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Climate Change Adaptations for Local Water Management in the San Francisco Bay Area

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CLIMATE CHANGE ADAPTATIONS FOR LOCAL WATER MANAGEMENT IN THE SAN FRANCISCO BAY AREA

A White Paper from the California Energy Commission's California Climate Change Center

Prepared for: California Energy Commission

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PREFACE

The California Energy Commission's Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California. The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

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- Energy Innovations Small Grants
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- Environmentally Preferred Advanced Generation
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- Renewable Energy Technologies
- Transportation

In 2003, the California Energy Commission's PIER Program established the California Climate Change Center to document climate change research relevant to the states. This center is a virtual organization with core research activities at Scripps Institution of Oceanography and the University of California, Berkeley, complemented by efforts at other research institutions.

For more information on the PIER Program, please visit the Energy Commission's website http://www.energy.ca.gov/research/index.html or contract the Energy Commission at (916) 327-1551.

ABSTRACT

Climate change will affect both sea level and the temporal and spatial distribution of runoff in California. These climate change impacts will affect the reliability of water supplies and operations of California's water supply system. To meet future urban water demands in the San Francisco Bay Area, local water managers can adapt by changing water supply portfolios and operations. An engineering economic model, CALVIN, which optimizes water supply operations and allocations for the State of California, was used to explore the effects on water supply of a severely warm dry climate and substantial sea level rise, and to identify economically promising long-term adaptations for San Francisco Bay Area water systems. This reconnaissance level modeling suggests that even under fairly severe forms of climate change, Bay Area urban water demands can be largely met, but at a cost. Costs are from purchasing water from agricultural users (with agricultural opportunity costs), more expensive water supply alternatives such as water recycling and desalination, and some increases in water scarcity (costs of water use reduction). The modeling also demonstrates the importance of water transfer and intertie infrastructure to facilitate flexible water management among Bay Area water agencies. The intertie capacity developed by Bay Area agencies for emergencies, such as earthquakes, becomes even more valuable for responding to severe changes in climate.

Keywords: water supply, San Francisco Bay Area, engineering economic model, climate change, optimization

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SECTION 1: Introduction

A changing climate will affect California's water supply management. The western United States and California can expect a shift in the temporal and spatial distribution of precipitation causing changes to streamflow, snowpack accumulation, snowmelt, and evapotranspiration (Cayan et al. 2009; Cayan et al. 2008b; Hamlet et al. 2007; Miller et al. 2003). These changes will affect the magnitude and timing of inflows into California's water supply system affecting costs, operations, and allocations of water.

Increases in average global temperature will also accelerate global sea level rise. Current projections suggest a range of mean sea level rise 30 to 45 centimeters (cm) from year 2000 levels by 2050 (Cayan et al. 2009; Cayan et al.2006). Sea level rise will shift salinity of the Sacramento-San Joaquin Delta (Delta) inland (Fleenor 2008; Williams 1985, 1987). Historically the Delta had behaved as a typical submerged delta estuary with shifts in salinity. For the last 70 years, the Delta has been maintained as a fresh water system through flow regulation and levee and Delta island maintenance. Combined with canals, aqueducts, pumps and storage reservoirs, a freshwater Delta facilitates the transfer of fresh water from the northern part of the state to the San Francisco Bay Area, San Joaquin and Tulare basins, and Southern California. Sea level rise accompanied by a change in the Delta salinity could significantly affect the use of the Delta as the hub of California's water supply system (Lund et al. 2010).

Urban water management plans (UWMP) in California describe how water agencies plan to meet water demand under current hydrologic conditions and short-term and extended droughts. The California Department of Water Resources (DWR) requires updates to the UWMP every five years, with the 2005 versions being the most recent finalized update at the time of this analysis and writing. In the San Francisco Bay Area, under current hydrologic conditions urban water agencies rely on a portfolio of water sources including local inflows, groundwater (banking and pumping), water conservation, imported and transferred water, and water recycling. To mitigate potential shortages during droughts, the water plans call for minimizing reliance on imported water through water conservation, expanded water recycling, desalination, firming up existing water transfer agreements, and entering into spot transfer or short-term water transfer agreements (Napa UWMP 2005; Sonoma UWMP 2005; CCWD UWMP 2005; EBMUD UWMP 2005; Marin UWMP 2005; North Marin UWMP 2005; SFPUC UWMP 2005; SCVWD UWMP 2005; Zone 7 UWMP 2005). More recent 2010 versions of local UWMPs are now available and East Bay Municipal Water District's (EBMUD) new investigation of expanding Contra Costa Water District's (CCWD) Los Vaqueros reservoir both indicate the increasing sophistication of water planning in this region and the practical capability to respond to many future changes with considerable flexibility (albeit at some inconvenience and cost), as demonstrated by the results of our study.

This modeling effort preliminarily explores potential effects of severe climate change on urban water supply in the San Francisco Bay Area. Water scarcity and costs of climate change are examined. Additionally, we identify important water supply infrastructure, and explore management actions such as increased water recycling, desalination, and water transfers to mitigate potential climate change impacts to the San Francisco Bay Area. The results of this modeling approach have limitations based on the simplification of the real world, assumptions necessary to model over a large scale, and because an optimization model uses an optimistic representation of what can be done institutionally. Some limitations are presented in Section 4.2 and more can be found in other reports and publications (Jenkins et al. 2001; Newlin et al. 2002; Draper et al. 2003; Tanaka et al. 2008; Jenkins et al. 2004; Pulido-Velázquez et al. 2004; Null and Lund 2006; Tanaka et al. 2006; Lund et al. 2007; Medellín-Azuara et al. 2008, Connell-Buck 2011).

This paper begins with an overview of the modeling approach used, including how the climate change cases are modeled. The next section presents and discusses the modeling results under several severe climate change cases, including water scarcity and the operating and scarcity costs, water supply portfolios, and infrastructure importance and expansion. The last section is a brief conclusion.

SECTION 2: Modeling Approach

To better understand the local water management impacts from and adaptations to climate change in the context of statewide water supply management, a large scale economic-engineering optimization model, California Value Integrated Network (CALVIN), is employed. A large scale optimization model can identify preliminary qualitative management options based on the details of system operations evaluated in future detailed simulation modeling of individual water supply systems.

2.1 CALVIN

2.1.1 Model

CALVIN is an engineering optimization model of California's statewide intertied water supply system. Overall, CALVIN operates and allocates surface water and groundwater resources to minimize scarcity and operating costs, within the physical and environmental constraints of California's water supply system and selected policy constraints (Draper et al. 2003).

CALVIN has been employed to explore various water management issues in California including conjunctive management of groundwater and surface water resources in Southern California, various forms of climate change, water markets in Southern California, and economic and water management effects of changes in Delta exports (Jenkins et al. 2001; Newlin et al. 2002; Draper et al. 2003; Tanaka et al. 2008; Jenkins et al. 2004; Pulido-Velázquez et al. 2004; Null and Lund 2006; Tanaka et al. 2006; Lund et al. 2007; Medellín-Azuara et al. 2008, Connell-Buck 2011).

CALVIN is a generalized network flow model that uses the optimization solver Hydrologic Engineering Center's Prescriptive Reservoir Model (HEC-PRM)provided by the U.S. Army Corps of Engineers. CALVIN represents only California's intertied water supply network, and includes 31 groundwater basins, 53 reservoirs, and 30 urban and 24 agricultural economically represented water demand areas (Figure 1) covering 92 percent of California's population and 88 percent of its irrigated land.

To characterize the water supply network, CALVIN requires many physical, policy, and economic parameters and physical inputs. Specification of physical parameters must include conveyance (canals, aqueducts, rivers, and streams), pumping plant, power plant, reservoir capacities, and reservoir operating rules (flood storage levels). Policy parameters include environmental requirements (minimum stream flow regulations) and inter-agency or inter-basin water transfer agreements (specified as capacities along a transfer intertie). Economic parameters include variable operating costs of water treatment, recycling, conveyance, hydropower, and groundwater pumping facilities and agricultural and urban demand functions. Hydrologic inputs to the model include surface water and groundwater inflow time series and return flow coefficients.

CALVIN operates the physical infrastructure and allocates water within the system's constraints to minimize statewide costs. The costs in the model are scarcity costs and operating costs. Scarcity occurs when an urban or agricultural delivery target is not met, and is defined as the difference between the target delivery (the amount of water for which the user is willing to pay) and the volume of water delivered. Shortage (scarcity) costs are assigned to the unmet demand based on the user's economic willingness-to-pay (WTP) for additional water delivered.

In this modeling exercise, urban and agricultural water demand levels are estimated for the year 2050 level of development. Urban and agricultural water demand functions were scaled to 2050 population. Urban water demand is based on data from Landis and Reilly (2002) for estimates of population and land use projected for 2050 and projected per capita urban water use by the detailed analysis unit from DWR. The development of urban demand functions used in CALVIN including assumptions and limitations are described by Jenkins et al. (2003) and Medellín-Azuara et al. (2008). Agricultural demands and demand functions were developed using the Statewide Agricultural Production model (SWAP) (Howitt et al. 2001).

Figure 2 displays CALVIN input and output. Equation 1 is the formulation of the objective function used in CALVIN, and equations 2 through 4 are the constraints.

Formulation:

Minimize: $Z = \sum_i \sum_j c_{ij} X_{ij},$ (1)

Subject to: $\sum_i X_{ij} = \sum_i a_{ij} X_{ij} + b_j$, for all nodes j, (2)

$X_{ij} \leq u_{ij}$ for all arcs, (3)

$X_{ij} \geq l_{ij}$ for all arcs, (4)

where Z is the total cost of flows throughout the network, X_{ij} is flow volume leaving node i towards node j, c_{ij} = economic costs (agricultural or urban), b_j = external inflow volumes to node j, a_{ij} = gains/losses on flows in arc ij, u_{ij} = upper bound on arc ij, and l_{ij} = lower bound on arc ij.

Although the model does not explicitly include water quality, costs and constraints often are used to represent water quality considerations. For example treatment costs for different water sources vary by their water quality. Also, constraints limit the availability of some water sources due to their water quality or their ability to be blended with better quality water. Similarly, to reflect limits on introducing recycled water into potable water systems, use of existing recycled water is limited by cost constraint and expanded water recycling capacity is limited by an increased cost constraint. More detailed representation of such water quality concerns are typically examined in later more detailed analyses. Many Bay Area utilities make considerable use of multiple water sources of differing qualities.

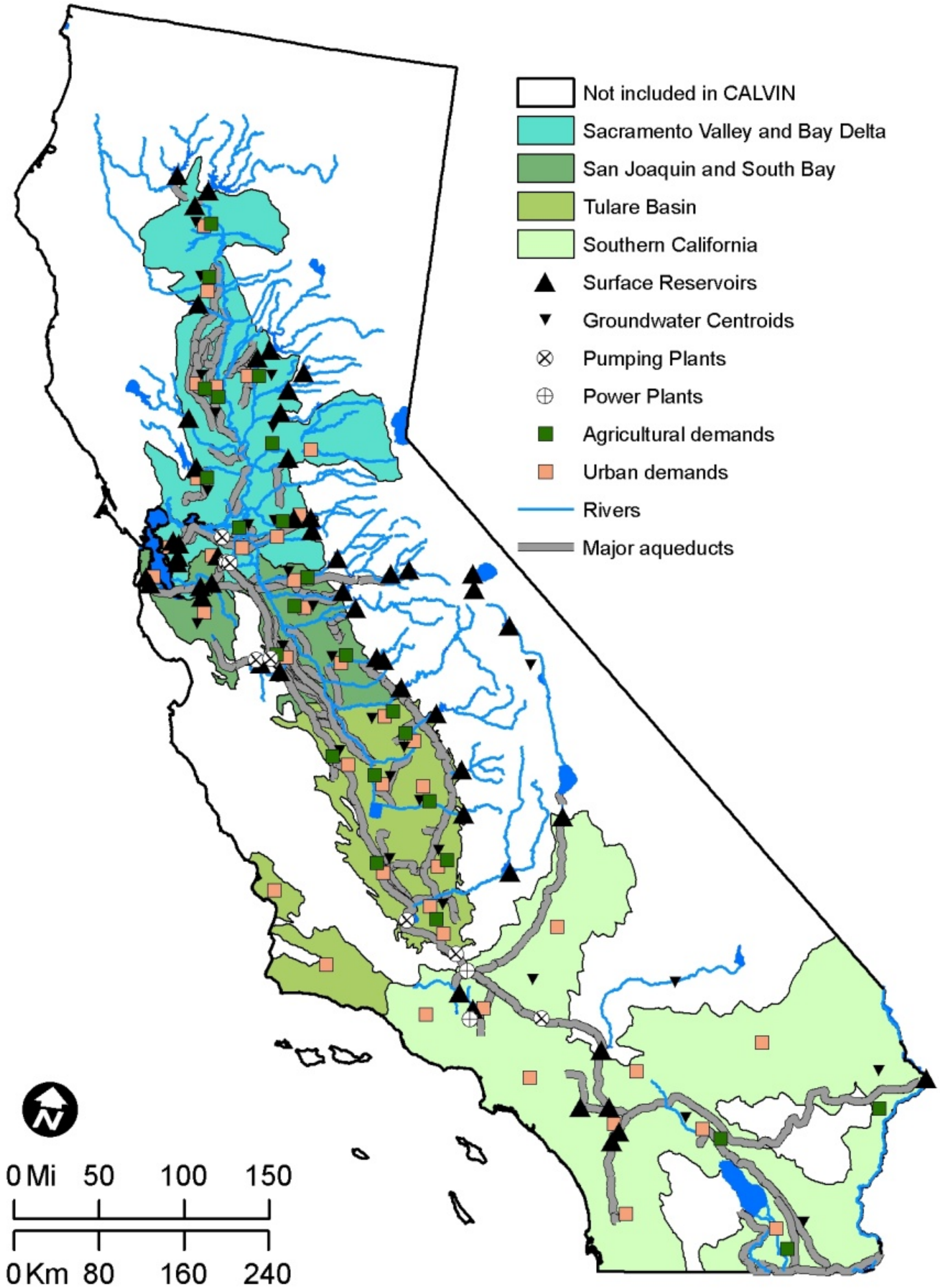


Figure 1: Water Supply Infrastructure, Inflows and Demand Areas Represented in CALVIN

