demand. Almost 40% of the time, no reduction in Delta outflow and the base case have more surplus Delta outflow than the other cases.

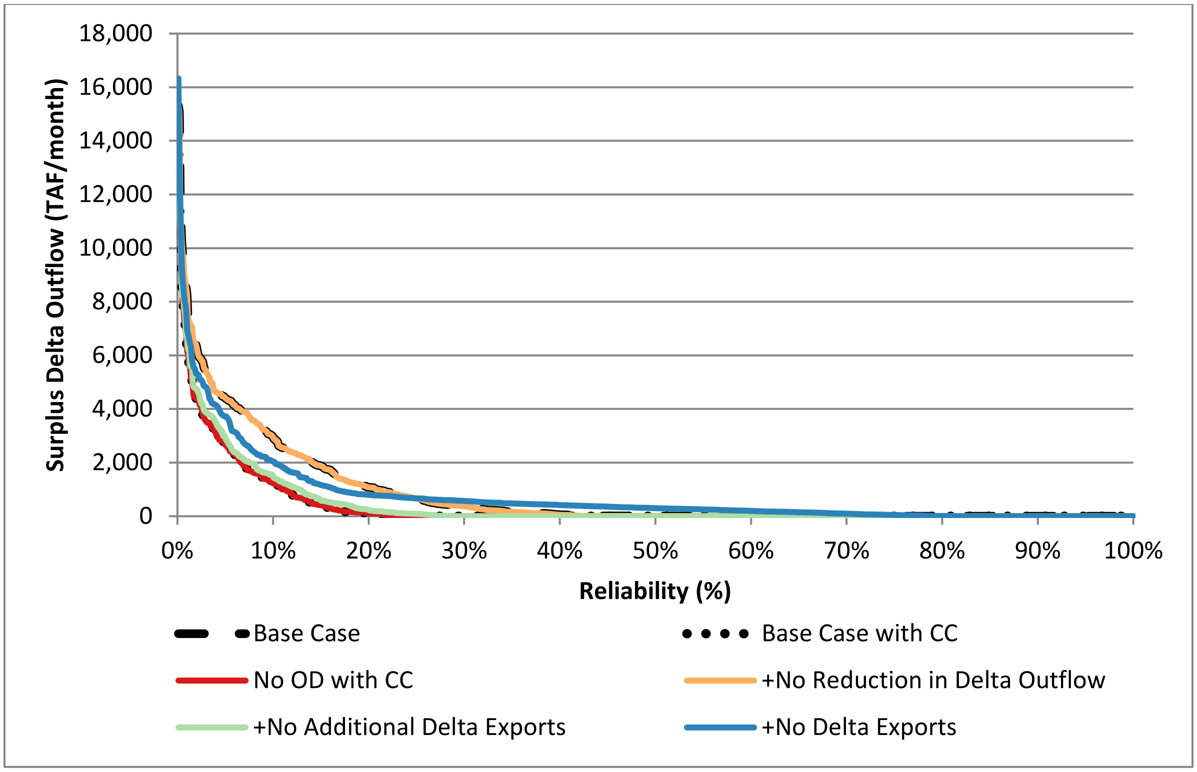


Figure 18. Frequency Curves of Monthly Surplus Delta Outflow

Water Delivery and Scarcity

Urban and agricultural water supply portfolios were assessed for each water management case. An urban water supply portfolio consists of surface water deliveries, groundwater pumping, potable and non-potable recycling, desalination, and water conservation activities. An agricultural water supply portfolio consists of surface water deliveries, groundwater pumping, agricultural reuse, and water conservation activities. Table 5 and Figure 19 show the urban water supply portfolios for the base cases. Urban water recycling and desalination increase statewide with climate change (supplying 2% to 5% of urban demand), while traditional surface water and groundwater supplies decrease due to reduced water availability. The Upper Sacramento Valley relies heavily on groundwater pumping (98% of urban demand in the base case), and changes minimally with climate change. Lower Sacramento Valley and Delta urban users receive surface and groundwater supplies evenly in the base case, and shift more heavily to surface water deliveries with climate change (58% of urban demand) as well as increase non-potable recycling and scarcity. This is due to use of surface water supplies by Yolo and Solano Counties, which has limited surface water use without climate change; and increases in Sacramento surface water use in all months.

The San Joaquin and South Bay region sees a similar trend with climate change, but a greater shift to surface water deliveries to meet urban demands (from 40% to 60% of urban demand) and reduction in groundwater deliveries (from 59% to 37%). The Tulare Basin also relies heavily on groundwater (63% of urban demand in the base case), which is reduced with climate change (down to 54%) and made up with additional surface water deliveries and scarcity. The Tulare Basin employs similar non-potable recycling and desalination for urban water users with and without climate change. This is from Central Coast communities off the Coastal Aqueduct (i.e. San Luis Obispo and Santa Barbara Counties), which are less defined in CALVIN and likely would result in a greater water transfer market otherwise over desalination. In addition, water recycling and desalination mostly occur during dry years and are not used consistently used over the 82 year period, which is potentially unrealistic. Although there is an overall trend of increased water recycling statewide. Southern California surface water deliveries fall significantly with climate change (from 53% to 39% of urban demand), and see significant increases in potable and non-potable recycling (3% and 8% of urban demand, respectively) as well as the highest water scarcity and additional water conservation (7%).

Table 5. Urban Water Supply Portfolio for Base Cases

Supply (TAF/year)	Upper Sacramento Valley	Lower Sacramento Valley and Delta	San Joaquin and South Bay	Tulare Basin	Southern California	Statewide
Base Case						
SW Delivery	7	929	518	415	3,633	5,502
GW Pumping	388	969	768	976	3,016	6,118
Potable Recycling	-	-	-	-	18	18
Non-potable Recycling	-	1	16	47	101	164
Desalination	-	-	-	97	-	97
Scarcity	-	1	-	6	98	105
Total	395	1,900	1,302	1,541	6,866	12,004
Base Case with Climate Change						
SW Delivery	17	1,101	777	514	2,665	5,073
GW Pumping	378	722	487	839	2,993	5,418
Potable Recycling	-	6	-	-	214	219
Non-potable Recycling	-	44	16	47	522	628
Desalination	-	-	-	97	-	97
Scarcity	-	29	24	44	472	569
Total	395	1,901	1,303	1,541	6,865	12,005

Key: GW = groundwater SW = surface water TAF = thousand acre-feet

Notes: “Base Case” is the base CALVIN operations with overdraft and historical hydrology. “Base Case with Climate Change Hydrology” is the base CALVIN operations with overdraft and climate change hydrology (warm-dry climate).

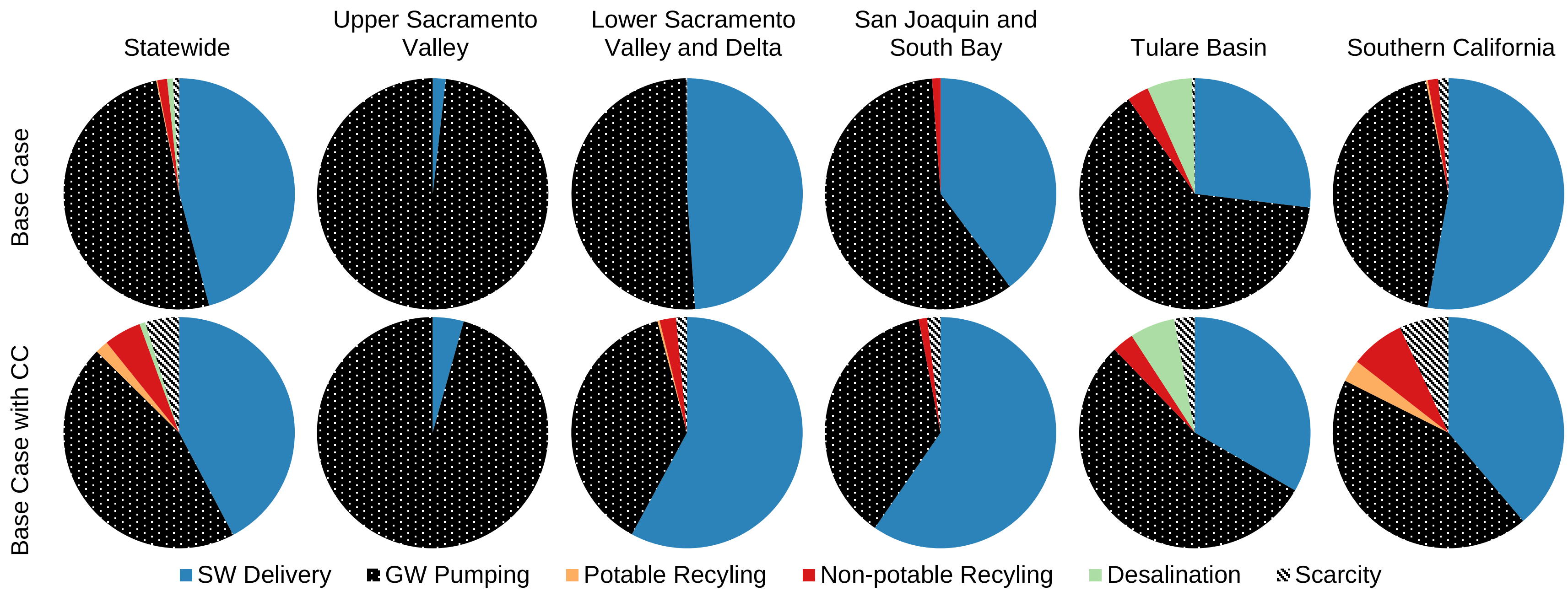


Figure 19. Urban Water Supply Portfolio for Base Cases

Table 6 and Figure 20 show the urban water supply portfolio for the no overdraft with climate change cases. No overdraft with climate change has almost no change to the urban water supply portfolios statewide. The Lower Sacramento Valley and Delta region slightly increases its reliance on surface water deliveries by 4% of urban demand compared to the base case with climate change. With no reduction in Delta outflow, all regions see more urban water scarcity with the Lower Sacramento Valley and Delta, and San Joaquin and South Bay regions having the greatest increase in scarcity relative to their demands due to outflow requirements for the Sacramento and San Joaquin Rivers. The San Joaquin and South Bay region increases its potable recycling to 10%, and non-potable recycling to 3% of urban demand to make up for the decrease in surface water and groundwater deliveries (52% and 26% of urban demand, respectively). This occurs the San Francisco Public Utility District (SFPUC) service area and Santa Clara Valley. Lower Sacramento Valley and Delta region urban users also slightly increase their potable and non-potable recycling to replace losses in surface and groundwater deliveries. This occurs in the Contra Costa Water District (CCWD) and East Bay Municipal Utility District (EBMUD) service areas; and Napa and Solano Counties. For the Tulare Basin, no reduction in Delta outflow slightly increases scarcity; however, the overall portfolio is similar to the base case with climate change. Southern California urban users have a decrease in surface water deliveries (39% to 30% of urban demand) due to the reduction in Delta exports to meet outflow requirements. This reduction is made up with potable water recycling (9% of urban demand) in the Metropolitan Water District of Southern California (MWD) service areas; Santa Clara Valley, Ventura, Antelope Valley, San Bernardino, and San Diego.

With no additional Delta exports, California experiences minimal changes to urban water supply portfolios compared to the base case with climate change. This is because surplus Delta outflows are available to make up for water supply impacts from climate change. The Lower Sacramento Valley and Delta, and San Joaquin and South Bay regions slightly increase urban surface water deliveries (4% increase in respective ratios) and decrease groundwater deliveries (5% decrease in ratios) compared to the base case with climate change. When there are almost no Delta exports (pumping limited to 5% of allowable capacity), SOD urban water users experience great scarcities (6% to 13%) and increase desalination. NOD urban water users increase surface deliveries (2% to 8% increase in respective ratios) and equivalent decreases in groundwater deliveries. The San Joaquin and South Bay region has the greatest decrease in urban surface water deliveries (from 60% to 13% of urban demand) compared to the base case with climate change, and balances this with significant increases in potable and non-potable recycling, and desalination (9%, 4%, and 19% of urban demand, respectively). Southern California also has a reduction in surface water deliveries (from 39% to 25% of urban demand) and increases potable recycling and desalination (10% and 3% of urban demand, respectively). The Tulare Basin sees a much smaller reduction in urban surface water deliveries, but also increases desalination (from 6% to 10% of urban demand) on the Central Coast.

Table 6. Urban Supply Portfolios for No Central Valley Overdraft with Climate Change Cases

Supply (TAF/year)	Upper Sacramento Valley	Lower Sacramento Valley and Delta	San Joaquin and South Bay	Tulare Basin	Southern California	Statewide
No Overdraft with Climate Change						
SW Delivery	13	1,181	797	510	2,646	5,147
GW Pumping	382	627	457	843	2,992	5,300
Potable Recycling	-	6	-	-	229	235
Non-potable Recycling	-	44	16	47	524	631
Desalination	-	-	-	97	-	97
Scarcity	-	43	34	44	473	595
Total	395	1,901	1,304	1,541	6,864	12,005
+No Reduction in Delta Outflow						
SW Delivery	-	1,029	678	499	2,032	4,238
GW Pumping	391	640	343	827	2,968	5,169
Potable Recycling	-	20	127	-	650	798
Non-potable Recycling	-	57	36	47	525	664
Desalination	-	-	-	97	-	97
Scarcity	4	154	124	71	685	1,038
Total	395	1,900	1,307	1,541	6,860	12,004
+No Additional Delta Exports						
SW Delivery	15	1,171	838	512	2,639	5,176
GW Pumping	380	633	414	841	2,992	5,261
Potable Recycling	-	6	-	-	230	236
Non-potable Recycling	-	43	16	47	525	630
Desalination	-	-	-	97	-	97
Scarcity	-	47	35	44	478	604
Total	395	1,901	1,304	1,541	6,864	12,005
+No Delta Exports						
SW Delivery	24	1,255	187	452	1,663	3,581
GW Pumping	371	565	582	799	2,854	5,171
Potable Recycling	-	12	127	-	650	789
Non-potable Recycling	-	33	60	47	525	665
Desalination	-	-	261	149	173	582
Scarcity	-	44	171	95	915	1,224
Total	395	1,908	1,388	1,541	6,780	12,012

Key: CC = climate change GW = groundwater OD = overdraft SW = surface water TAF = thousand acre-feet

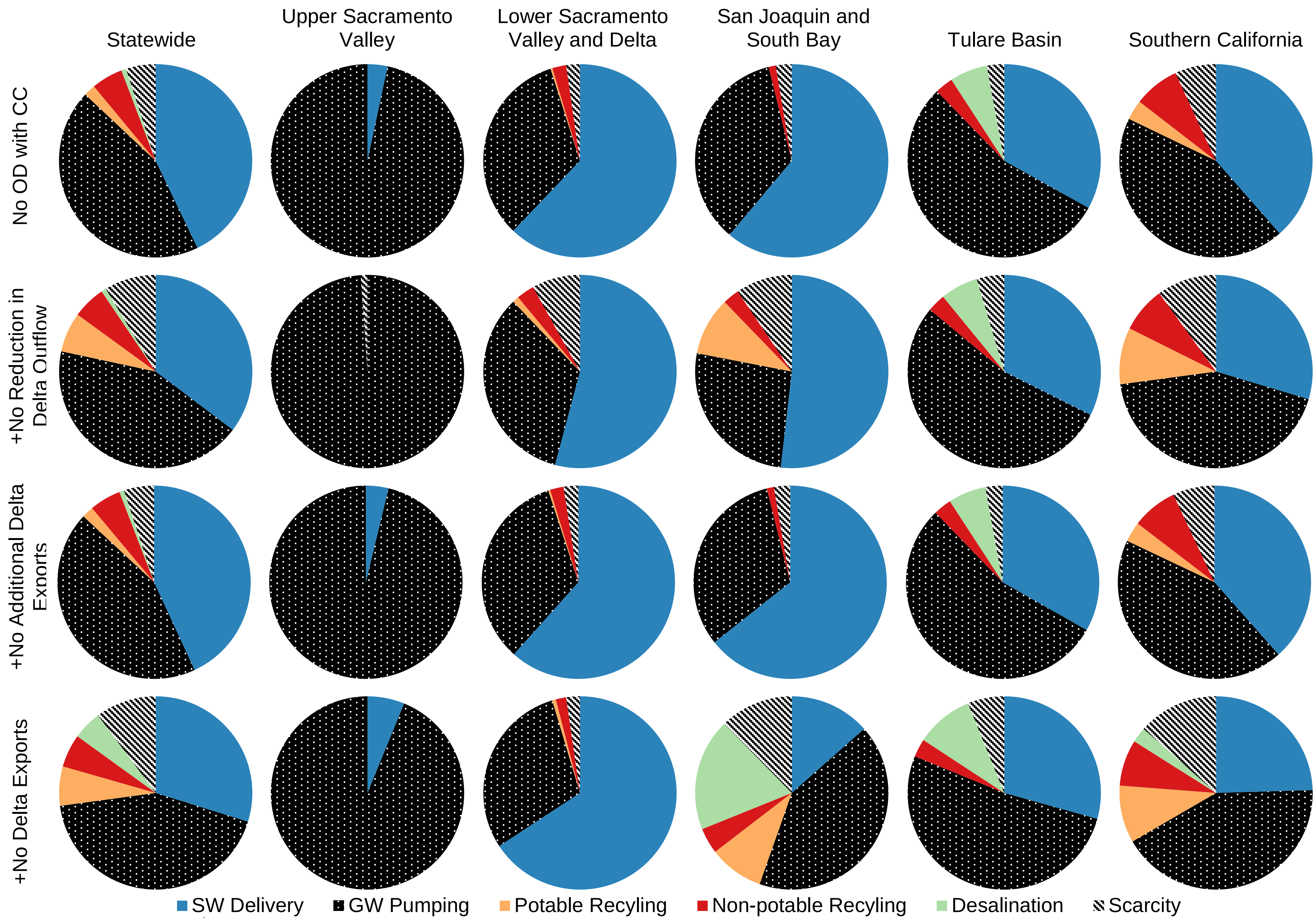


Figure 20. Urban Supply Portfolio for No Central Valley Overdraft with Climate Change Cases