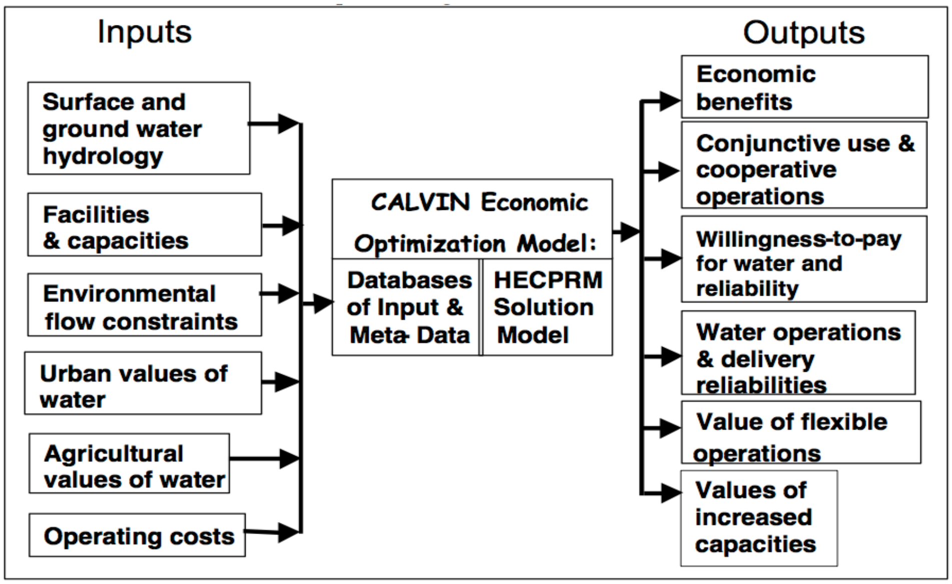


Figure 2: CALVIN Data Flow

2.1.2 Operating Costs

Water supply from surface water and groundwater are subject to operating costs of pumping, artificial recharge, and treatment. The development of generalized variable operating costs used in CALVIN are discussed in detail in a CALFED Bay-Delta Program report, *Improving California Water Management: Optimizing Value and Flexibility* (Jenkins, 2001). CALVIN models most major facilities of California's intertied water supply system including recently completed Bay Area infrastructure such as the Freeport Regional Water Project (FRWP), the EBMUD-Hayward-San Francisco Public Utilities Commission (SFPUC) Intertie, and the EBMUD-CCWD Intertie. Urban areas were assumed to be able to recycle a portion of their wastewater flows (limited to local non-potable use). Urban areas with projected water recycling capacity by 2020 can use this capacity as baseline recycling capacity at a cost of $500 per acre-ft. Urban areas with plans to expand water recycling capacity by 2050 were given expanded recycling capacity, up to 50 percent of urban wastewater flows, at a cost of $1,500 per acre-foot. Additionally, urban coastal areas were allowed desalination at a cost of $2,100 per acre-foot. The cost of recycled water and desalination is variable across the state and dependent on treatment plant location, operation, conveyance system availability, and treatment standards. CALVIN uses general estimates of variable costs initially taken from California Department of Water Recourses Bulletin 160-98. The water recycling and desalination variable costs are discussed in detail by Jenkins et al. (2001) and were updated in the CALVIN model by Bartolomeo (2011). Water recycling and desalination are capital intensive projects and ideally would be modeled as two-stage optimization with initial capital cost decisions and then operating costs decisions. In this study, we model total average annualized costs as operating costs. All costs are in 2008 dollars.

2.1.3 Bay Area Demand Locations

Many water supply wholesalers and retailers (e.g., water districts, public utility commissions, irrigation districts) operate within and across county boundaries in California. Figure 3a shows service areas of major water supply purveyors within the nine counties of the San Francisco Bay area. CALVIN is a large scale model, and as such, it aggregates the water purveyors who receive deliveries from the intertied water supply network into agricultural and urban demand locations. Aggregation is based on proximity, and outtake from the network. Figure 3b illustrates aggregation of urban water demand in the nine Bay Area counties.

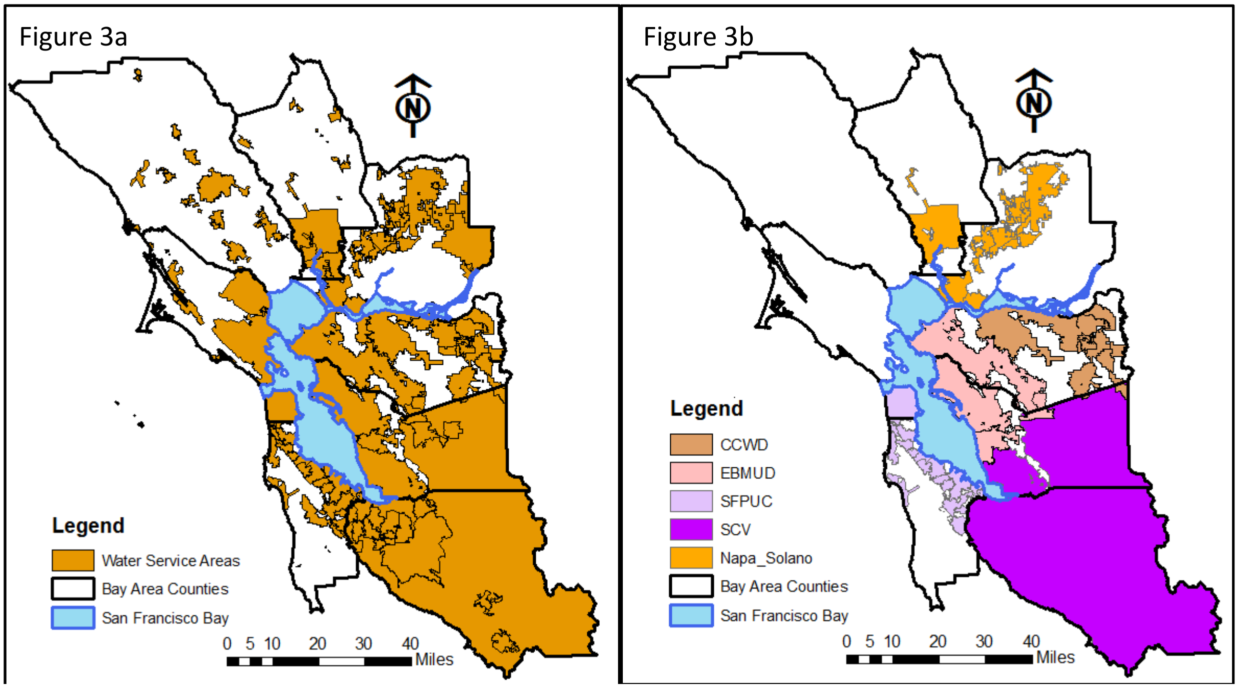


Figure 3: Water Supply Retailers and Wholesalers in the Nine San Francisco Bay Area Counties. Figure 3a shows the boundaries of individual water service areas in the San Francisco Bay Area. Figure 3b shows the aggregated CALVIN urban demand locations in the San Francisco Bay Area.

2.1.4 Supply Sources and Infrastructure

Five urban demand locations in CALVIN represent the San Francisco Bay Area portion of California's intertied water supply system. Each demand area has access to a variety of water sources to meet demand and increase water supply reliability. Many water sources rely on specialized infrastructure to treat or convey the water. Water sources and associated infrastructure for each demand area appear in the CALVIN schematic in Figure 4 and conceptually in Figure 5.

The water supply for Napa-Solano is primarily United States Bureau of Reclamation's (USBR) Central Valley Project (CVP) water stored in Lake Berryessa and conveyed through the South Putah Canal and DWR's State Water Project (SWP) water pumped from the Sacramento River north of the Delta and conveyed through the North Bay Aqueduct. Napa-Solano has access to small amounts of groundwater to supply Dixon and rural north Vacaville. Other sources include water recycling (Napa UWMP 2005; Cal Water Dixon UWMP 2005).

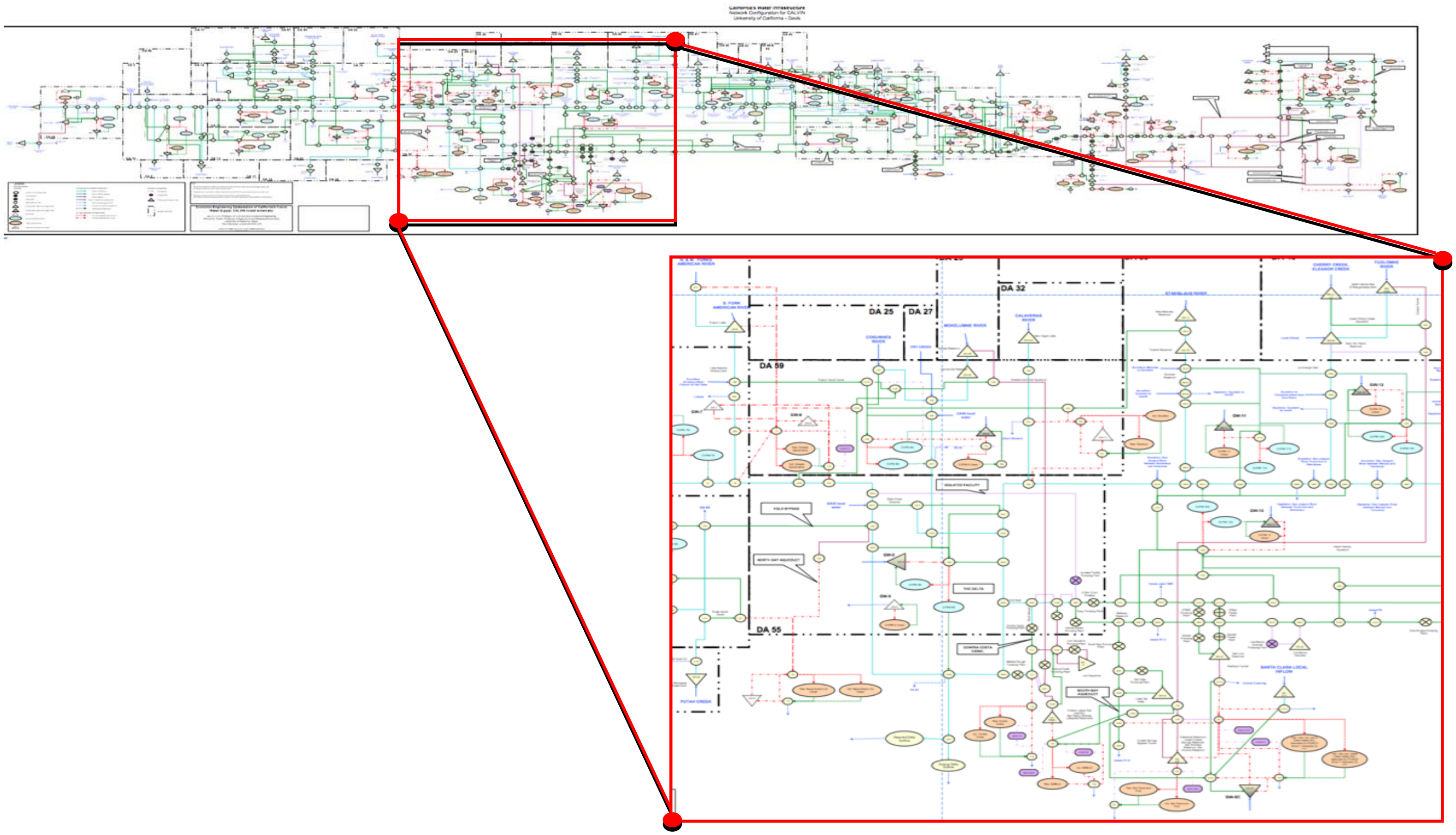
Contra Costa Water District has its own water rights and also relies on USBR CVP water. It accesses this water through pumping plants in the Delta (Mallard Slough, Rock Slough, and San

Joaquin River). Other sources include water transfers along the EBMUD-CCWD Intertie and water recycling (CCWD UWMP 2005). The EBMUD-CCWD Intertie was built for use in emergencies. For modeling future operations, seawater desalination is included as a water source for CCWD.

The East Bay Municipal Utility District relies primarily on imported water from the Mokelumne River Aqueduct. The Aqueduct carries water from the Mokelumne River stored in EBMUD's Pardee Reservoir, and some Sacramento River water conveyed through the recently completed USBR South Folsom Canal and Freeport Regional Water Project facilities. Other sources include water recycling and water transfers along the recently completed EBMUD-Hayward-SFPUC Intertie (EBMUD UWMP 2005). For modeling future operations, seawater desalination is included as a water source for EBMUD.

San Francisco Public Utilities Commission (SFPUC) relies principally on water imports from the Hetch Hetchy Reservoir on the Tuolumne River through the Hetch Hetchy Aqueduct. Hetch Hetchy reservoir is operated by SFPUC for water supply and hydropower. Other sources include water recycling and water transfers along the recently completed EBMUD-Hayward-SFPUC Intertie, and some local service area inflows (omitted from the model due to data availability) (SFPUC UWMP 2005). For modeling future operations, seawater desalination is included as a water source for SFPUC.

In CALVIN, Santa Clara Valley water districts (SCV) include Santa Clara Valley Water District, Alameda County Water District, and Zone 7 Water Agency, the primary water suppliers of Alameda and Santa Clara counties. The SCV has access to a diverse water supply portfolio. The SWP and CVP water is exported through Delta pumping and conveyed by the South Bay Aqueduct and San Luis Reservoir-Pacheco Tunnel respectively. Other water imports include SFPUC service to areas of northern Santa Clara Valley to supplement water supply or to recharge groundwater. The SCV employs conjunctive use of surface and groundwater by banking local, imported, and recycled water in over drafted aquifer space, giving it large naturally and artificially recharged groundwater supplies in the Livermore and Santa Clara Valleys. Other sources include water recycling (SCVWD UWMP 2005; Alameda County UWMP 2005; Zone 7 UWMP 2005). For modeling future operations, seawater desalination is included as a water source for SCV.



*Due to the size of the CALVIN schematic, a legible version would not fit in this document. An electronic version is available at http://cee.engr.ucdavis.edu/faculty/lund/CALVIN/#Statewide_Water_Model_Schematics.

Figure 4: CALVIN Schematic. Schematic representation of water supply infrastructure and water supply sources that contribute to meeting demand in the San Francisco Bay Area.

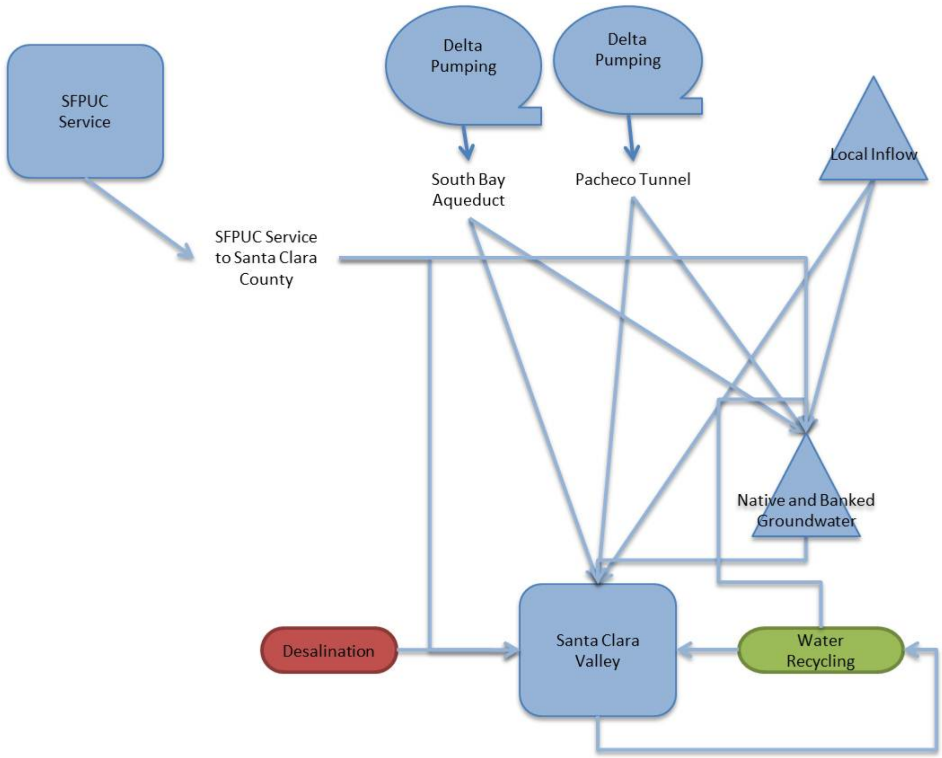


Figure 5: Conceptualization of Aggregate Demand Areas in the San Francisco Bay Area

2.1.5 Hydrology

In CALVIN, hydrologic variability is represented using 72 years of monthly hydrology data (1921–1993). Hydrologic representation includes surface water inflows (rim inflows) and urban and agricultural return flows to surface and groundwater. Hydrologic inflows come from existing surface and integrated surface-groundwater models (Draper et al. 2003; Jenkins et al. 2001; Zhu et al. 2005).

CALVIN makes water management decisions for each month. For each CALVIN optimization, model results include time series of urban and agricultural water deliveries; stream, canal, and aqueduct flows; deliveries for each demand area; marginal value of additional water at every node in the network; the economic shadow values of the binding constraints; and the storage volumes in reservoirs and groundwater basins. Analysis and interpretation of these results provide insights into promising water management alternatives.

2.2 Modeling Climate Change

Two distinct climate changes are expected to affect water supply in California: changes in hydrology and sea level rise. Hydrologic change will be in the form of spatial and temporal distribution precipitation and streamflow. Sea level rise will affect salinity in the Sacramento-San Joaquin Delta (DWR 2009). Five climate cases will consider these two climate change impacts. The cases are (1) a future climate with a warm dry hydrology, (2) a future climate with historical hydrology and sea level rise that results in a 50 percent reduction diversion capacity from the Delta, (3) a future climate with historical hydrology and sea level rise that results in no exports or diversions from the Delta, (4) a future climate with both warm dry hydrology and sea level rise that results in a 50 percent reduction in diversion capacity from the Delta, and (5) a future climate with both warm dry hydrology and sea level rise that results in no exports or diversions from the Delta.

2.2.1 Hydrologic Change

Global Circulation Models (GCMs) are often used to model climate change considering a range of emissions, population growth, socio-economic development, and technological progress. The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report 2007 describes these scenarios and summarizes climate change (temperature and precipitation) projections (Christensen et al. 2007). The regional results of these models and scenarios for California are discussed by Cayan et al. (2008). Perturbation of surface water inflows to the CALVIN model, and changes in evaporation rates from surface water reservoirs was completed to simulate a future warm dry climate (Connell 2008, Connell-Buck 2011). Connell-Buck used downscaled effects of the Geophysical Fluid Dynamics Laboratory (GFDL) CM2.1 model with a climate emissions scenario with relatively high emissions (A2)to create a warm dry input hydrology for CALVIN. The warm dry climate effectively reduced overall inflows to CALVIN by about 27 percent on average, but inflow reduction percentages varied over model domain. For input into CALVIN, the NOAA Geophysical Fluid Dynamics Laboratory CM2.1 A2 emissions scenarios were downscaled to capture the effects of a warm dry form of climate change by year 2050 (Medellín-Azuara et al. 2009; Medellín-Azuara et al. 2008). The methods described in Zhu et al. (2005) were employed to perturb historical (1921–1993) time series of rim inflows in CALVIN, temperature and precipitation The temperature and precipitation from the downscaled GFDL CM2.1 A2 scenario for a period of 30 years centered in year 2085 were employed indicating a 2°C (3.6°F) increase in temperature and 3.5 percent decrease in precipitation in California's Central Valley.

2.2.1.1 Rim Inflows

Perturbation ratios for surface stream flows were built comparing a 30-year historical period centered in year 1979 with a future 30-year time period centered in year 2085. Downscaling of the GFDL CM2.1 A2 was translated into six rivers including the rain-fed Smith River at Jed Smith Park, the Sacramento River at the Delta, the Feather River at Oroville Dam, the American River at North Fork Dam, the Merced River at Pohono Bridge, and Kings River at Pine Flat Dam. These were employed in Medellín-Azuara et al. (2008) following the methods in Miller et al.(2003). Connell (2008) expanded the number of index rivers to 18, and showed that there were no significant gains in precision from adding more index river stream flows. This study employed the 18 index river information. Roughly a 27 percent statewide reduction in stream flows is expected under the GFDL CM2.1 A2 scenario for the basins. To perturb the 37 CALVIN rim inflows with the obtained 18 monthly river index ratios, correlation mapping was prepared following the methods in Zhu et al. (2005) matching rim inflows with index rivers. Monthly time series of historical rim inflows in CALVIN were then multiplied by the ratio of the most correlated river index basin.

2.2.1.2 Groundwater Deep Percolation

Deep percolation for each CALVIN groundwater basin was estimated by using an empirical relationship between deep percolation and recharge using simulation results from the Central Valley Groundwater-Surface Model or CVGSM (USBR 1997). Each groundwater basin centroid was mapped and matched with the closest grid element (sized 1/8° by 1/8°) in the downscaled GFDL CM2.1 A2 scenario. Using the same centering years (1979 and 2085), the obtained ratios are employed to calculate changes in precipitation for each groundwater basin. Considering also the area of each groundwater basin and the empirical relationship between changes and precipitation and deep percolation (Zhu et al. 2005), perturbed (climate change) time series of deep percolation are obtained.

2.2.1.3 Reservoir Evaporation and Net Local Accretions

As with the groundwater basins, all surface reservoir locations in CALVIN were mapped to match the closest grid of the downscaled GFDL CM2.1 A2 scenario to employ temperature and precipitation ratios. A linear relationship described in Zhu et al. (2005) for each reservoir was used. Net evapotranspiration is obtained as the difference between evaporation and precipitation considering the area-elevation-capacity of each reservoir. Local accretions, on the other hand, use changes in deep percolation and precipitation in each CALVIN depletion area.

2.2.2 Sea Level Rise

Most of the Delta is currently maintained as a largely fresh water system. This facilitates the movement of water from Northern California sources and storage facilities to the Bay Area, southern Central Valley, and Southern California through pumping plants. The combined physical pumping capacities for the State Water Project (Banks), Central Valley Project (Jones), and the Contra Costa Water District (Old River and Rock Slough) are 16,500 cubic feet per second (cfs) (11.95 million acre-feet [maf]/year). Increasing the salinity of the Delta will potentially reduce or end diversions or water exports from the Delta, either by directly fostering sea water intrusion, by collapsing some island levees which will foster sea water intrusion, or a combination of both combined with stricter regulations on drinking water disinfection by-products (Chen et al. 2010). Sea level rise is modeled in CALVIN by reducing the capacity of Delta pumping to 50 percent and to zero. This will directly affect water users that rely on Delta water rights and CVP and SWP water that passes through the Delta.

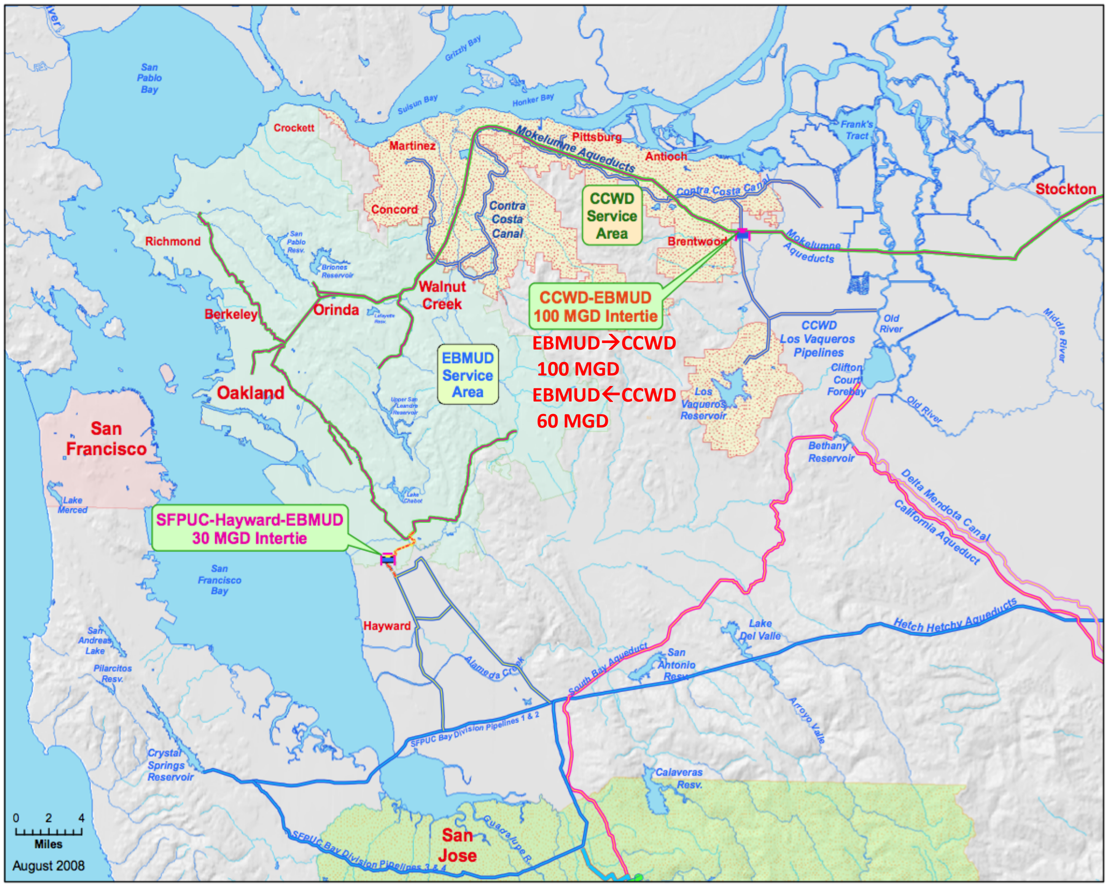
2.2.3 Long-term Urban Water Conservation

Long-term urban water conservation is implemented in the model to provide insight into how water conservation might reduce the water supply related impacts of climate change. For 2050 demand levels, urban residential water demand in CALVIN is 221 gallons per capita per day (gpcd) (Jenkins et al. 2004; Medellín-Azuara et al. 2008).Urban water conservation is implemented by adjusting the piece-wise linear urban demand functions as detailed by Ragatz (2011). To model 30 percent urban water conservation both the target demand and the associated cost in the piece-wise linear economic demand function are multiplied by 0.70 to produce a demand curve with the same slope (or marginal cost) as the original demand curve. Thirty percent conservation in CALVIN results in urban demand of 154 gpcd. This value is similar to the State's goal to achieve a 20 percent reduction in urban per capita water use in California by 2020 (SWRCB 2010). There will be costs to the implementation of long-term urban water conservation that are not addressed in this model. These costs may include outreach, public announcement campaigns, and efficient water use technologies.

2.2.4 Intertie Conveyance Policy Constraints

In the San Francisco Bay Area, local water agencies have recently constructed water conveyance interties to allow for water supplies to be moved between neighboring water agencies. Major interties in the San Francisco Bay Area are the EBMUD-Hayward-SFPUC Intertie, the EBMUD-CCWD Intertie, and the FRWP. The interties capacities allow for the large water transfers; however, policy constraints can limit the frequency of use and available capacity.

The EBMUD-Hayward-SFPUC Intertie is a partnership between East Bay Municipal Utility District, San Francisco Public Utilities Commission, and the City of Hayward. The intertie consists of a pump station and 1.5 miles of pipeline (Figure 6). The intertie capacity is 30 million gallons per day (MGD). The EBMUD-CCWD Intertie is a partnership between East Bay Municipal Utility District and Contra Costa Water District. The intertie facilities include 170 feet of pipeline to connect CCWD's Los Vaqueros Pipeline with EBMUD's Mokelumne Aqueduct (Figure 6).The intertie capacity allows EBMUD to transfer 60 MGD to CCWD, and CCWD can transfer 100 MGD to EBMUD. Both the EBMUD-Hayward-SFPUC and the EBMUD-CCWD Interties were constructed for emergency response to increase water supply reliability following catastrophic events such as an earthquake. The interties will boost water supply when needed and, under current policy agreements, are not intended to be used as regular service.

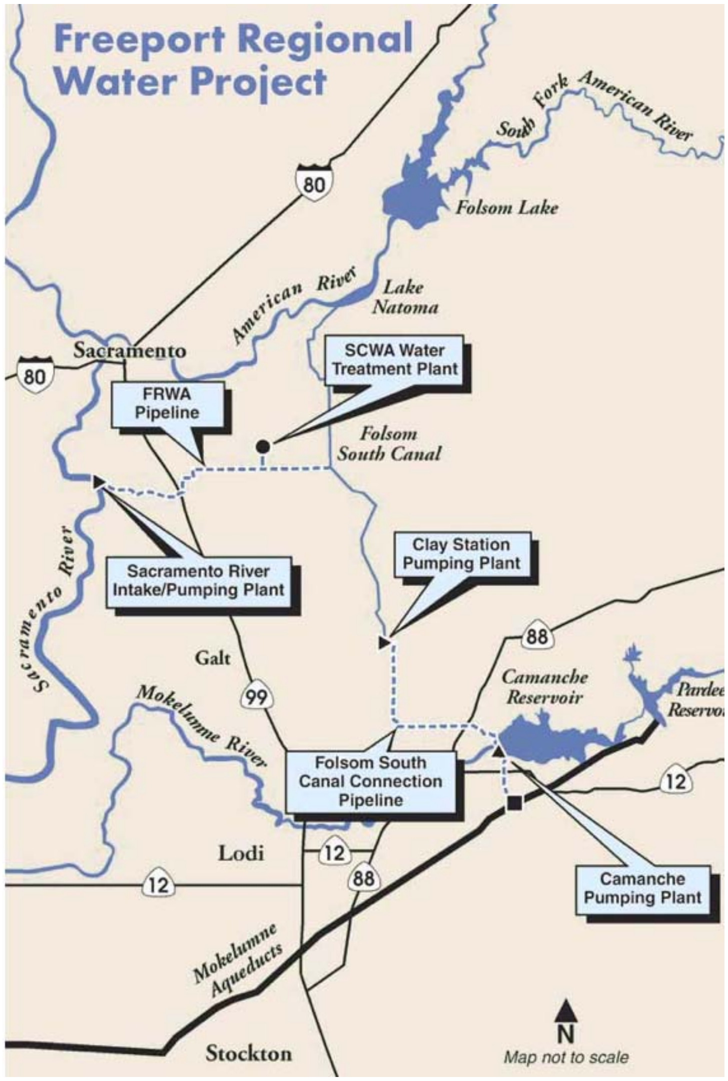


(Modified from EBMUD 2005)

Figure 6: Location and Capacity of the EBMUD-Hayward-SFPUC and EBMUD-CCWD Interties

The FRWP is an agreement between Sacramento County Water Authority (SCWA) and East Bay Municipal Utility District. The project consists of intake pumps and pipelines in Freeport that convey water to the South Folsom Canal, and an extension of the South Folsom Canal connecting it to EBMUD's Mokelumne River Aqueduct at Camanche Reservoir (Figure 7).