Table 7 and Figure 21 display the agricultural water supply portfolio for the historical hydrology and climate change base cases. Agricultural water scarcity increases significantly statewide with climate change (from 2% to 28% of agricultural demand), due to decreased surface water supplies. Agricultural reuse also decreases with climate change, probably due to reductions in agricultural return flows. All regions except Southern California have a large reduction in agricultural surface water supplies, from 22% to 37% reduction in relative ratios to demand. The Upper Sacramento Valley has the worst relative scarcity impact at 39% of agricultural demand due to huge reductions in surface water (from 71% to 49% of agricultural demand) and groundwater deliveries (from 21% to 6% of agricultural demand). The Lower Sacramento Valley and Delta region experiences a similar impact to surface water deliveries (from 63% to 36% of agricultural demand) and 35% scarcity. The Tulare Basin experiences the highest total scarcity of almost 3 MAF per year, and is the only region that increases groundwater pumping in its agricultural water supply portfolio to make up for loss in surface water under climate change. Southern California agricultural water supply portfolios are minimally impacted by climate change because of their reliance on Colorado River supplied, which are assumed here to be unaffected by climate change (California having first priority among lower Colorado River users).

Table 7. Agricultural Supply Portfolio for Base Cases

Supply (TAF/year)	Upper Sacramento Valley	Lower Sacramento Valley and Delta	San Joaquin and South Bay	Tulare Basin	Southern California	Statewide
Base Case (historical hydrology and overdraft)						
SW Delivery	1,818	2,915	3,400	5,790	3,314	17,238
GW Pumping	543	1,438	1,433	3,598	265	7,277
Agricultural Reuse	195	162	88	58	-	503
Scarcity	19	89	20	146	152	426
Total	2,576	4,604	4,940	9,591	3,731	25,444
Base Case with Climate Change						
SW Delivery	1,260	1,671	1,982	2,202	3,299	10,413
GW Pumping	163	1,230	1,395	4,346	265	7,399
Agricultural Reuse	161	111	62	48	-	381
Scarcity	992	1,593	1,502	2,980	168	7,235
Total	2,576	4,604	4,940	9,575	3,731	25,427

Key: CC = climate change GW = groundwater SW = surface water TAF = thousand acre-feet

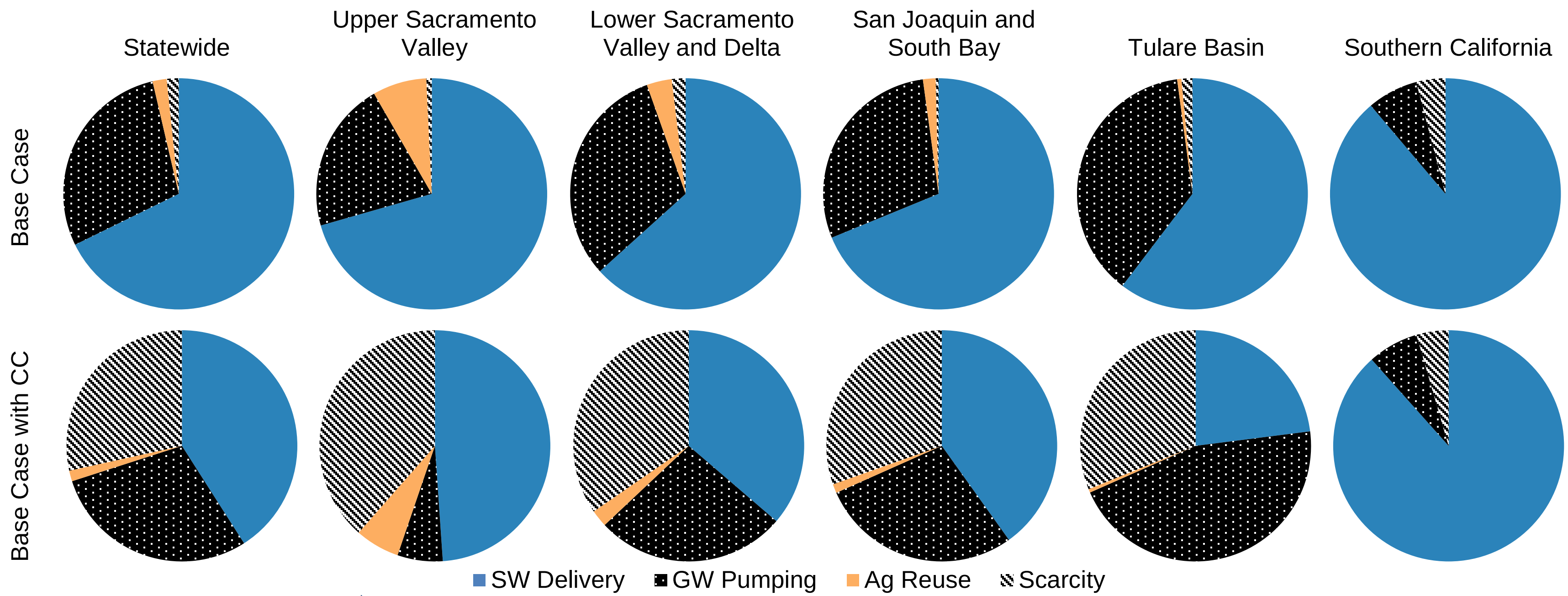


Figure 21. Agricultural Supply Portfolio for Base Case Climate Change Cases

Table 8 and Figure 22 show the agricultural water supply portfolio for the no Central Valley overdraft with climate change cases. No overdraft with climate change has almost no change to agricultural water supply portfolios for the Upper Sacramento Valley and Southern California compared to the base case with climate change. The Lower Sacramento Valley and Delta region decreases both surface water and groundwater deliveries, increasing scarcity to 45%. The San Joaquin and South Bay region and Tulare Basin have similar reductions to groundwater deliveries (4% decrease in respective ratios) and similar increase in scarcity (34% to 38% of agricultural demand). With no reduction in Delta outflow, all regions except Southern California have severe scarcities. The Lower Sacramento Valley and Delta region have 82% scarcity due to large decreases in surface and groundwater pumping (5% and 13% of agricultural demand, respectively). The San Joaquin and South Bay, and Upper Sacramento Valley regions suffer similar decreases in relative surface water deliveries, and with smaller decreases in groundwater deliveries.

With no additional Delta exports, regions do not suffer the same scarcities as with no reduction in Delta outflows because surplus Delta outflows are available. The agricultural water supply portfolio for the Upper Sacramento Valley is almost identical to the base case with climate change. The Lower Sacramento Valley and Delta region has decreases in deliveries resulting in 55% scarcity. SOD agricultural water users have the largest decrease in deliveries; although relatively less severe than NOD users. With no Delta exports (pumping limited to 5% of allowable capacity), NOD agricultural water users actually increase surface water deliveries and decrease scarcities to 10% to 13%. The San Joaquin and South Bay region receives no agricultural surface water deliveries as expected and has limited groundwater supplies (6% of agricultural demands), resulting in 93% scarcity for agricultural use. The Tulare Basin receives some surface and groundwater supplies (6% and 30% of agricultural demand, respectively), but still has a scarcity of 63%. Southern California agricultural users are unaffected by no Delta exports compared to the base case with climate change.