The project has a capacity to supply SCWA users with 85 MGD, and its capacity as an intertie between SCWA and EBMUD is 100 MGD. The intertie portion of the project was built to provide water to EBMUD during water shortages driven by droughts. Freeport operation is restricted to dry years or drought periods as defined by EBMUD's CVP contract. The policy constraints on the intertie allow EBMUD to receive up to 100 MGD in dry years only, which are expected to be three years out of every ten.



Source: Freeport Regional Water Authority, 2011

Figure 7: Location of the Freeport Regional Water Project infrastructure

The effects of policy constraints on the interties were investigated by reducing the conveyance capacity of the interties in the model. The infrastructure capacity in the model was reduced to 20 percent of maximum capacity to represent limited water transfers. An additional local water transfer in the San Francisco Bay Area is water service provided by the SFPUC to the Santa Clara Valley. This water supply is modeled as a water transfer in CALVIN similar to an intertie. For the purposes of investigating the effects of intertie/local water transfer management, the SFPUC service in the Santa Clara Valley was decreased to 20 percent of physical capacity. The modeled unconstrained and constrained intertie capacities are listed in Table 1.

Table 1: Modeled Intertie Capacities

Intertie	Modeled Physical Capacity TAF/Month	Modeled Policy Constraint Capacity TAF/Month
EBMUD-Hayward-SFPUC	2.8	0.56
EBMUD→CCWD	9.3	1.87
EBMUD←CCWD	5.6	1.12
FRWP	9.3	1.87
SFPUC service in Santa Clara Valley	13.5	2.7

TAF = thousand acre-feet

2.2.5 Model Runs

Eleven model runs were completed with CALVIN to evaluate three climate cases. Table 2 lists the model runs and their representation. All model runs use 2050 level of development (population and land use). Model run H is a base case for comparison with climate change scenarios. Model run H uses historical hydrology to represent the spatial and temporal variability of inflows into the system. Model runs WD, H-SLR50, H-SLR, WD-SLR50, and WD-SLR represent the five climate change cases. Model run WD represents a warm dry future climate. Model run H-SLR50 represents a future climate where the hydrology is unchanged from the historical record, but sea level rise occurs resulting in a reduction of Delta diversions capacity to 50 percent. Model run H-SLR represents a future climate where the hydrology is unchanged from the historical record, but sea level rise and other changes prevent Delta diversions. As modeled here, the sea level rise (combined with other Delta problems) is severe enough to significantly reduce or preclude all direct Delta Exports (Lund et al. 2010). Model run WD-SLR50 represents the effects of a warm dry future climate combined with sea level rise that reduces Delta diversions capacity by 50 percent. Model run WD-SLR represents the effects of a warm dry future climate combined with sea level rise that results in ending Delta diversions. Model runs "-C" model the effects that long-term urban water conservation will have on mitigating the impacts of the climate change case. The final model runs, "-P," evaluate the system flexibility that can be gained by relaxing policy constraints on intertie conveyance capacity by comparing the initial unconstrained intertie cases with the final cases where the intertie capacity is reduced to 20 percent of maximum physical capacity. All climate change and policy constrained runs are intended to severely test the system rather than to be a statistically valid representation of the future.

Table 2: Model Runs

Run	**Hydrology**	**Sea Level Rise**	**Long-Term Urban Water Conservation**	**Intertie Policy Constraint**
H (Base case)	Historical	None	None	None
Climate Change				
H-SLR50	Historical	50% reduction	None	None
H-SLR	Historical	No Delta exports	None	None
WD	Warm Dry	None	None	None
WD-SLR50	Warm Dry	50% reduction	None	None
WD-SLR	Warm Dry	No Delta exports	None	None
Climate Change and Long-term Urban Water Conservation				
H-SLR50-C	Historical	50% reduction	30% of Demand	None
H-SLR-C	Historical	No Delta exports	30% of Demand	None
WD-C	Warm Dry	None	30% of Demand	None
WD-SLR50-C	Warm Dry	50% reduction	30% of Demand	None
WD-SLR-C	Warm Dry	No Delta exports	30% of Demand	None
Climate Change and Policy Constraints				
H-P	Historical	None	None	20% of Capacity
H-SLR50-P	Historical	50% reduction	None	20% of Capacity
H-SLR-P	Historical	No Delta exports	None	20% of Capacity
WD-P	Warm Dry	None	None	20% of Capacity
WD-SLR50-P	Warm Dry	50% reduction	None	20% of Capacity
WD-SLR-P	Warm Dry	No Delta exports	None	20% of Capacity

The sea level rise cases that reduce Delta diversion capacity by 50 percent (-SLR50) do not show different average results from the related historical case or the warm dry case (e.g., H vs. H-SLR50 and WD vs. WD-SLR50), and therefore are not included separately in the results. This result is likely due to the significant storage available to the water supply network.

SECTION 3: Results

The results presented here, while preliminary, provide some perspective and insights on how the Bay Area could adapt to some fairly severe forms and consequences of climate change.

3.1 Water Scarcity and Scarcity Cost

Water shortages indicate the vulnerability of California's water supply system to climate change impacts. Under climate change scenarios, water shortage or scarcity increases because of reduced inflows, reduced water in the system, and sea level rise and the inability to continue large water exports and diversions from the Sacramento-San Joaquin Delta. Scarcity cost is the penalty for not meeting the target demand of an agricultural or urban water user. Scarcity costs represent the economic cost to the water user in the form of agricultural shortage costs or costs of short-term conservation by households and businesses.

Table 3 and Table 4 display the scarcity, scarcity cost, and willingness-to-pay for additional deliveries for Bay Area urban water users, statewide urban water users, and statewide agricultural water users. In the base case with historical hydrology, Bay Area urban sector water demands are all met. By contrast, urban and agricultural users statewide have a yearly average scarcity of 32 and 871 thousand acre-ft (taf) respectively. These water shortages in the base case reflect variability in water supply availability, infrastructure capacity, environmental flow constraints, and costs of water supply that preclude some users from purchasing their full demand. Under the influence of individual climate change impacts of reduced hydrology and sea level rise (no Delta exports) and the combined impacts of reduced hydrology and sea level rise, Bay Area water users see little to no increased scarcity, while statewide urban water users suffer scarcity. Water shortages and shortage costs affect Santa Clara Valley water districts the most under no export cases. This is directly attributed to Santa Clara and Alameda counties relying on imported SWP and CVP water. Table 3 shows that the agricultural water users are selling water and bearing the shortage cost of Bay Area and statewide urban water users continuing to receive deliveries under climate scenarios. With reduced water availability because of runoff changes and the inability to divert Delta water, the agricultural sector is in the position to sell water to the urban sector (spot, short-term or long-term transfers). The sea level rise case that results in 50 percent reduction in Delta exports and diversions shows no increase in scarcity or scarcity costs from the base case.

The agricultural WTP for additional water listed in Table 4 is the average marginal value of an additional unit of water to agricultural water users. These values are the opportunity cost of transferring agricultural water to the urban sector. The agricultural opportunity cost is lowest under the no Delta diversions case and is the highest in the combined reduced stream flow and no Delta diversions case. Achieving 30 percent urban conservation alleviates all Bay Area urban shortages even under severe climate change impacts. Additionally, with long-term urban water conservation, agricultural WTP decreases, suggesting decreased economic motivation to transfer agricultural water to the urban sector.

Scarcity in the San Francisco Bay Area does not increase in the policy constraint model runs under no Delta diversions conditions. However, CCWD employs increased desalination to meet demand. With the EBMUD-CCWD Intertie constrained to 20 percent of its capacity CCWD, has no alterative water source when it can no longer pump water from the Delta. As will be seen in the operating costs section, the increased reliance on desalination comes at a high operational cost.

3.2 Operating Costs

Operating costs are associated with operating the system to supply water. These include groundwater and surface water pumping, water treatment, waste water recycling, and desalination. Figure 8 and Appendix A:Table A-6 show the average annual net variable costs of operating the water supply system. The operating costs north of the Delta including, the Bay Area, increase due to climate change as water sources that require greater operations and maintenance costs such as desalination and water recycling are used to meet urban demand.

Table 3: Average Bay Area Urban Water Scarcity Cost and Agricultural Opportunity Cost

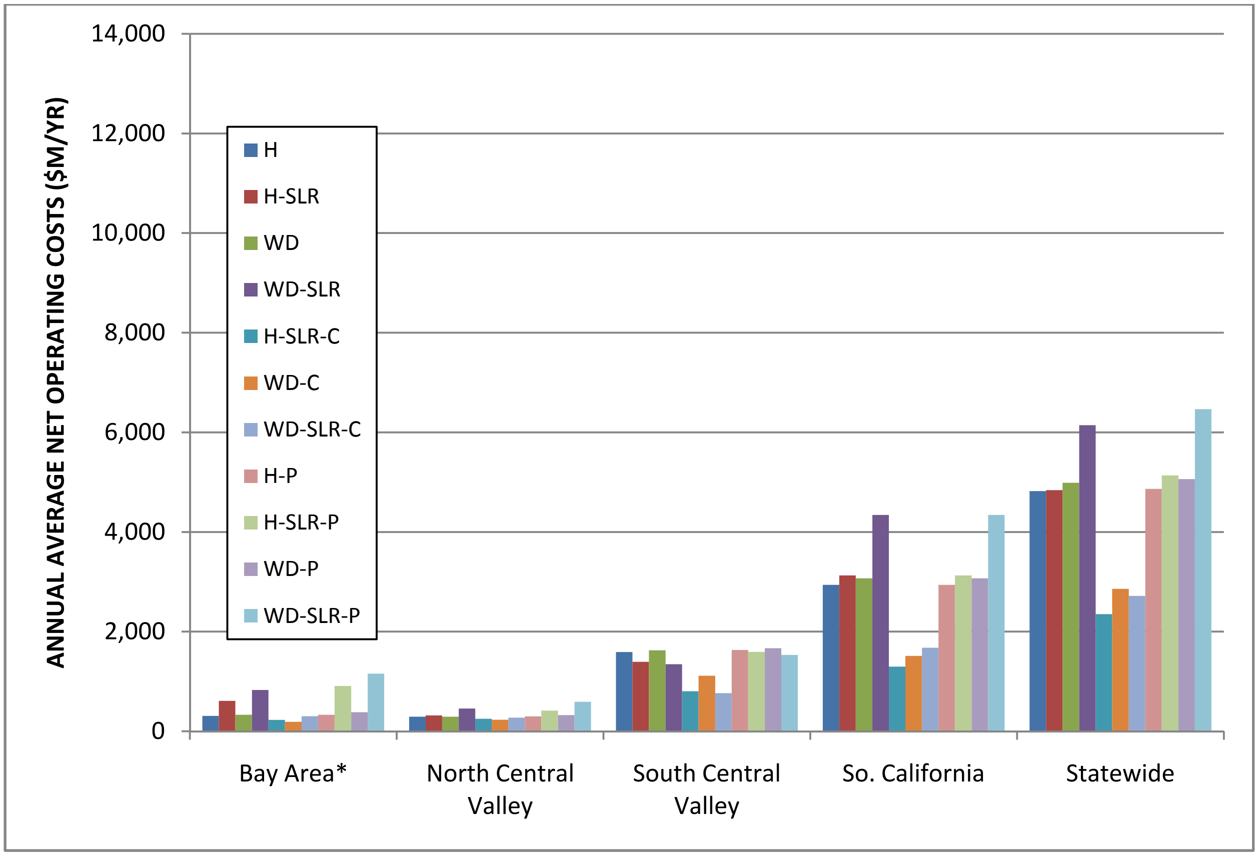
Abbreviations for model runs: Historical Hydrology, WD-Warm Dry Hydrology, SLR-Sea Level Rise, C-Long-term Urban Water Conservation, and P-Policy Constraints on Interties

	Base Case	Climate Change			Climate Change with Long-term Urban Water Conservation			Historical Hydrology and Climate Change with Intertie Policy Constraints			
	H	**WD**	**H-SLR**	**WD-SLR**	**WD-C**	**H-SLR-C**	**WD-SLR-C**	**H-P**	**WD-P**	**H-SLR-P**	**WD-SLR-P**
Scarcity, TAF/year											
Napa-Solano	0	0	0	0	0	0	0	0	0	0	0
CCWD	0	0	0	0	0	0	0	0	0	0	0
EBMUD	0	0	0	3	0	0	0	0	0	0	3
SFPUC	0	0	3	10	0	0	0	0	0	0	0
SCV-WD	0	0	26	26	0	0	0	0	0	26	26
Bay Area Urban	0	0	29	40	0	0	0	0	0	26	29
Statewide Urban	32	116	417	636	8	50	142	32	32	414	616
Statewide Ag.	871	7,666	5,539	9,132	4,366	4,027	8,301	871	7,656	9,061	9,061
Statewide Total	903	7,782	5,956	9,768	4,374	4,077	8,444	903	7,688	9,475	9,677
Scarcity Cost, $K/year											
Napa-Solano	0	0	0	0	0	0	0	0	0	0	0
CCWD	0	0	0	0	0	0	0	0	0	0	0
EBMUD	0	0	0	5,830	0	0	481	0	0	0	5,830
SFPUC	0	0	4,532	17,721	0	0	88	0	0	0	0
SCV-WD	0	0	46,495	46,495	0	0	0	0	0	46,495	46,495
Bay Area Urban	0	0	51,026	70,047	0	0	569	0	0	46,495	52,325
Statewide Urban	46,817	222,203	1,242,660	2,000,098	12,990	86,029	302,741	93,634	93,634	1,229,066	1,939,072
Napa-Solano	0	0	0	0	0	0	0	0	0	0	0
CCWD	0	0	0	0	0	0	0	0	0	0	0

Table 4: Average Bay Area Urban and Agricultural Willingness-to-Pay for an Additional Unit of Water

Abbreviations for model runs: H-Historical Hydrology, WD-Warm Dry Hydrology, SLR-Sea Level Rise, C-Long-term Urban Water Conservation, and P-Policy Constraints on Interties

	Base Case	Climate Change			Climate Change with Long-term Urban Water Conservation			Historical Hydrology and Climate Change with Intertie Policy Constraints			
	H	**WD**	**H-SLR**	**WD-SLR**	**WD-C**	**H-SLR-C**	**WD-SLR-C**	**H-P**	**WD-P**	**H-SLR-P**	**WD-SLR-P**
Average Marginal Willingness-to-Pay, $K/TAF											
Napa-Solano	0	0	0	0	0	0	0	0	0	224	224
CCWD	0	0	0	0	0	0	0	0	0	0	0
EBMUD	0	0	0	423	0	0	50	0	0	0	423
SFPUC	0	0	393	706	0	0	11	0	0	0	0
SCV-WD	0	0	751	751	0	0	0	0	0	751	751
Bay Area Urban	0	0	229	376	0	0	12	0	0	195	280
Statewide Urban	25	86	263	420	23	52	106	25	25	241	378
Statewide Ag.	33	230	186	301	148	162	285	33	230	299	299

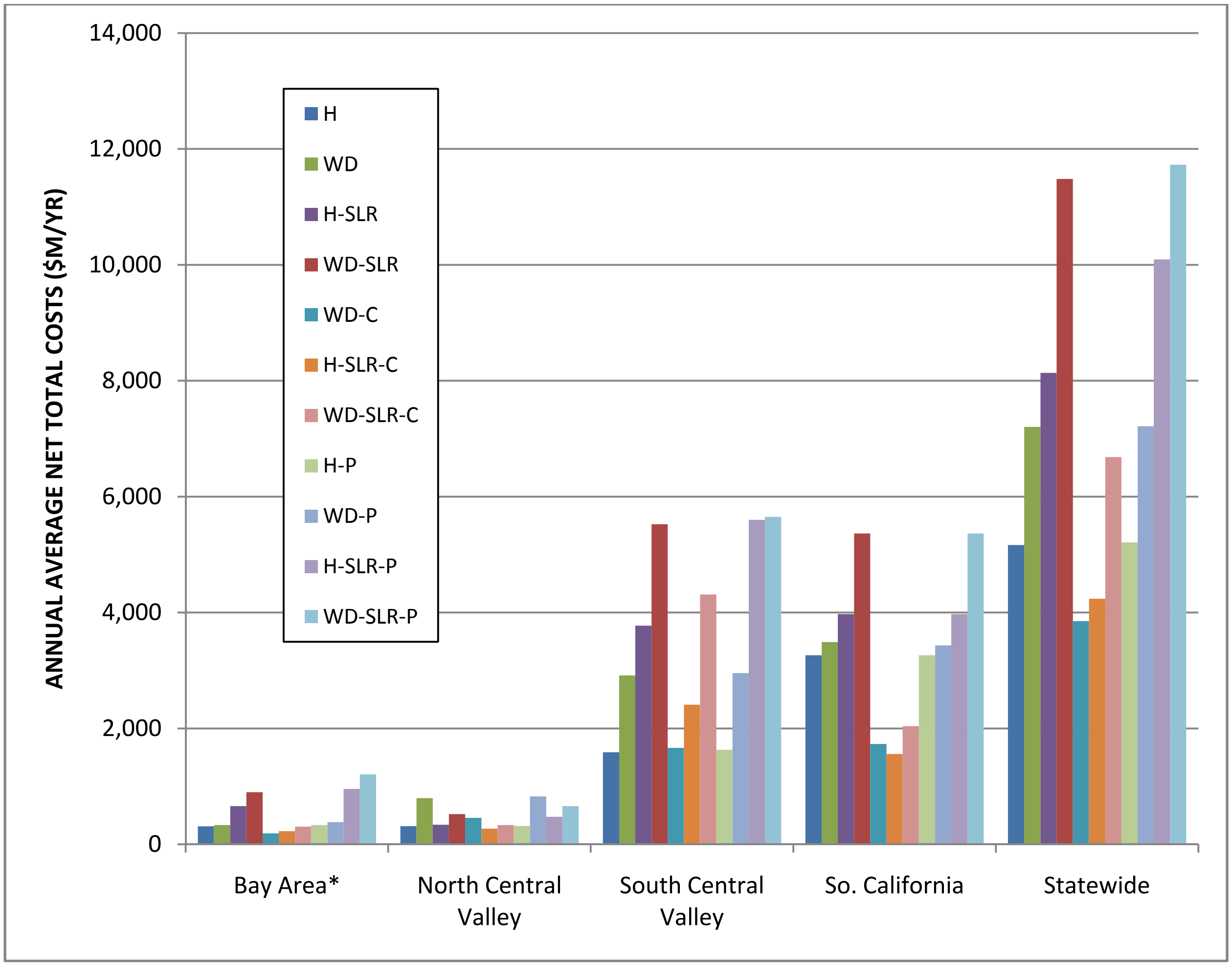


*Bay Area includes the portion of costs of operating south Delta pumps that deliver water through the South Bay Aqueduct and Pacheco Tunnel.

Abbreviations for model runs: H-Historical Hydrology, WD-Warm Dry Hydrology, SLR-Sea Level Rise, C-Long-term Urban Water Conservation, and P-Policy Constraints on Interties

Figure 8: Average Annual Net Variable Operating Costs

The combination of reduced streamflow and no Delta exports or diversions is the most costly scenario. South of the Delta operating costs decrease with climate change because reduced water availability and no Delta exports means no costly pumping of water south of the Delta. Like Northern California, Southern California operating costs increase with climate change as Southern California urban water users turn to water recycling and desalination to meet water supply needs. Operating costs in the scenarios with urban water conservation are greatly reduced. However, the intertie policy constraints increase operating costs as expensive alternative water supply options such as desalination are required to meet high-value urban demand. Figure 9 and Appendix A: Table A-7 display the total cost of operations and allocations, the sum of the scarcity and variable operating costs.



***Bay Area includes the portion of costs of operating south Delta pumps that deliver water through the South Bay Aqueduct and Pacheco Tunnel.

Abbreviations for model runs: H-Historical Hydrology, WD-Warm Dry Hydrology, SLR-Sea Level Rise, C-Long-term Urban Water Conservation, and P-Policy Constraints on Interties

Figure 9: Average Annual Net Total Costs (Scarcity and Operating) ($M/yr)

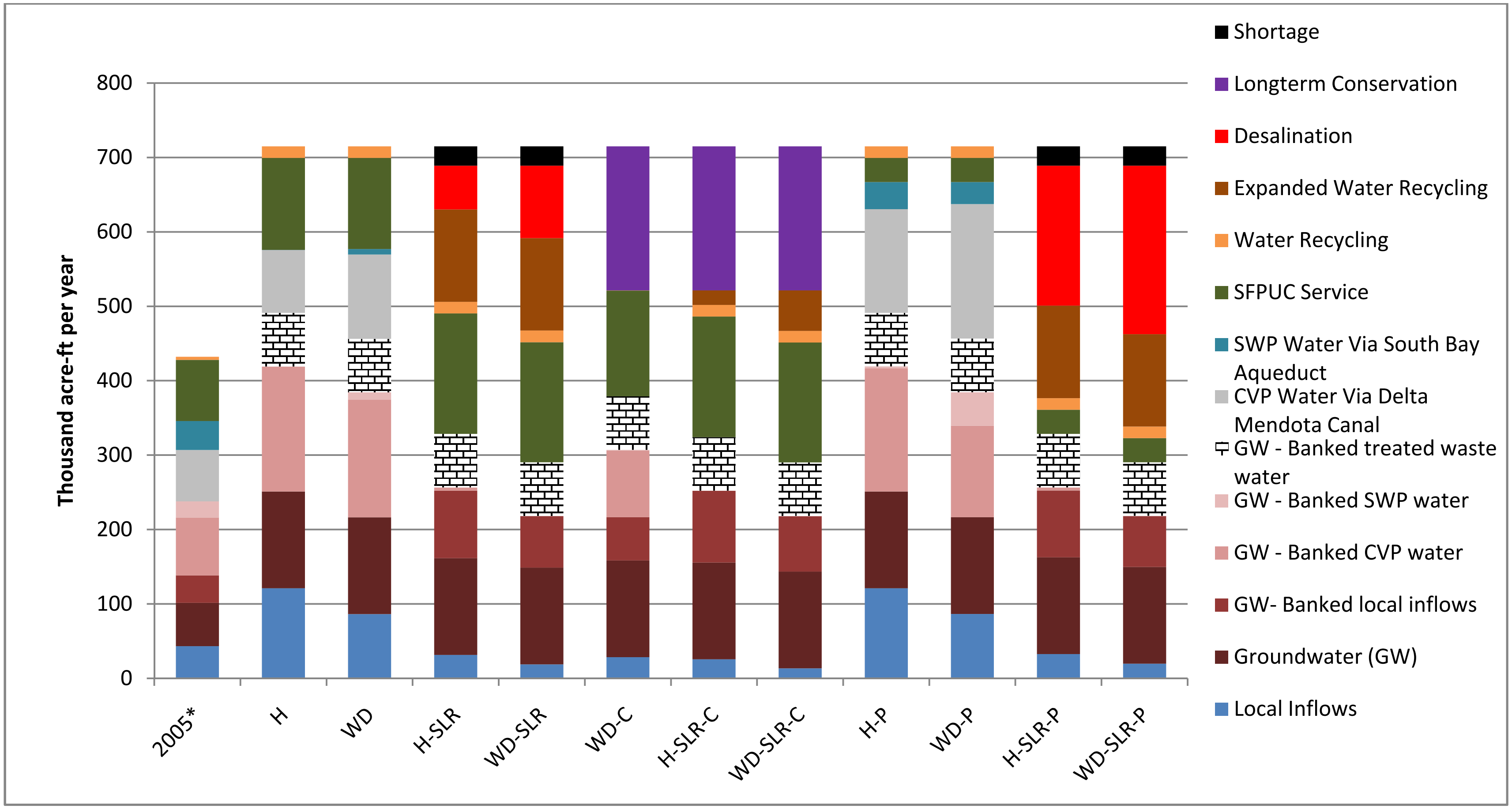
3.3Supply Portfolio

As illustrated conceptually in Figure 5, each Bay Area demand area relies on water supplies from a variety of sources such as local water resources, imported water and water transfers, groundwater pumping, water recycling, and desalination. There may be a shift in supply under climate change as water becomes less available generally, as agricultural opportunity costs raise the cost of water transfers, and as water imports from the two state water projects (SWP and CVP) through the Delta are reduced or no longer available. These factors may result in more costly water supply options such as recycled water, desalination, groundwater banking, and pumping becoming more economically attractive. Results from CALVIN optimization suggest water supply portfolios that add operational efficiency when accompanied by a functional water market.

3.3.1 Santa Clara Valley Water Districts Demand Area

Santa Clara Valley Water District is the largest Bay Area urban demand area in CALVIN with a projected demand of 715,000 acre-ft/year by 2050. The SCV relies on imported SWP and CVP water pumped from the Delta, local supplies, recycled water, and groundwater. Some of this area is serviced by SFPUC, represented as a water transfer to the SCV demand area in CALVIN. Additionally, SCV banks surface water in its aquifer for conjunctive use and to mitigate land subsidence from historical overdraft. Figure 10 and Appendix A: Table A-1 show how the supply portfolio for SCV shifts due to the impacts of climate change, long-term urban water conservation, and policy constraints on intertie operations.

Taking the historical hydrology as a base case, SCV relies heavily on SWP and CVP water from the Delta. Delta water accounts for 253 thousand acre-feet/year, or 36 percent of water delivered, on average. Groundwater pumping, local sources, and SFPUC service account for about 17 percent each or 125 taf/year average. Water recycling is about 2 percent of water supply, 16 taf/year, on average. Interestingly recycling of water has already reached capacity under the base case scenario. A warm dry climate produces less local inflow. However, water imports through the Delta increase slightly, suggesting that water is purchased and transferred from agricultural users to cover decreased local supplies. This suggests that it is more economically efficient to pay the agricultural opportunity cost than to begin paying for desalination or expanded wastewater recycling. The sea level rise cases with a 50 percent reduction in Delta diversion capacity (SLR50) show very little change in the water supply portfolio from the base case. The sea level rise scenarios (H-SLR and WD-SLR) have the largest effect on water supplies. When the Delta exports are unavailable, SCV can no longer rely on SWP and CVP water. Furthermore, without the Delta, purchases and transfers of water from the agricultural sector become more restricted. Figure 10 shows that under these scenarios scarcity and scarcity cost reach a point where the urban water users in SCV are willing to pay for expanded water recycling capacity and desalination. Expanded water recycling capacity accounts for 18 percent of supply in both the sea level rise (H-SLR50) and warm dry and sea level rise (WD-SLR50) cases, respectively.



*2005 water use estimates based on 2005 urban water management plans and State Water Plan

Abbreviations for model runs: H-Historical Hydrology, WD-Warm Dry Hydrology, SLR-Sea Level Rise, and C-Long-term Urban Water Conservation, and P -Policy Constraints on Interties

Figure 10: Average Santa Clara Valley Demand Area Water Supply Portfolio

Desalination accounts for 9 percent and 14 percent of supply in the sea level rise (H-SLR50) and warm dry and sea level rise (WD-SLR50) cases, respectively. Water conservation of 30 percent in the warm dry climate case (WD-C) reduces dependence on imported SWP and CVP water. In the sea level rise (H-SLR50-C) and warm dry climate sea level rise cases (WD-SLR50-C), water conservation reduces the use for more expensive desalination/expanded wastewater reuse. The policy constraint model runs show that under sea level rise conditions, SCV must rely on high cost desalination in the absence of CVP and SWP water supply through the Delta and reduction in water supplied by SFPUC. Figure 10 and Appendix A: A-1show that under sea level rise, the total groundwater banking/conjunctive use drops.

3.3.2 San Francisco Public Utility Commission Demand Area

The San Francisco Public Utility Commission demand area has access to water from the Hetch Hetchy Aqueduct, the Hayward Intertie, water recycling and desalination. Figure 11 and Appendix A: Table A-2 show the shifting water supply portfolio for the different cases. The model omits a small local surface water supply near the SFPUC's service area reservoirs. The policy constrained runs show that under all climate change cases the Hetch Hetchy supply is robust enough to maintain supply to SFPUC to meet 2050 demand. Small variation in the supply portfolio under unconstrained policy cases suggest operational cost savings that may be achieved through flexible operations of interties and through water transfer agreements. SFPUC did not provide estimates of local inflows to their system, so these were conservatively neglected in the model.

3.3.3 Contra Costa Water District Demand Area

Contra Costa Water District demand area relies mainly on CVP water and its own water rights from the Delta conveyed through the Contra Costa Canal and Los Vaqueros Reservoir. Figure 12 and Appendix A: Table A-3 show the water supply portfolio that minimizes operation and scarcity costs under the base case and climate change scenarios. In the base case model run, CVP water pumped from the Delta accounts for 92 percent of CCWD water supply. The remainder of the supply is from water recycling. In the warm dry climate, water recycling becomes more important. Sea level rise that results in a 50 percent reduction in Delta diversion capacity does not change the water supply portfolio from the base case. In the sea level rise runs when Delta pumping is shut off, the water supply portfolio will depend on the hydrology and the intertie policy. With the historical hydrology, the model suggests that there may be sufficient water in the Mokelumne River system for water transfer agreements through EBMUD-CCWD Intertie to offset the loss of Delta pumping. This would require purchasing water from diverters of Mokelumne River water. Under limited water transfers through EBMUD-CCWD Intertie (H-SLR50-P and WD-SLR50-P) desalination becomes a cost effective water supply option in the absence of Delta diversions. In all cases of a warm dry climate combined with no Delta diversions, water recycling and desalination become water supply considerations. Figure 12 also shows that long-term urban water conservation can limit the need for costly desalination and water recycling.