Table 8. Agricultural Supply Portfolio for No Central Valley Overdraft with Climate Change Cases

Supply (TAF/year)	Upper Sacramento Valley	Lower Sacramento Valley and Delta	San Joaquin and South Bay	Tulare Basin	Southern California	Statewide
No Overdraft with Climate Change						
SW Delivery	1,256	1,365	2,013	2,009	3,299	9,942
GW Pumping	155	1,071	1,196	3,999	265	6,685
Agricultural Reuse	159	83	59	48	-	348
Scarcity	1,006	2,085	1,672	3,636	168	8,568
Total	2,576	4,604	4,940	9,691	3,731	25,544
+No Reduction in Delta Outflow						
SW Delivery	766	221	586	1,288	3,298	6,159
GW Pumping	43	590	973	3,453	265	5,324
Agricultural Reuse	55	7	30	36	-	128
Scarcity	1,712	3,787	3,352	4,807	168	13,827
Total	2,576	4,604	4,940	9,585	3,731	25,437
+No Additional Delta Exports						
SW Delivery	1,245	1,137	1,870	1,895	3,299	9,446
GW Pumping	154	892	1,205	3,786	265	6,302
Agricultural Reuse	157	57	57	45	-	315
Scarcity	1,021	2,518	1,807	3,958	168	9,472
Total	2,576	4,604	4,940	9,683	3,731	25,536
+No Delta Exports						
SW Delivery	1,725	2,357	15	592	3,279	7,968
GW Pumping	414	1,480	320	2,903	284	5,401
Agricultural Reuse	181	150	-	28	-	359
Scarcity	256	616	4,606	6,051	169	11,699
Total	2,576	4,604	4,940	9,575	3,731	25,427

Key: CC = climate change GW = groundwater OD = overdraft SW = surface water TAF = thousand acre-feet

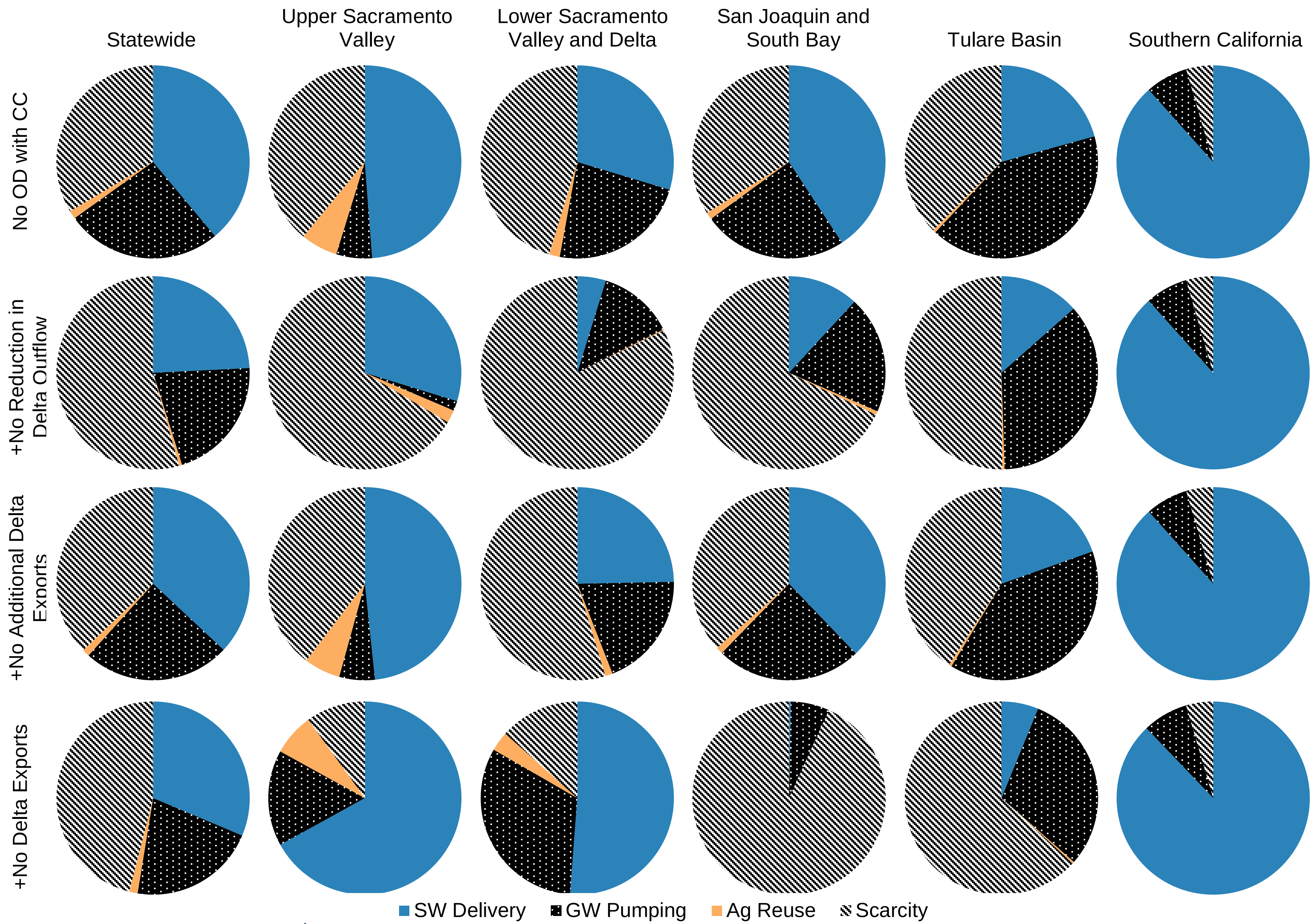


Figure 22. Agricultural Supply Portfolio for No Central Valley Overdraft with Climate Change Cases

Climate change alone increases water scarcity impacts for agricultural and urban water users. Table 9 compares the agricultural and urban water scarcities of the base cases. Agricultural water users are disproportionately affected because urban water users have higher user willingness-to-pay for water, and so seek to purchase available supplies (Dogan, 2015b). In addition, climate change affects agricultural and urban water users differently, depending on the region. Overall scarcity increases from 1% to 20% of total demands with climate change. Southern California agricultural and urban water scarcities are 5% and 7% with climate change, respectively. Whereas, agricultural water scarcity ranges from 30% to 39% and urban water scarcity from 0% to 3% for other regions. The Tulare Basin had the largest water scarcity quantity increase with over 20 times more scarcity. However, the Upper Sacramento Valley region has the largest relative impact due to the climate change with an overall water scarcity of 33% (50 times more scarcity).

Table 9. Annual Average Agricultural and Urban Water Scarcities for Base Cases

Scarcity (TAF/year)	**Base Case**		**Base Case with Climate Change**	
Region	**Agriculture**	**Urban**	**Agriculture**	**Urban**
Upper Sacramento Valley	19	-	992	-
Lower Sacramento Valley and Delta	89	1	1,593	29
San Joaquin and South Bay	20	-	1,502	24
Tulare Basin	146	6	2,980	44
Southern California	152	98	168	472
Statewide	**426**	**105**	**7,235**	**569**

Key: TAF = thousand acre-feet

Ending groundwater overdraft with climate change will require less groundwater pumping and will increase economic demands for surface water supplies. Table 10 compares the agricultural and urban water scarcities for the no Central Valley overdraft with climate change cases. Agricultural users again see more scarcities due to ending overdraft than urban water users. No overdraft with climate change has about 25% water scarcity for agricultural and urban water users. The agricultural water scarcity increased by 5%, whereas there is a minimal change to scarcity for urban water users compared to the base case with climate change. With no reduction in Delta outflows, agricultural and urban water scarcities are 55% and 9%, respectively with the largest impacts to the Lower Sacramento Valley and Delta, and San Joaquin and South Bay regions due to the need for Sacramento and San Joaquin River outflows. When there are no additional Delta exports, agricultural and urban water scarcities are less with 37% and 5%, respectively as the surplus Delta outflows are reduced and water transfers from the north-of-Delta (NOD) to south-of-Delta (SOD) water users help make up for the water supply deficit. When Delta exports are limited to 5% of capacity, the Lower Sacramento Valley and Delta, and San Joaquin and South Bay agricultural regions are significantly impacted with 93% and 63% water scarcity, respectively. Whereas, agricultural regions in the north benefit from the availability of upper watershed deliveries from the Sacramento River. Northern California is the least affected when there are no

Delta exports compared to the other no overdraft cases, because some of the previously exported supplies become available to them.

Table 10. Annual Average Agricultural and Urban Water Scarcities for No Central Valley Overdraft with Climate Change Cases

Scarcity (TAF/year)	No Overdraft with Climate Change		+No Reduction in Delta Outflow		+No Additional Delta Exports		+No Delta Exports	
Region	**Agr.**	**Urban**	**Agr.**	**Urban**	**Agr.**	**Urban**	**Agr.**	**Urban**
Upper Sacramento Valley	1,006	-	1,712	4	1,021	-	256	-
Lower Sacramento Valley and Delta	2,085	43	3,787	154	2,518	47	616	44
San Joaquin and South Bay	1,672	34	3,352	124	1,807	35	4,606	171
Tulare Basin	3,636	44	4,807	71	3,958	44	6,051	95
Southern California	168	473	168	685	168	478	169	915
Statewide	**8,568**	**595**	**13,827**	**1,038**	**9,472**	**604**	**11,699**	**1,224**

Key: Agr. = agriculture TAF = thousand acre-feet

Scarcity costs from lost agricultural production increase with climate change by almost 50 times that of the base case. Table 11 compares the agricultural and urban water scarcity costs of the base cases. The highest scarcity costs are in the Tulare Basin and San Joaquin and South Bay region as they have the greatest water scarcities and high value crops. Although the urban water scarcity in Southern California is relatively small (5% of total demand), the average unit cost is high at over $1,000 per acre-foot.