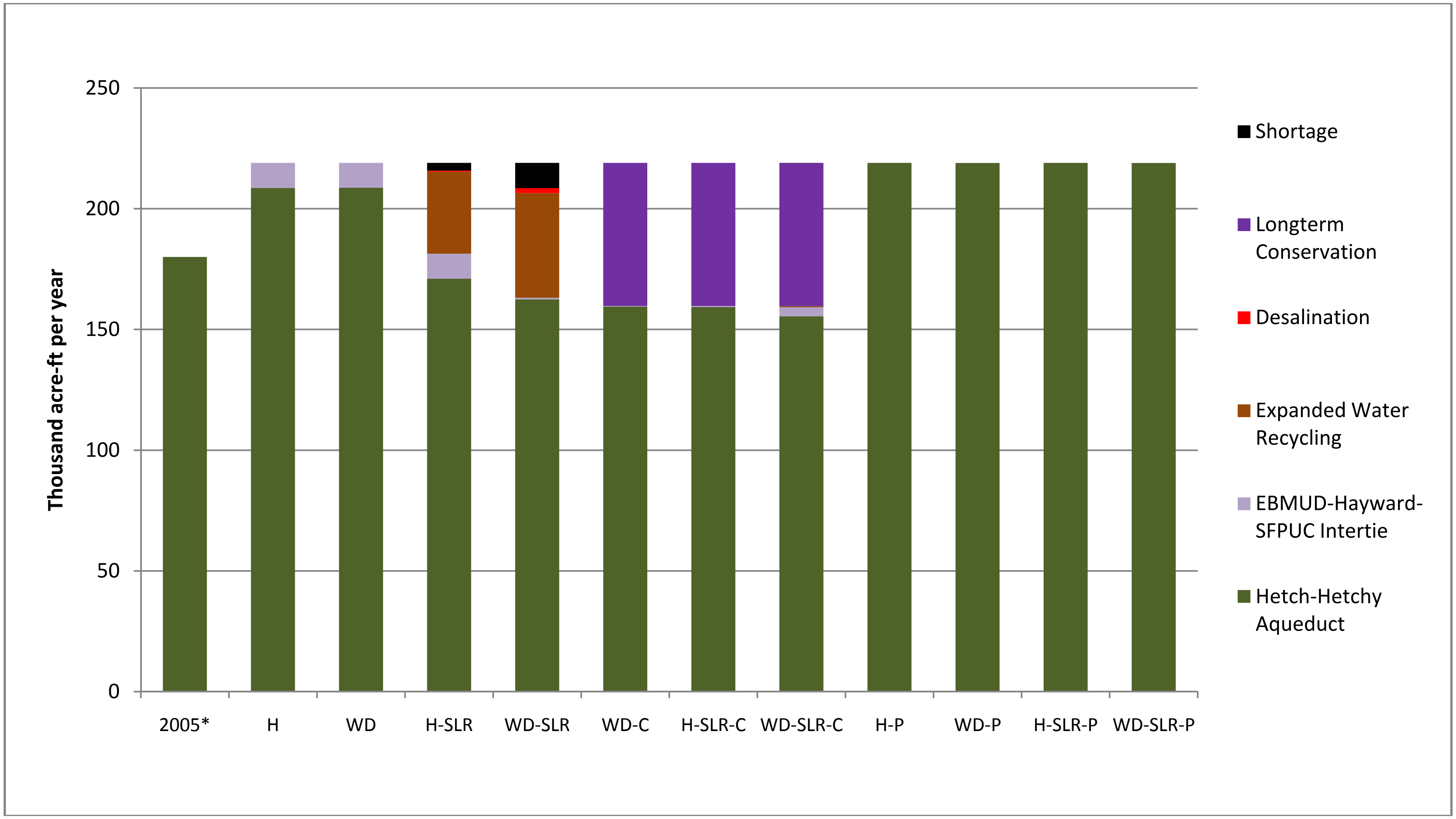
3.3.4 East Bay Municipal Utility District Demand Area

The East Bay Municipal Utility District demand area relies mainly on water from the Mokelumne River Aqueduct. In the base case, Mokelumne River Aqueduct and transfers from CCWD account for all of the water supply (Figure 13 and Appendix A: Table A-4). Reduced

Delta exports and diversion capacity do not significantly change the water supply portfolio from the historical hydrology case. With ending Delta exports or diversions, water recycling makes up 3 percent of the total water supply. With a warm dry climate, Freeport Project diversions become 31 percent of supply and water recycling expands to 9 percent. Sea level rise ends CCWD transfers of Delta water and reliance shifts heavily to Mokelumne River Aqueduct water. With the combined effect of a warm dry hydrology and sea level rise (ending Delta exports), EBMUD suffers small shortages on average, and must rely on all elements of its water supply portfolio to meet demand cost-effectively. The significant result from the policy constraint on intertie operations occurs with both warm dry climate changes and the end of Delta exports with sea level rise. With diversions from the Sacramento River north of the Delta through the FRWP reduced, EBMUD must rely on costly desalination to meet demand.

3.3.5 Napa-Solano Demand Area

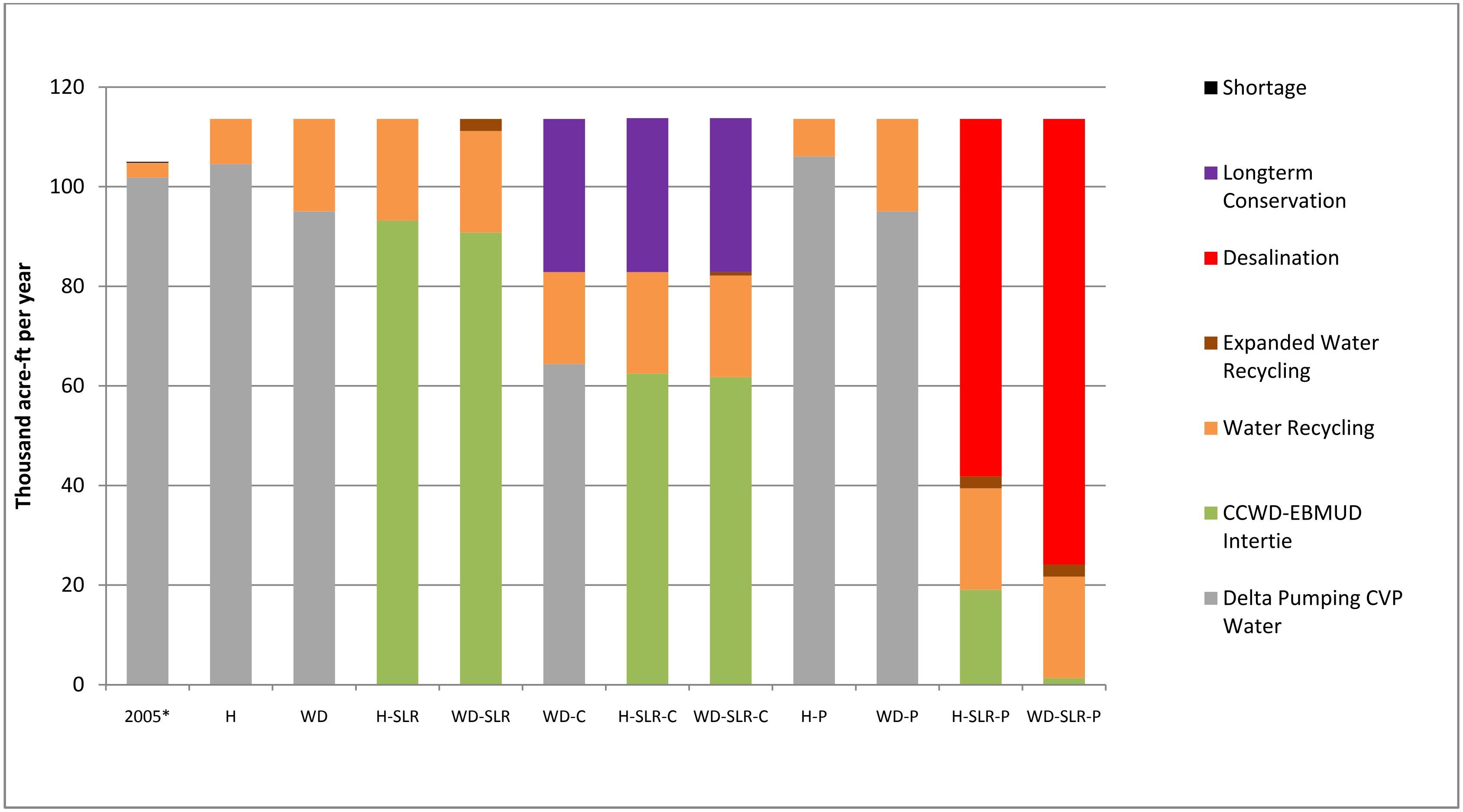
The Napa-Solano demand area water supply portfolio appears in Figure 14 and Appendix A: Table A-5. The base case and climate change cases are not significantly different. In all climate change cases, Napa-Solano relies on purchasing agricultural users' CVP and SWP water to respond to reductions in water availability. Napa-Solano demands are not affected by policy constraints on intertie operations. Being largely north of the Delta hydrologically eliminates problems from reduced south-of-the-Delta diversions.



*2005 water use estimates based on 2005 urban water management plans and State Water Plan

Abbreviations for model runs: H-Historical Hydrology, WD-Warm Dry Hydrology, SLR-Sea Level Rise, and C-Long-term Urban Water Conservation, and P-Policy Constraints on Interties

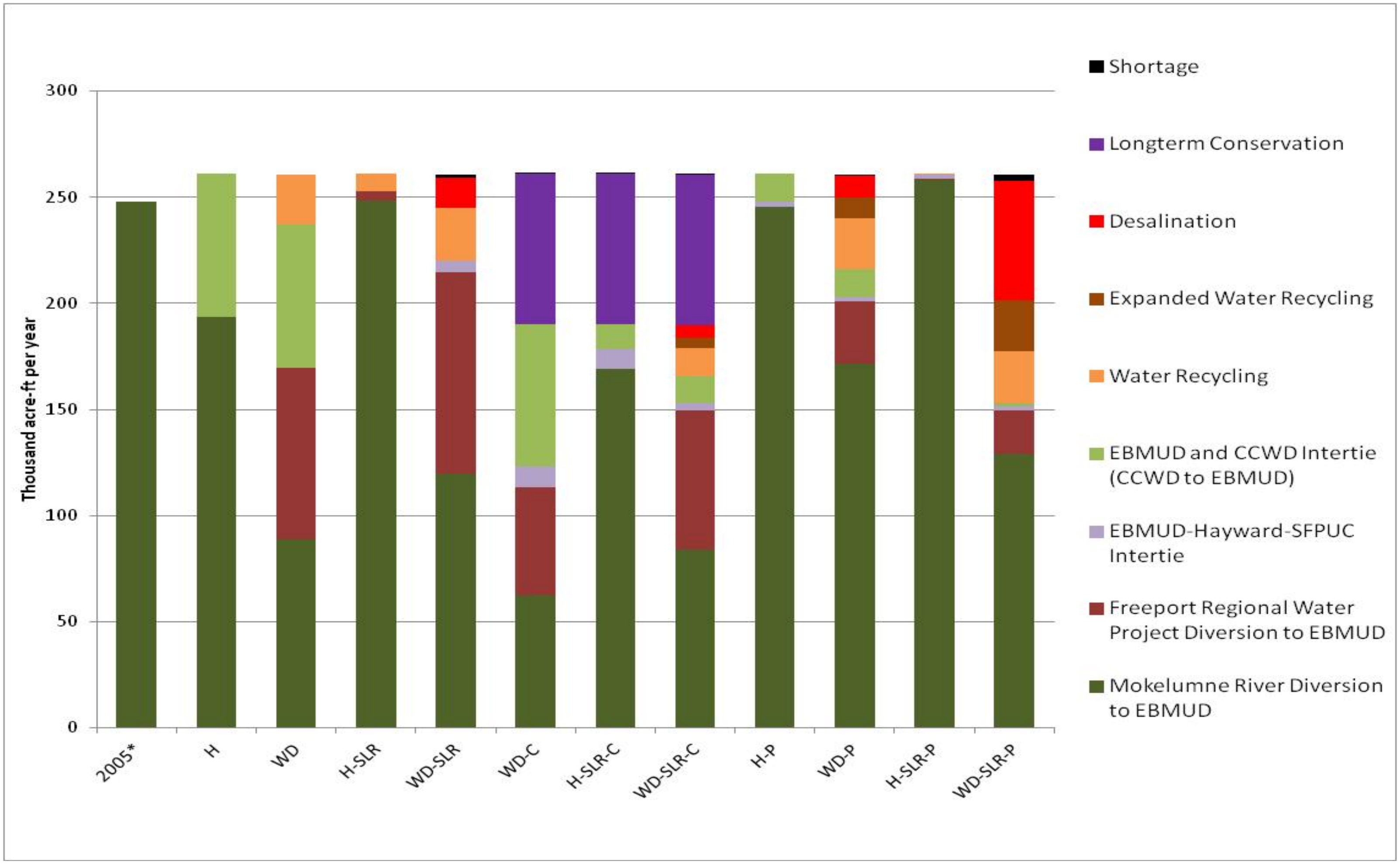
Figure 11: Average SFPUC Demand Area Water Supply Portfolio



*2005 water use estimates based on 2005 urban water management plans and State Water Plan

Abbreviations for model runs: H-Historical Hydrology, WD-Warm Dry Hydrology, SLR-Sea Level Rise, and C-Long-term Urban Water Conservation, and P-Policy Constraints on Interties

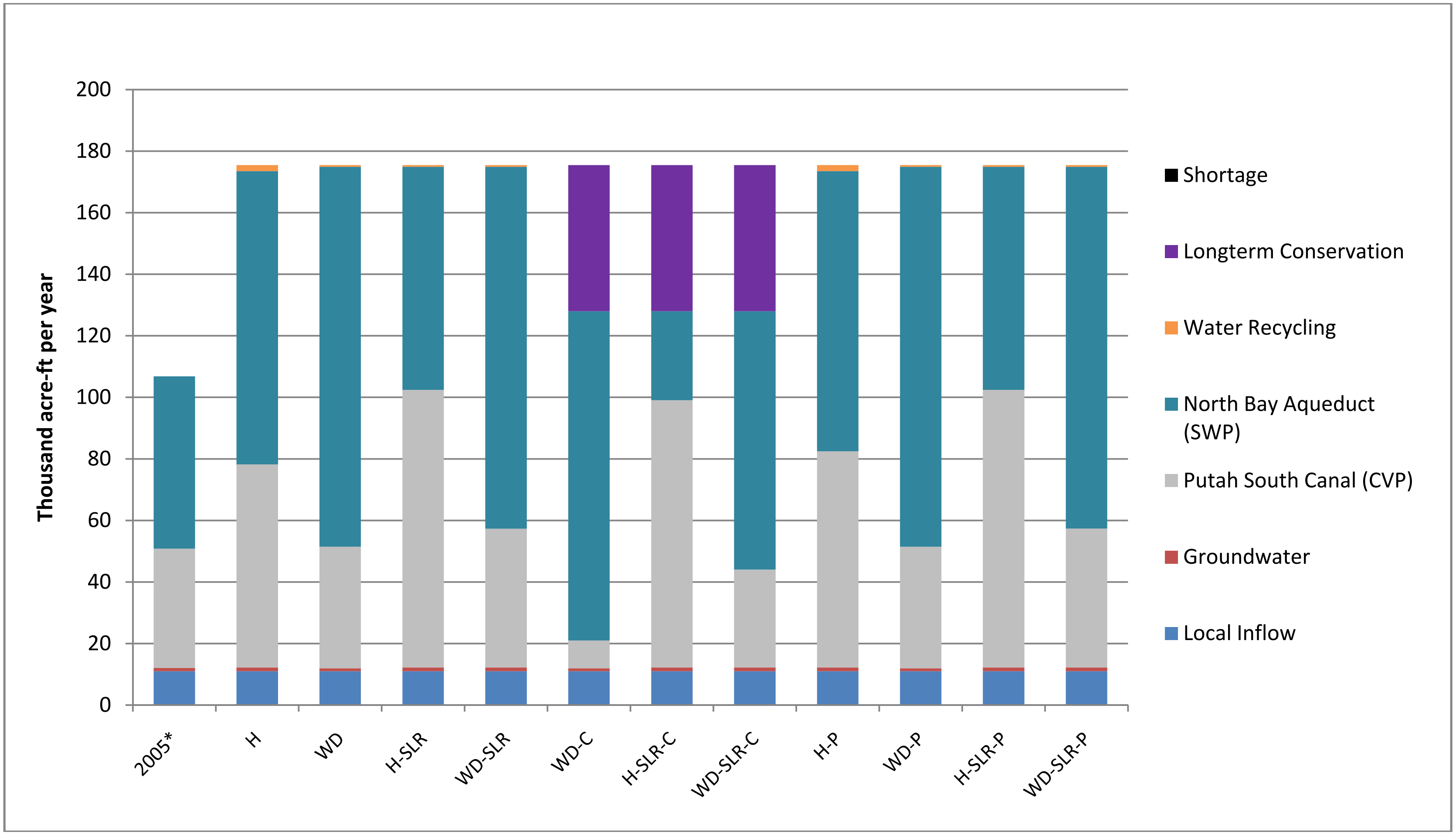
Figure 12: Average CCWD Demand Area Water Supply Portfolio



*2005 water use estimates based on 2005 urban water management plans and State Water Plan

Abbreviations for model runs: H-Historical Hydrology, WD-Warm Dry Hydrology, SLR-Sea Level Rise, and C-Long-term Urban Water Conservation, and P-Policy Constraints on Interties

Figure 13: Average EBMUD Demand Area Water Supply Portfolio



*2005 water use estimates based on 2005 urban water management plans and State Water Plan

Abbreviations for model runs: H-Historical Hydrology, WD-Warm Dry Hydrology, SLR-Sea Level Rise, and C-Long-term Urban Water Conservation, and P-Policy Constraints on Interties

Figure 14: Average Napa-Solano Demand Area Water Supply Portfolio

3.4Infrastructure Importance and Expansion Opportunities

CALVIN provides a platform for evaluating the importance of system components. The output from the network flow optimization solver provides input commonly used for a sensitivity analysis (Hillier and Lieberman 2005). Linear optimization solvers provide shadow value (marginal value or marginal cost) matrices for each cost coefficient or constraint in the model.

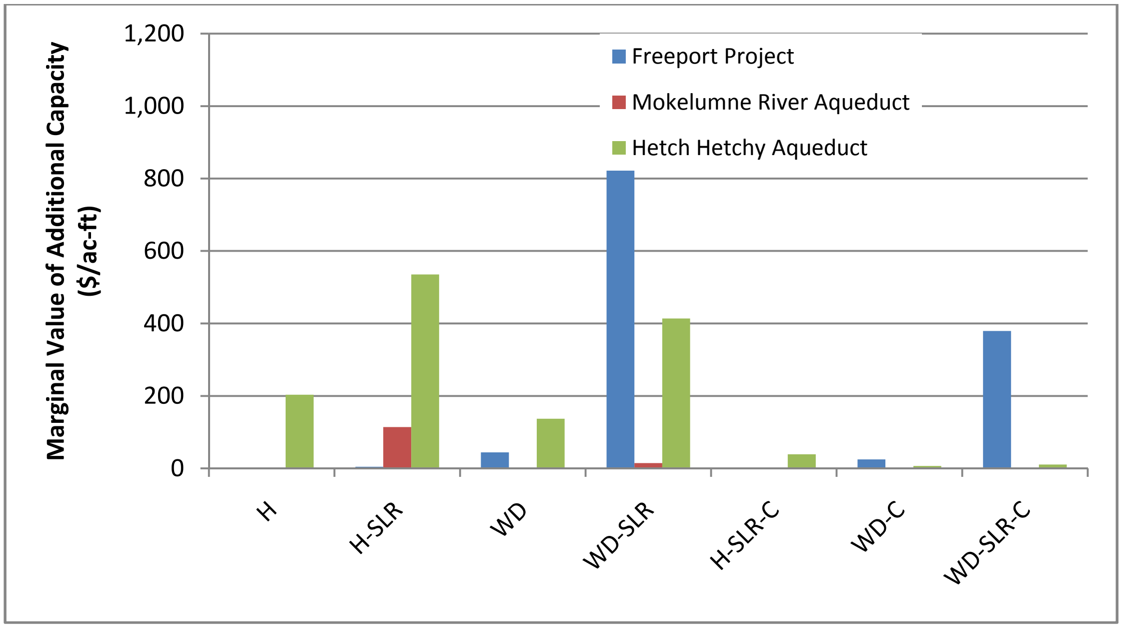
The shadow values indicate the flexibility within the system and how sensitive the performance is to parameter uncertainty. The shadow value is the amount by which the objective function value will change for a unit relaxation or tightening of a system constraint. The shadow value, in the case of storage capacity or conveyance capacity, represents the marginal value of that resource. The model runs performed for this analysis consider uncertain hydrology by looking at different climate change scenarios and looking at uncertainty and variability within each using the 72-year time series.

Conveyance, water recycling, and storage capacities are represented in CALVIN as upper bounds on conveyance links and storage nodes, respectively. As part of the sensitivity output from CALVIN, marginal value of additional conveyance and storage capacity are reported as the reduction in the total system costs for a unit increase in a constraint. As expected, when a conveyance or storage capacity is not reached in a time step, the marginal value of additional capacity is zero. However, when the capacity is reached, a non-zero marginal value results. The non-zero marginal value suggests a binding point in the system. A comparison of the marginal values between model runs suggests the importance of a system component, the relative flexibility of the system to manage climate change effects, and the potential for infrastructure expansion to improve system flexibility. Additionally, the magnitude of flow through a system component, frequency of flows through a system component, and the frequency with which a system component binds system operation indicate the importance of a system component. These values can also help indicate the value of expanding a component's capacity, or the flexibility provided by the system component to deal with hydrologic uncertainty.

3.4.1Marginal Cost of Infrastructure Expansion and Policy Relaxation

Table 5 contains the average value of one additional unit of increased capacity for selected conveyance and water recycling components in the Bay Area's water supply system. The review of the water supply portfolios in the previous sections indicated the importance of the EBMUD's FRWP and Mokelumne River Aqueduct and SPFUC's Hetch Hetchy Aqueduct under climate change conditions. Figure 15 shows that the marginal values of infrastructure capacity expansion reflect the same importance. For the Mokelumne River Aqueduct and the Freeport Project, on average, the capacity does not bind the system in the base case of historical hydrology. Under warm dry hydrologic conditions there is little to no change in the marginal value, because there is so little water in the system that the conveyance components do not flow at capacity.

The Hetch Hetchy Aqueduct is seen to bind the system in all non-water conservation cases. This does not suggest that the Hetch Hetchy Aqueduct will not meet its primary design objective of supplying water to SFPUC. As was seen in the water supply portfolio for the SFPUC demand area (Figure 11), the Hetch Hetchy Aqueduct adequately meets demand under the policy-constrained intertie cases. These data suggest operational cost savings afforded by the water conveyance capacity of the interties. As expected, ending exports or diversions from the Delta begins to stress the capacity of infrastructure as the model relies on conveyance through these remaining system components to meet demand. Long-term urban water conservation reduces the stress on these system components and reduces the value of increased capacity under climate change cases.



Abbreviations for model runs: H-Historical Hydrology, WD-Warm Dry Hydrology, SLR-Sea Level Rise, and C-Long-term Urban Water Conservation

Figure 15: Average Marginal Value of Additional Aqueduct Conveyance Capacity

Table 5: Average Marginal Value of Conveyance and Water Recycling Capacity ($/af)

Conveyance, Water Recycling, and Desalination Infrastructure	Base Case	Climate Change			Climate Change with Long-term Urban Water Conservation			Historical Hydrology and Climate Change with Intertie Policy Constraints			
	H	WD	H-SLR	WD-SLR	WD-C	H-SLR-C	WD-SLR-C	H-P	WD-P	H-SLR-P	WD-SLR-P
Freeport Project	0	44	4	1,122	25	0	379	0	446	5	1,135
Mokelumne River Aqueduct	0	0	114	15	0	0	0	0	0	0	0
Hetch Hetchy Aqueduct	204	137	535	414	7	39	11	1	2	1	1
CCWD-EBMUD Intertie	0	0	14	19	0	0	0	0	0	944	58
EBMUD-Hayward-SFPUC Intertie	160	150	518	104	46	76	176	141	494	138	932
SFPUC service to Santa Clara Valley	1	7	399	122	15	823	497	367	329	1,315	993
SCV Water Recycling	53	369	950	950	0	619	650	96	399	950	950
SCV Expanded Water Recycling	0	0	300	300	0	0	0	0	0	300	300
EMBUD Recycled water	0	88	1	956	0	0	240	0	501	0	927
EMBUD Expanded Recycled water	0	0	0	317	0	0	45	0	91	0	315
CCWD Water Recycling	7	264	310	1,280	124	100	458	2	256	1,050	1,050
CCWD Expanded Water Recycling	0	0	0	630	0	0	97	0	0	400	400

Abbreviations for model runs: H-Historical Hydrology, WD-Warm Dry Hydrology, SLR-Sea Level Rise, and C-Long-term Urban Water Conservation, and P-Policy Constraints on Interties

Figure 16 shows the marginal value of intertie conveyance capacity. The CCWD-EBMUD Intertie's capacity is only slightly stressed on average under all climate change scenarios. However, the marginal value of increased capacity of the EBMUD-Hayward-SFPUC Intertie increases under climate change conditions as more water users depend on the intertie to transfer and wheel local and imported water from various sources. Again, long-term urban water conservation reduces the marginal value of intertie increased capacity.

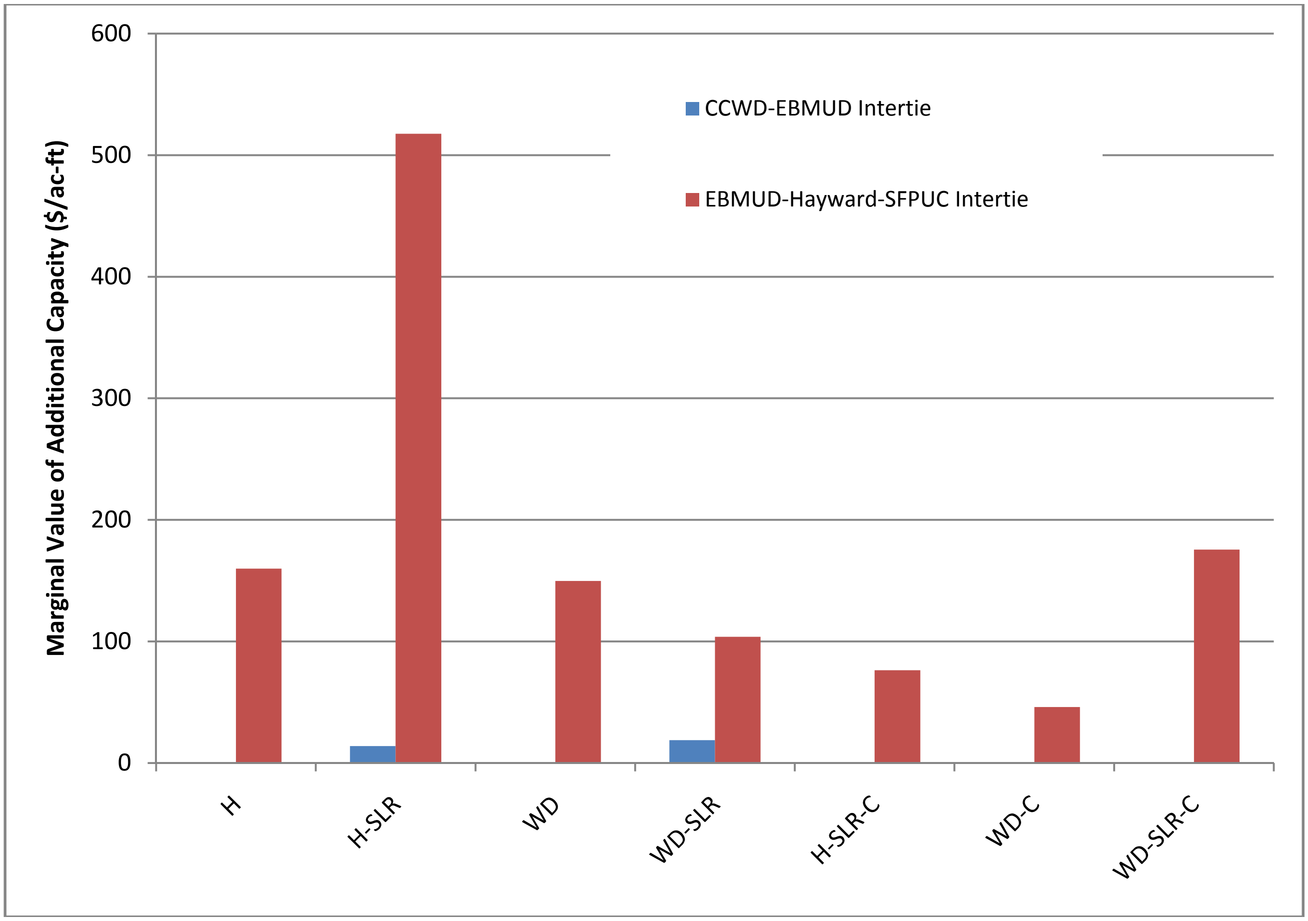
Figure 17 shows the marginal value of base water recycling capacity and expanded water recycling capacity. Given the cost in CALVIN of base level water recycling at $500 per acre-ft and expanded water recycling at $1,500 per acre-ft, CALVIN will use base water recycling capacity before using expanded water recycling capacity. Therefore, the marginal values indicate the importance of all water recycling capacity in increasing system flexibility under all climate change scenarios. The marginal value of expanded water recycling capacity suggests the opportunity for infrastructure expansion mainly under a warm dry hydrology with sea level rise.

The marginal value of increased storage capacity was surveyed over the entire system and generally showed that greater surface and groundwater storage capacity would not greatly increase the performance or flexibility of the water supply system (Table 6). However, the robust existing water storage capacity raised system resiliency in the "-SLR50" cases (sea level rise cases that model reduced Delta diversion capacity by 50 percent). Recall that the "-SLR50" cases results were not included in the tables and figures for clarity because the results on average did not differ from the related historical and warm dry cases (e.g., H vs. H-SLR50 and WD vs. WD-SLR50). Future work could include model cases that look at the performance of the reservoir systems in managing seasonal changes Delta salinity that could seasonally affect diversion capacity.