Table 11. Annual Average Agricultural Water Scarcity Cost for Base Cases

Scarcity Cost ($M/year)	Base Case		Base Case with Climate Change	
Region	**Agr.**	**Urban**	**Agr.**	**Urban**
Upper Sacramento Valley	0.4	0.0	266.7	0.0
Lower Sacramento Valley and Delta	6.1	1.2	363.5	26.1
San Joaquin and South Bay	1.3	0.0	510.0	24.4
Tulare Basin	12.7	12.3	1,183.6	36.3
Southern California	28.2	79.3	35.5	511.7
Statewide	**49**	**93**	**2,359**	**599**

Key: $M = million dollars Agr. = agriculture

With the no overdraft case, scarcity costs increase significantly for the Tulare Basin and Lower Sacramento Valley and Delta regions consistent with their respective increases in water scarcity. Table 12 compares the agricultural and urban water scarcity costs for the no Central Valley overdraft with climate change cases. Although there is more total water scarcity with the no reduction in Delta outflow case, the no Delta exports case has the greatest scarcity cost because of the impact to high value crops south of the Delta (approximately $7.6 billion per year for agriculture). NOD agricultural water users see the greatest water scarcity costs with no reduction in Delta outflow; however, the average unit cost is much lower at $340 per acre-foot because scarcity costs are compensated from water transfers and fallowing of lower value crops. Northern California agricultural water users have the lowest scarcity costs when there are no Delta exports compared to the other no overdraft cases, and even the base case with climate change.

Table 12. Annual Average Agricultural Water Scarcity Cost for No Central Valley Overdraft with Climate Change Cases

Scarcity Cost ($M/year)	No Overdraft with Climate Change		+No Reduction in Delta Outflow		+No Additional Delta Exports		+No Delta Exports	
Region	**Agr.**	**Urban**	**Agr.**	**Urban**	**Agr.**	**Urban**	**Agr.**	**Urban**
Upper Sacramento Valley	273.8	0.0	549.4	3.5	281.9	0.01	24.9	0.0
Lower Sacramento Valley and Delta	570.4	36.4	1,319.0	154.6	760.9	39.0	138.7	53.0
San Joaquin and South Bay	604.0	34.7	1,888.1	154.1	684.2	35.5	3,271.7	231.0
Tulare Basin	1,600.0	36.3	2,433.3	61.5	1,807.9	36.3	4,153.2	93.9
Southern California	35.8	513.5	36.3	829.6	36.1	522.2	36.9	1,234.9
Statewide	**3,084**	**621**	**6,226**	**1,203**	**3,571**	**633**	**7,625**	**1,613**

Key: $M = million dollars Agr. = agriculture CC = climate change OD = overdraft

Agricultural scarcity costs are unequally distributed and show that Delta exports are important for ending groundwater overdraft in the Central Valley (Dogan, 2015b). Table 13 shows the distribution of annual average agricultural scarcity costs in the Central Valley. The highest scarcity costs are south of the Delta; SOD agricultural water users have an annual average scarcity cost of $14 million per year for the base case, and $1.7 billion per year with climate change. Agricultural scarcity cost increases to $7.4 billion per year with almost no Delta exports. NOD agricultural water users are minimally affected by a no overdraft policy on top of the base case with climate change except when there is also no reduction in Delta outflows.

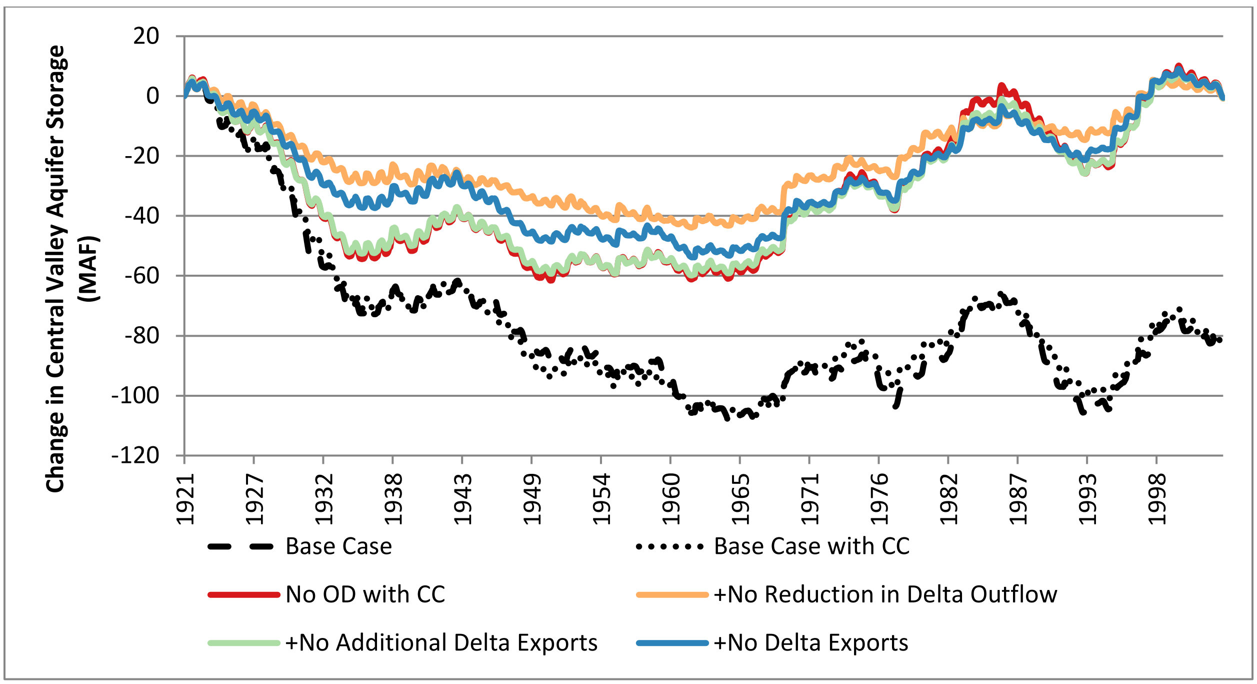
Table 13. Distribution of Annual Average Agricultural Scarcity Costs in the Central Valley

Agricultural Demand Area	Region	Annual Average Scarcity Cost ($M/year)					
		Base Case	Base Case with Climate Change	No Overdraft with Climate Change	+No Reduction in Delta Outflow	+No Additional Delta Exports	+No Delta Exports
CVMP01	USV	0.0	12.5	10.7	17.1	9.8	0.3
CVMP02	USV	0.3	20.3	27.9	40.2	28.9	8.0
CVPM03A	USV	-	25.0	28.1	269.3	32.6	6.5
CVPM03B	USV	0.1	8.0	8.2	29.0	10.6	2.8
CVPM04	USV	0.0	200.9	198.9	193.8	200.0	7.3
CVPM05	LSVD	0.5	45.8	153.1	431.5	264.9	5.0
CVPM06	LSVD	0.0	77.7	106.9	270.3	111.4	27.2
CVPM07	LSVD	-	93.8	100.9	117.7	96.7	0.9
CVPM08	LSVD	-	45.3	65.6	96.9	66.2	97.4
CVPM09	LSVD	5.6	101.0	143.8	402.5	221.7	8.2
CVPM10	SJSB	-	119.1	161.5	899.9	197.6	899.9
CVPM11	SJSB	0.0	60.9	72.8	265.6	82.2	652.3
CVPM12	SJSB	1.1	116.1	133.7	373.7	134.0	698.5
CVPM13	SJSB	0.1	213.9	236.1	348.9	270.4	1,021.1
CVPM14A	TB	-	30.0	38.4	202.6	50.7	778.7
CVPM14B	TB	-	1.5	2.8	24.8	4.6	68.4
CVPM15A	TB	-	155.6	288.8	445.2	339.3	445.2
CVPM15B	TB	0.0	3.1	3.2	5.9	3.3	5.9
CVPM16	TB	0.7	18.2	19.9	47.2	25.9	103.1
CVPM17	TB	0.3	30.9	30.9	62.5	30.9	115.9
CVPM18	TB	11.6	744.7	929.0	929.0	929.0	929.0
CVPM19A	TB	-	3.4	11.1	38.0	11.4	385.1
CVPM19B	TB	-	58.9	92.2	144.0	100.1	530.8
CVPM20	TB	0.0	36.8	36.8	102.3	53.3	322.4
CVPM21A	TB	-	90.6	131.3	399.8	241.2	399.8
CVPM21B	TB	-	8.7	12.7	25.9	15.1	49.1
CVPM21C	TB	-	1.3	2.8	6.2	2.9	19.9
Central Valley		**20**	**2,324**	**3,048**	**6,190**	**3,535**	**7,589**

Key:
$M = million dollars
LSVD = Lower Sacramento Valley and Delta
SJSB = San Joaquin and South Bay
TB = Tulare Basin
USV = Upper Sacramento Valley

Change in Groundwater Storage

Central Valley groundwater aquifer storage was modelled for the various water management cases over the 82-year hydrologic period (Figure 23). The historical hydrology and climate change base cases show similar results with each over 80 MAF in long-term overdraft. The Tulare Basin has the highest overdraft for both cases, and some northern California basins have zero or positive change in long-term storage. For the no overdraft with climate change cases, the initial and ending storages were set the same for each Central Valley groundwater sub-basin, making the net long-term overdraft zero as shown in Figure 23. Figure 23 also shows the filling and drawdown periods that each no overdraft case goes through to meet the no overdraft policy. In general, groundwater storage increases in wet years when surface water is in excess and recharged to aquifers, and decreases in dry years with additional pumping to meet demand. Both base cases have lower groundwater storage compared to the no overdraft with climate change cases for the whole 82-year period. The no overdraft cases vary the most from 1930 to 1980 with the no overdraft with climate change and no additional Delta export cases being the lowest storages. The no reduction in Delta outflow case shows the least reduction in groundwater storage during that period. Overall, there are two large drawdown and refill periods for the no overdraft with climate change cases, 1922 to 1986 (64 years) and 1986 to 2000 (14 years). These durations demonstrate the need to consider long-term groundwater planning for no groundwater overdraft policies to minimize economic impacts.



Key: CC = climate change MAF = million acre-feet OD = overdraft

Figure 23. Change in Central Valley Aquifer Storage

Artificial Recharge and Conjunctive Management

Groundwater basins in the Central Valley rely on conjunctive use management such as in lieu recharge from surface water irrigation return flows and artificial recharge to be sustainable. Artificial recharge increases groundwater storage by using available surface water and infiltrating it into the aquifer to balance groundwater pumping, and improve the long-term reliability of supply. Water is typically recharged using percolation ponds or injection wells during wetter periods when there is surplus surface water, and water is less expensive. That water is then stored in the aquifer for use during drier periods to reduce scarcities, also known as groundwater banking (Dogan, 2015b; Meillier at al, 2008). Several groundwater sub-basins in the Tulare Basin can artificially recharge because of suitable soils, and are included in CAVLIN (Figure 24). CALVIN also includes southern California groundwater sub-basins capable of artificial recharge. Return flows from agricultural and urban users are not considered in CALVIN as potential inflows for artificial recharge, but often are directed to recharge aquifers underlying fields, without additional cost (Dogan, 2015b).

Figure 24. CALVIN Central Valley Groundwater Sub-basins with Artificial Recharge (Dogan, 2015b)

Figure 25 shows monthly average artificial recharge statewide for the base cases and no overdraft with climate change cases. Climate change increases recharge in all months by at least 50 TAF/month compared to the base case and by as much as 300 TAF/month during winter months due to the time shift in precipitation. Artificial recharge increases the most with no overdraft and climate change compared to the other cases. While no Delta exports (exports to limited to 5% of allowable capacity) recharges the least among the other overdraft cases as surplus water cannot be exported from northern California through the Delta.

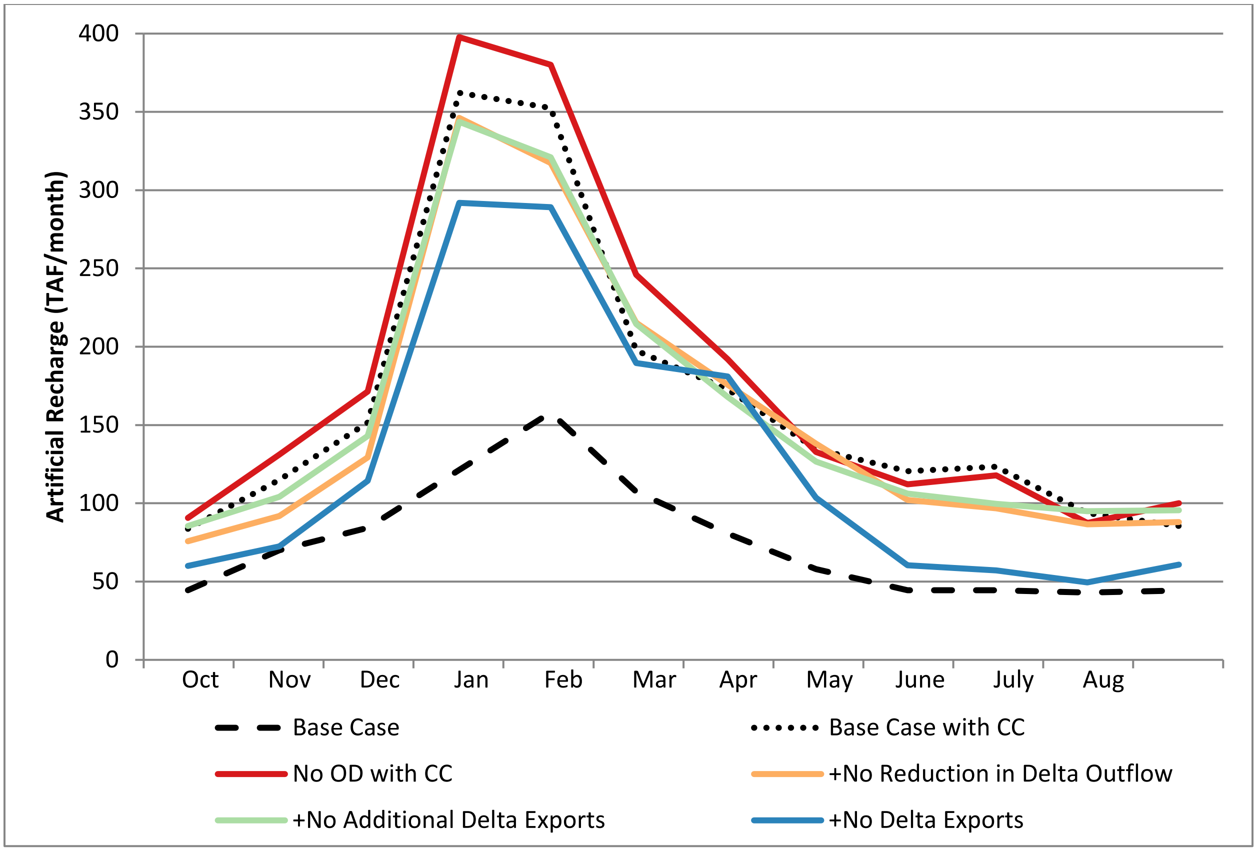


Figure 25. Monthly Average Artificial Recharge Statewide

With climate change, statewide artificial recharge is more than double the base case. Table 14 shows the annual average artificial recharge by region and case. Most climate change cases have similar artificial recharge amounts of 1.9 MAF per year. With no overdraft and climate change artificial recharge is as much as 2.2 MAF per year as the main constraint is to balance the groundwater table. With no Delta exports, annual average recharge is 1.5 MAF per year due to the Delta export constraint and high water scarcities.

Table 14. Annual Average Artificial Recharge Statewide

Case	Annual Average Artificial Recharge by Region (TAF/year)		
	Tulare Basin	Southern California	Statewide
Base Case	327	574	901
Base Case with Climate Change	1,321	574	1,993
No Overdraft with Climate Change	1,487	574	2,159
+No Reduction in Delta Outflow	1,208	571	1,863
+No Additional Delta Exports	1,230	574	1,903
+No Delta Exports	1,038	492	1,530

Key: TAF = thousand acre-feet

Statewide Summary

Statewide operating costs are very similar across the management cases, ranging from $4.8 to $5.5 billion per year (Table 15). Operating costs are broken out by desalination, diversions, groundwater pumping, groundwater recharge, surface water pumping, wastewater treatment, and water treatment. With climate change, costs decrease for surface water pumping and water treatment, but are made up with increased wastewater treatment. Prohibiting Central Valley overdraft increases wastewater treatment even more. With no reduction in Delta outflow and no Delta exports cases, wastewater treatment is the highest, and the lowest for groundwater and surface water pumping, and diversion costs as traditional supplies are less available.

Table 15. Annual Average Statewide Operating Costs by Management Case

Annual Average Operating Cost ($M/year)	Base Case	Base Case with CC	No OD with CC	+No Reduction in Delta Outflow	+No Additional Delta Exports	+No Delta Exports
Desalination	201	201	201	201	201	1,206
Local Distribution and Conveyance	925	819	820	707	821	613
GW Pumping	1,051	1,043	955	841	917	806
GW Recharge	13	21	22	19	20	17
SW Pumping	894	497	498	299	462	133
Wastewater Treatment	232	1,090	1,118	1,994	1,119	2,001
Water Treatment	1,630	1,267	1,261	956	1,260	747
Total	**4,947**	**4,939**	**4,876**	**5,017**	**4,801**	**5,523**

Key:
$M/yr = million dollars per year
CC = climate change
GW = groundwater
OD = overdraft
SW = surface water

Operating costs are considered in the total net statewide costs along with agricultural and urban scarcities, and hydropower benefit (Table 16). Agricultural and urban scarcity costs rise significantly with climate change, and increase more with the end of Central Valley overdraft due to lost production and conservation. Largely ending Delta exports has the worst agricultural and urban scarcity costs for all cases, which disproportionately affects SOD users. No reduction in Delta outflow is the next worst case, and more evenly spreads the impact statewide; although the Tulare Basin is affected most in all cases. Both cases have reduced hydropower benefits from decreased flows with climate change and less California Aqueduct exports.

Table 16. Annual Average Statewide Net Cost by Management Case

Item	Base Case	Base Case with CC	No OD with CC	+No Reduction in Delta Outflow	+No Additional Delta Exports	+No Delta Exports
Agricultural Scarcity Cost ($M/yr)	49	2,359	3,084	6,226	3,571	7,625
Urban Scarcity Cost ($M/yr)	93	599	621	1,203	633	1,613
Operating Cost ($M/yr)	4,947	4,939	4,876	5,017	4,801	5,523
Hydropower Benefit ($M/yr)	862	564	561	500	559	481
Net Statewide Cost ($M/yr)	**4,227**	**7,333**	**8,020**	**11,946**	**8,446**	**14,280**

Key: $M/yr = million dollars per year CC = climate change OD = overdraft

Water scarcities increase with the dry form of climate change and no Central Valley overdraft. Under the base case, scarcity is already 281 TAF per year. With climate change, this increases to 7.2 MAF per year while also decreasing the surplus Delta outflow by almost 5 MAF per year, which provides some alternative supply. No overdraft with climate change increases scarcities to 8.5 MAF per year while surplus Delta outflow remains the same. Surplus Delta outflow was unchanged because timing of these flows does not always coincide with demand. Larger storage facilities south of the Delta could be used to store these surplus flows. No reduction in Delta outflow has the worst Central Valley scarcity (14 MAF per year) as surplus Delta outflows cannot be used as a substitute supply for water supply losses due to climate change and ending overdraft.

Table 17. Annual Average Surplus Delta Outflow and Central Valley Water Scarcities

Item	Base Case	Base Case with CC	No OD with CC	+No Reduction in Delta Outflow	+No Additional Delta Exports	+No Delta Exports
Central Valley Scarcity (TAF/year)	281	7,164	8,520	14,011	9,430	11,839
Surplus Delta Outflow (TAF/year)	9,424	4,588	4,587	9,424	5,260	8,945

Conclusions

Water scarcities will increase with a warmer, drier climate, and even more so when trying to end Central Valley overdraft. It will bring less groundwater pumping and increase economic demands for surface water supplies. All regions except Southern California have a large reduction in agricultural surface water supplies. Scarcity costs from lost agricultural production increase with climate change by almost 50 times with the highest in the Tulare Basin, and San Joaquin and South Bay region as they have the greatest water scarcities and high value crops. Agricultural water users are disproportionately affected by scarcity, leading to less irrigated land statewide. The worst economic impact is to agricultural production because urban water users have higher user willingness-to-pay for water, and so seek to purchase available supplies. NOD water users will have relatively worse percent scarcities; however, total scarcities are much greater SOD. Scarcity costs can be compensated from water transfers and fallowing lower value crops.

Ending groundwater overdraft in the Central Valley increases economic demands for Delta exports. The Delta will continue to be central to the state's water issues and maintaining the existing levels of outflow will become very expensive for the state. The marginal value of Delta exports is higher for all management cases than in the base case. With climate change, exports increase during winter and almost all pumping capacity is used in January to capture surplus Delta outflow, whereas exports decrease during spring and summer compared to the base case. Increasing Delta exports is a useful adaptation to mitigate water supply impacts; however, potential future Delta constraints could limit this opportunity. On average, there is about 14.4 MAF per year in Delta outflow, of which only 5 MAF per year is required. If there is no reduction in Delta outflow, the state suffers worse scarcities than when there are no additional Delta exports because surplus Delta outflows are available to help compensate for climate change, forcing greater reductions in water use statewide. Water trading helps reduce scarcity costs to SOD water users from willing NOD sellers. Delta pumping capacity and SOD storage could be expanded to capture excess Delta outflows, which on average exceed required outflows during winter; but, this would be unavailable if total existing Delta outflows become required.

Urban water recycling and desalination increase statewide with climate change (supplying 2% to 5% of urban demand), while traditional surface water and groundwater supplies decrease due to reduced water availability. With no reduction in Delta outflow, all regions see more urban water conservation and scarcity with the Lower Sacramento Valley and Delta, and San Joaquin and South

Bay regions having the greatest increase in scarcity relative to their demands. In all conditions Southern California has the highest urban scarcity due to the reduction of SWP supplies and increased desalination.

Over the 82 year hydrologic period, there were two large drawdown and refill periods for the no overdraft with climate change cases (64 and 14 years), which demonstrate the need to consider long-term groundwater planning to minimize economic impacts. Artificial recharge is a useful conjunctive management action, and would increase with climate change in all months and especially during winter due to the time shift in precipitation. Artificial recharge increases more without overdraft, but is reduced when surplus Delta outflows cannot be exported.

This study demonstrated how California's water system reacts to ending groundwater overdraft in the Central Valley with climate change and uncertain future Delta operational constraints using a hydro-economic model. Water in California is crucial to urban and agricultural economies, which will suffer in a warmer-drier climate. SGMA will force many areas of the state to properly manage groundwater. These changes are inevitable and will require changes to the state's water management.

References

Bates, B. C., Kundzewicz, Z., Wu, S., and Palutikof, J. (2008). Climate Change and Water. In "Technical Paper of the Intergovernmental Panel on Climate Change", pp. 210, IPCC Secretariat, Geneva, Switzerland.

Bartolomeo, E. S. (2011). Economic responses to water scarcity in southern california. Master Thesis, University of California, Davis, Davis, CA.

Cayan, D., Luers, A., Franco, G., Hanemann, M., Croes, B., and Vine, E. (2008). Overview of the California climate change scenarios project. Climatic Change, 87(1), 1-6. http://doi.org/doi:10.1007/s10584-007-9352-2

California Department of Water Resources (DWR). (2015). How Water Is Used in California.

California Department of Water Resources (DWR). (2003). "California's Groundwater. DWR Bulletin 118." California Department of Water Resources, Sacramento, CA.

California Department of Water Resources (DWR). (2009). The California Water Plan, Update, Bulletin 160-09. Sacramento, California. December.

California Department of Fish and Wildlife (CDFW) (formerly California Department of Fish and Game). (1970). Fish Bulletin 151: Migrations of Adult King Salmon Oncorhynchus tshawytscha In The San Joaquin Delta As Demonstrated by the Use of Sonic Tags.

Chou, H. (2012). Groundwater overdraft in California's Central Valley: updated CALVIN modeling using recent CVHM and C2VSIM representations. Master Thesis, University of California, Davis, Davis, CA.

Connell-Buck, C., Medellín-Azuara, J., Lund, J., and Madani, K. (2011). Adapting California’s water system to warm vs. dry climates. Climatic Change, 109(1), 133-149. http://doi.org/doi:10.1007/s10584-011-0302-7

Connell, C. R. (2009). Bring the Heat, but Hope for Rain: Adapting to Climate Warming for California. Master Thesis, University of California, Davis, Davis, CA.

Custodio, E. (2002). Aquifer overexploitation: what does it mean? Hydrogeology Journal, 10(2), 254-277. http://doi.org/10.1007/s10040-002-0188-6

Dogan, M.S. (2015a). CALVIN Surface and Groundwater Hydrology Perturbation Processes. University of California, Davis, Davis, CA.

Dogan, M.S. (2015b). Integrated Water Operations in California: Hydrology, Overdraft, and Climate Change. Master Thesis, University of California, Davis, Davis, CA.

Dracup, J. A., and Vicuna, S. (2005). An Overview of Hydrology and Water Resources Studies on Climate Change: The California Experience. In "Impacts of Global Climate Change", pp. 1-12. doi:10.1061/40792(173)483

Draper, A. J. (2000a). "Appendix I: Surface Water Hydrology." University of California, Davis, Davis, CA.

Draper, A. J. (2000b). "Appendix K: Irrigation Water Requirements." University of California, Davis, Davis, CA.

Draper, A. J. (2001). Implicit stochastic optimization with limited foresight for reservoir systems. Dissertation, University of California, Davis.

Draper, A. J., Jenkins, M. W., Kirby, K. W., Lund, J. R., and Howitt, R. E. (2003). Economic-Engineering Optimization for California Water Management. Journal of Water Resources Planning and Management, 129(3), 155-164. http://doi.org/doi:10.1061/(ASCE)0733-

9496(2003)129:3(155)
Draper, A. J., Munévar, A., Arora, S. K., Reyes, E., Parker, N. L., Chung, F. I., and Peterson, L. E. (2004). CalSim: Generalized Model for Reservoir System Analysis. Journal of Water Resources Planning and Management, 130(6), 480-489. http://doi.org/doi:10.1061/(ASCE)0733-9496(2004)130:6(480)
Faunt, C. C. (2009). Groundwater availability of the Central Valley Aquifer, California. Reston, VA.: U.S. Geological Survey.
Ficklin, D. L., Stewart, I. T., and Maurer, E. P. (2013). Effects of climate change on stream temperature, dissolved oxygen, and sediment concentration in the Sierra Nevada in California. Water Resources Research, 49(5), 2765-2782. http://doi.org/10.1002/wrcr.20248
Gorelick, S. M., and Zheng, C. (2015). Global change and the groundwater management challenge. Water Resources Research. http://doi.org/10.1002/2014WR016825
Grabert, V. K., and Narasimhan, T. N. (2006). California's evolution toward integrated regional water management: a long-term view. Hydrogeology Journal, 14(3), 407-423. http://doi.org/10.1007/s10040-005-0005-0
Hanak, E., and Lund, J. R. (2012). Adapting California’s water management to climate change. Climatic Change, 111(1), 17-44. http://doi.org/doi:10.1007/s10584-011-0241-3
Hancock, K., Chung, C.-F., and Mills, W. (2004). Climate Change and its Effects on California Water Resources. In "Critical Transitions in Water and Environmental Resources Management", pp. 1-8. doi:10.1061/40737(2004)19
Harou, J. J., and Lund, J. R. (2008). Ending groundwater overdraft in hydrologic-economic systems. Hydrogeology Journal, 16(6), 1039-1055. http://doi.org/doi:10.1007/s10040-008-0300-7
Hazen and Sawyer (2016). Analysis of Changes in Water Use Under Regional Climate Change Scenarios. http://www.hazenandsawyer.com/work/projects/waterrf-project-4263-analysis-of-changes-in-water-use-under-regional-climat/
Howitt, R. E., Medellín-Azuara, J., MacEwan, D., and Lund, J. R. (2012). Calibrating disaggregate economic models of agricultural production and water management. Environmental Modelling & Software, 38(0), 244-258. http://doi.org/10.1016/j.envsoft.2012.06.013
Ilich, N. (2008). Shortcomings of linear programming in optimizing river basin allocation. Water Resources Research, 44(2). http://doi.org/10.1029/2007WR006192
Ireland, R.L. (1986). Land Subsidence in the San Joaquin Valley, California as of 1983, U.S. Geological Survey Water Resources Investigations Report 85-4196.
Konikow, L., and Kendy, E. (2005). Groundwater depletion: A global problem. Hydrogeology Journal, 13(1), 317-320. http://doi.org/10.1007/s10040-004-0411-8
Knapp, K., and Vaux, H. J. (1982). Barriers to Effective Ground-Water Management: The California Case. Groundwater, 20(1), 61-66.
Lettenmaier, D. P., and Sheer, D. P. (1991). Climatic Sensitivity of California Water Resources. Journal of Water Resources Planning and Management, 117(1), 108-125. http://doi.org/doi:10.1061/(ASCE)0733-9496(1991)117:1(108)
Lund, J.R. (2016). Inevitable Changes to Water in California. California WaterBlog. https://californiawaterblog.com/2016/05/08/inevitable-changes-to-water-in-california/

Lund, J. R., R. E. Howitt, J. Medellin-Azuara, M. W. Jenkins. (2009). Water Management Lessons for California from Statewide Hydro-economic Modeling Using the CALVIN Model.

Madani, K. and J.R. Lund. (2010). "Estimated Impacts of Climate Warming on California's High Elevation Hydropower," Climatic Change, Vol. 102, No. 3-4, pp. 521–538, October 2010.

Meillier, L., Loáiciga, H. A., and Clark, J. F. (2008). Groundwater Dating and Flow-Model Calibration in the Kern Water Bank, California. *Journal of Hydrologic Engineering, 13*(11), 1029-1036. http://doi.org/10.1061/(ASCE)1084-0699(2008)13:11(1029)

Miller, N. L., Bashford, K. E., and Strem, E. (2003). Potential Impacts of Climate Change on California Hydrology. JAWRA Journal of the American Water Resources Association, 39(4), 771-784. http://doi.org/doi:10.1111/j.1752-1688.2003.tb04404.x

Nelson, T. J. (2014). Using the updated CALVIN model to develop optimized reservoir operations for the Sacramento Valley. Master Thesis, University of California, Davis, Davis, CA.

Phinney, S., California Energy, C., Systems, A., Facilities Siting, D., Aspen Environmental, G., and Management, M. C. A. (2005). Potential changes in hydropower production from global climate change in California and the western United States. [Sacramento]: California Energy Commission.

Poland, J.F., B.E. Lofgren, R.L. Ireland, and R.G. Pugh. (1975). Land Subsidence in the San Joaquin Valley, California, As of 1972 (Studies of Land Subsidence), U.S. Geological Survey Professional Paper 437-H.

Tanaka, S., Zhu, T., Lund, J., Howitt, R., Jenkins, M., Pulido, M., Tauber, M., Ritzema, R., and Ferreira, I. (2006). Climate Warming and Water Management Adaptation for California. Climatic Change, 76(3-4), 361-387. http://doi.org/doi:10.1007/s10584-006-9079-5

U.S. Department of the Interior, Bureau of Reclamation (Reclamation). (2014a). Upper San Joaquin River Basin Storage Investigation, Draft Feasibility Report. January.

U.S. Department of the Interior, Bureau of Reclamation (Reclamation). (2014b). Upper San Joaquin River Basin Storage Investigation, Draft Environmental Impact Statement. August.

U.S. Department of the Interior, Bureau of Reclamation (Reclamation). (2016). Mid-Pacific Region, About the Central Valley Project. Updated May 18, 2016. Available at: http://www.usbr.gov/mp/cvp/about-cvp.html.

VanRheenen, N. T., Wood, A. W., Palmer, R. N., Payne, J. T., and Lettenmaier, D. P. (2001). The Effects of Climate Change on Water Management Strategies and Demands in the Central Valley of California. In "Bridging the Gap", pp. 1-10. doi:10.1061/40569(2001)329

Vasconcelos, J. J. (1987). Water resources management in the semi-arid central valley of California. Water Science & Technology, 19(9), 97-106.

Vicuna, S., and Dracup, J. A. (2007). The evolution of climate change impact studies on hydrology and water resources in California. Climatic Change, 82(3-4), 327-350. http://doi.org/doi:10.1007/s10584-006-9207-2

Vicuna, S., Dracup, J. A., Lund, J. R., Dale, L. L., and Maurer, E. P. (2010). Basin-scale water system operations with uncertain future climate conditions: Methodology and case studies. Water Resources Research, 46(4). http://doi.org/doi:10.1029/2009WR007838

Vicuna, S., Maurer, E. P., Joyce, B., Dracup, J. A., and Purkey, D. (2007). The Sensitivity of California Water Resources to Climate Change Scenarios1. JAWRA Journal of the

American Water Resources Association, 43(2), 482-498. http://doi.org/doi:10.1111/j.1752-1688.2007.00038.x

Water Education Foundation. (WEF). (2015). The 2014 Sustainable Groundwater Management Act: A Handbook to Understanding and Implementing the Law.

Williamson, A.K., D.E. Prudic, and L.A. Swain. (1989). Groundwater Flow in the Central Valley, California, U.S. Geological Survey Professional Paper 1401-D, 127 p.

Zektser, S., Loáiciga, H. A., and Wolf, J. T. (2005). Environmental impacts of groundwater overdraft: selected case studies in the southwestern United States. Environmental Geology, 47(3), 396-404. http://doi.org/10.1007/s00254-004-1164-3

Zhu, T., M. W. Jenkins, J. R. Lund. (2003). Appendix A: Climate Change Surface and Groundwater Hydrologies for Modeling Water Supply Management. University of California, Davis, Davis, CA.

Zhu, T., Jenkins, M. W., and Lund, J. R. (2005). Estimated Impacts of Climate Warming on California Water Availability under Twelve Future Climate Scenarios. JAWRA Journal of the American Water Resources Association, 41(5), 1027-1038. http://doi.org/10.1111/j.1752-1688.2005.tb03783.x

Zikalala, P. G. (2013). Representing groundwater management in California's Central Valley: CALVIN and C2VSIM. Master Thesis, University of California, Davis, Davis, CA.