Table 6: Average Marginal Value of Storage Capacity ($/af)

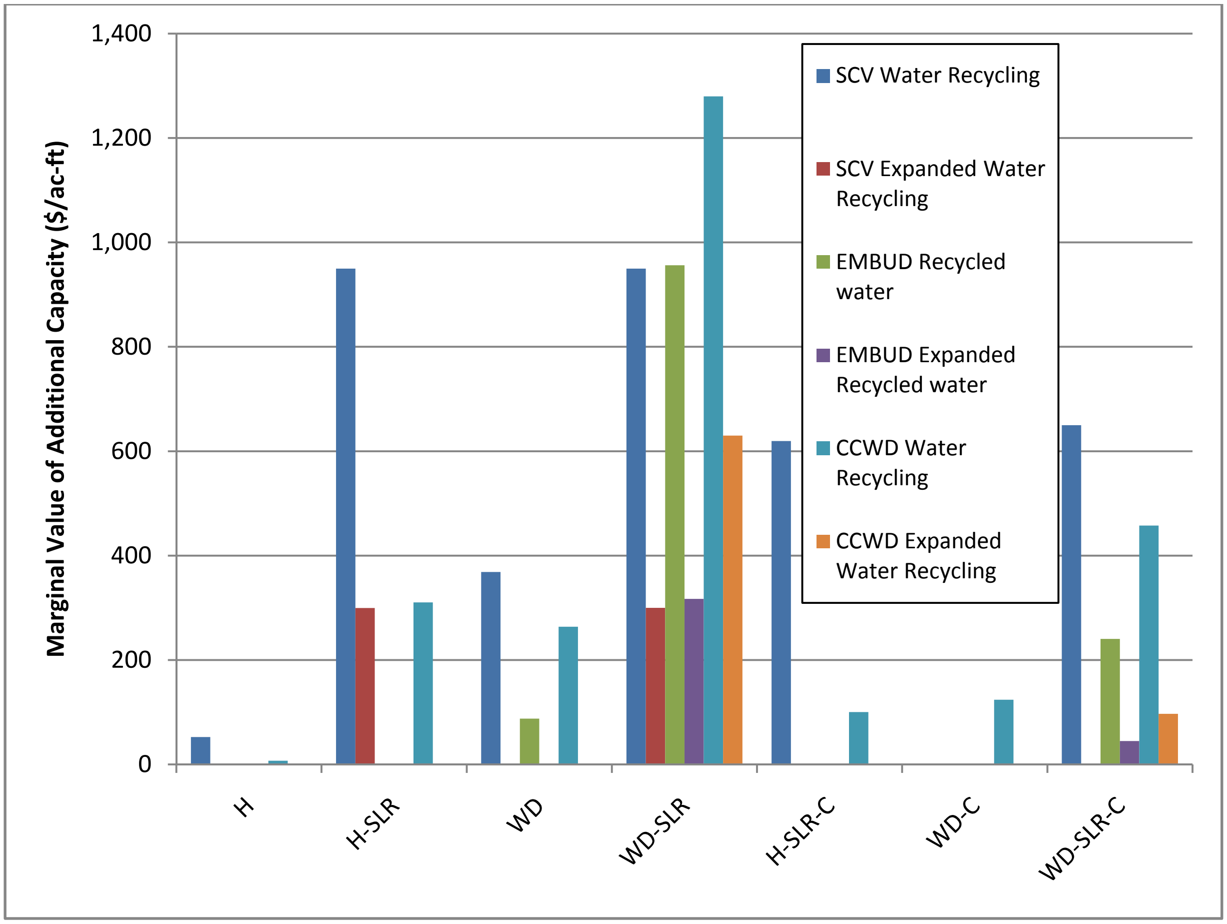
Conveyance, Water Recycling, and Desalination Infrastructure	Base Case	Climate Change			Climate Change with Long-term Urban Water Conservation			Historical Hydrology and Climate Change with Intertie Policy Constraints			
	H	WD	H-SLR	WD-SLR	WD-C	H-SLR-C	WD-SLR-C	H-P	WD-P	H-SLR-P	WD-SLR-P
Shasta Lake	5	45	5	23	35	5	23	6	53	2	14
Clair Engle Lake	2	27	2	20	21	2	22	5	47	3	12
Black Butte Lake	6	169	3	43	98	3	42	10	77	7	13
Lake Oroville	10	53	7	12	38	7	11	6	103	1	1
Thermalito Afterbay	7	77	2	10	47	2	9	9	116	0	23
New Bullards Bar Reservoir	12	106	11	13	60	11	12	2	32	7	0
Englebright Lake	30	220	30	30	124	30	29	0	28	11	23
Clear Lake & Indian Valley Reservoir	1	32	0	1	17	0	1	1	33	30	0
Camp Far West Reservoir	4	116	2	13	63	1	9	1	33	3	30
Folsom Lake	9	103	7	14	57	6	10	4	32	0	20
New Melones Reservoir	6	2	7	2	2	7	4	0	6	64	13
San Luis Reservoir	0	8	0	0	8	0	0	0	25	12	0
New Don Pedro Reservoir	6	3	6	2	3	6	4	3	3	11	0
Hetch Hetchy Reservoir	4	5	5	4	3	5	5	10	3	4	0
Millerton Lake	4	25	64	81	38	42	22	6	34	36	4
Lake Kaweah	38	182	309	178	152	256	172	33	13	0	5
Lake Success	33	244	272	244	208	230	241	3	0	0	0
Lake Skinner	551	100	0	0	2	0	0	0	0	0	0
Shasta Lake	5	45	5	23	35	5	23	6	53	2	14
Clair Engle Lake	2	27	2	20	21	2	22	5	47	3	12
Black Butte Lake	6	169	3	43	98	3	42	10	77	7	13

Abbreviations for model runs: H-Historical Hydrology, WD-Warm Dry Hydrology, SLR-Sea Level Rise, and C-Long-term Urban Water Conservation, and P-Policy Constraints on Interties



Abbreviations for model runs: H-Historical Hydrology, WD-Warm Dry Hydrology, SLR-Sea Level Rise, and C-Long-term Urban Water Conservation

Figure 16: Average Marginal Value of Additional Intertie Conveyance Capacity



Abbreviations for model runs: H-Historical Hydrology, WD-Warm Dry Hydrology, SLR-Sea Level Rise, and C-Long-term Urban Water Conservation

Figure 17: Average Marginal Value of Additional Water Recycling Capacity

Figure 18 displays the marginal value of relaxing the policy constraint on intertie operations. As was seen in the water supply portfolios, Bay Area water users suffer small shortages or must rely on costly water alternatives such as desalination or by relaxing policy constraints on intertie operations. The interties increase the variety of an agency's water supply portfolio, they allow for wheeling of water between agencies, and could allow agencies to cooperate on water supply alternatives such as water recycling and desalination. Figure 18 shows that the CCWD-EBMUD intertie is very important to reducing shortages at CCWD. Overall the interties are most valuable under sea level rise conditions that result in no Delta exports or diversions when the overall water supply portfolio of the Bay Area is reduced by eliminating SWP and CVP water.

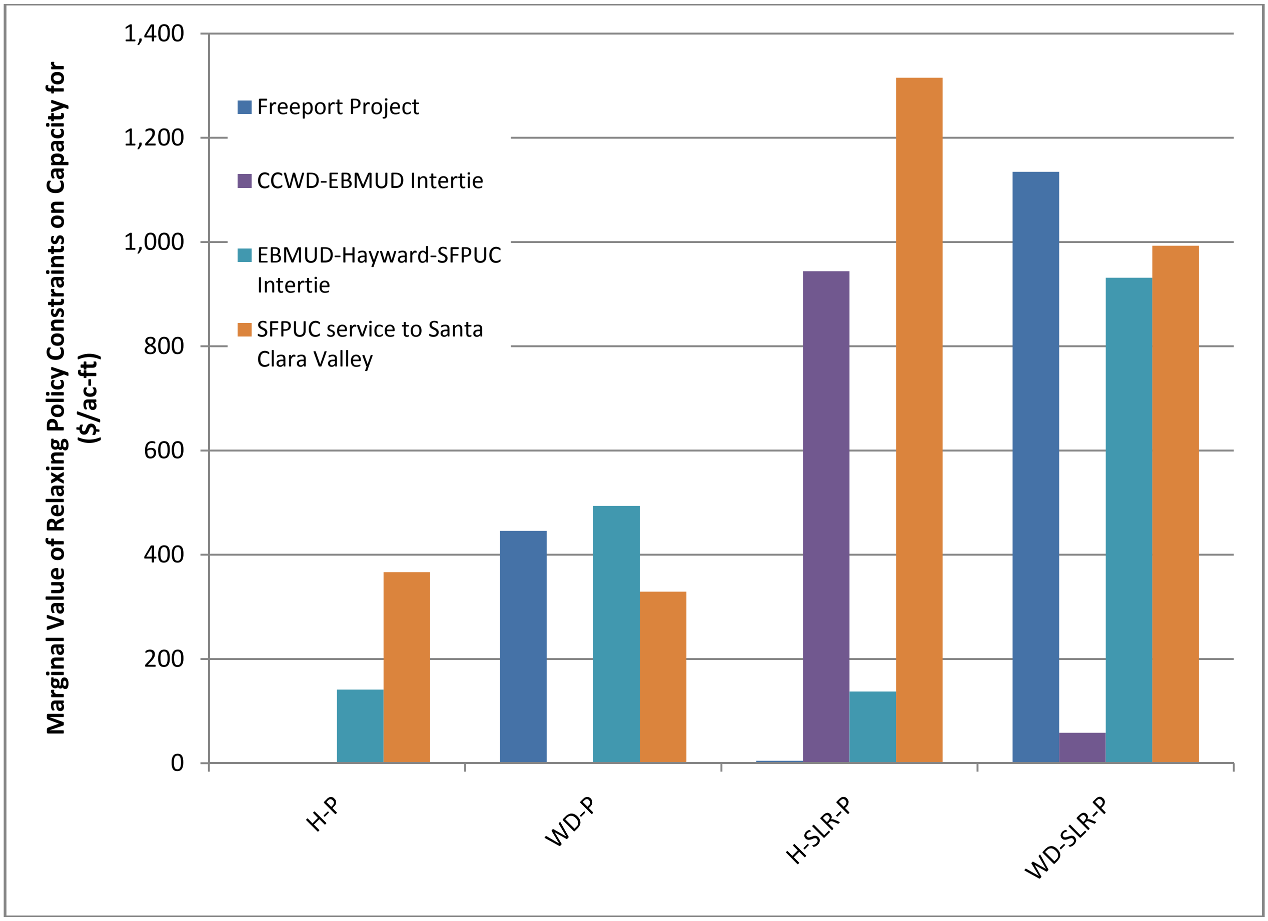


Figure 18: Average Marginal Value of Relaxing Policy Constraints on Intertie Capacity

3.5 Environmental Flows

Environmental flows are represented in CALVIN as minimum flow constraints in environmentally sensitive river reaches and minimum diversions to environmental wildlife refuges. Although these environmentally sensitive areas do not necessarily lie within the nine counties of the San Francisco Bay Area, their degradation if flows and diversions are not met would be an externality of deliveries to urban and agricultural sectors. CALVIN reports marginal opportunity costs to agricultural and urban users for meeting environmental requirements. The *marginal cost* represents the reduction in total system-wide cost if the environmental constraint was reduced one acre-foot.

Marginal costs of environmental flows can be thought of as the opportunity costs for environmental flow water. A marginal cost of zero indicates that local urban and agricultural demands and operating costs can be unaffected by maintaining the minimum environmental flow. A high marginal cost for a specific environmental flow indicates the increased economic value of reducing that environmental flow.

Table 7 shows the marginal costs of environmental flows statewide, preliminarily using current environmental flow requirements (which also are likely to change in the coming 40 years for many reasons). The table shows that, as expected, the competition for water increases under climate change conditions. When water is relatively abundant, the cost of maintaining environmental flows is low. The warm dry hydrology climate condition and the warm dry hydrology sea level rise condition result in the highest cost for maintaining environmental flows over the entire system. Marginal costs of environmental flows north of the Delta in the Sacramento River, Yuba River, American River, Feather river, and the Sacramento Wildlife Refuges increase from the base case (historical hydrology) to the warm dry hydrology case (WD), but do not see an increased cost due to sea level rise (SLR).

The marginal costs of environmental flows on the Mokelumne and Tuolumne River are most illustrative of impacts under climate changes. The Mokelumne and Tuolumne River both have minimum environmental flow requirements downstream of water supply reservoirs operated to supply the EBMUD and the SFPUC, respectively. The effects of maintaining environmental flows in a warm dry hydrology alone are greater than the impact of losing Delta diversions alone, but the combined impact is the most costly. Sea level rise affects SWP and CVP diversions from the Delta to the Bay Area, such as those for Contra Costa and Santa Clara Valley water users, and forces greater reliance on Mokelumne River and Tuolumne River supplies. The CCWD-EBMUD Intertie, EBMUD-Hayward-SFPUC Intertie, and SFPUC service to the Santa Clara Valley can allow all water users to benefit from Mokelumne Aqueduct and Hetch Hetchy Aqueduct water, increasing competition for environmental flows. Competition for Mokelumne River and Tuolumne River water is highest if sea level rise ends Delta diversions, while a warm dry climate alone affects the competition for Sacramento River water diversions to the refuges and minimum flow to the Delta. Policy constraints on intertie operations have little effect on competition for environmental flows except for Mokelumne River water under the policy constrained warm dry case (WD-P). In this case, the competition for Mokelumne River water increases because diversions through the FRWP are reduced by policy constraints. Long-term water conservation has a great effect on reducing competition for environmental flows for the Mokelumne River, Sacramento Wildlife Refuges, and the Delta.

Table 7: Average Marginal Costs of Environmental Flows ($/af/yr)

	Base Case	Climate Change			Climate Change with Long-term Urban Water Conservation			Historical Hydrology and Climate Change with Intertie Policy Constraints			
	H	WD	H-SLR	WD-SLR	WD-C	H-SLR-C	WD-SLR-C	H-P	WD-P	H-SLR-P	WD-SLR-P
Sacramento R.	27	287	4	377	163	5	378	4	287	5	378
Yuba	5	141	2	20	93	2	15	5	144	2	19
American River	8	458	7	239	235	5	79	7	464	7	237
Calaveras River	0	4	0	5	0	0	0	0	4	0	5
Feather River	4	373	3	18	190	3	12	4	376	3	17
Mokelumne R.	23	507	24	7,001	283	2	2,496	24	3,112	3	7,191
Tuolumne	22	441	41	1,371	289	36	1,273	18	413	35	1,222
Sacramento East Refuges	29	2,777	3	45	1,420	3	35	28	2,773	3	42
Sacramento West Refuges	188	3,002	157	744	1,657	156	738	188	2,993	157	743
Delta	32	2,859	3	44	1,441	1	34	31	2,851	2	42
San Joaquin R.	166	528	2,572	9,473	692	1,520	3,057	167	529	2,573	9,695
Merced River	63	720	332	1,904	549	334	1,874	65	707	338	1,742
Stanislaus	39	787	70	2,086	532	60	2,091	35	777	59	1,860
Clear Creek	205	30,406	200	30,986	30,646	201	30,975	205	30,416	200	30,987
Trinity River	425	33,886	387	31,613	32,600	387	31,584	424	33,892	387	31,612
Pixley National Wildlife Refuge	378	3,507	3,220	3,527	3,033	2,748	3,531	378	3,506	3,220	3,527
Kern National Wildlife Refuge	452	4,234	12,109	23,058	2,280	5,712	9,652	452	4,234	12,109	23,058
Mendota	276	3,695	6,581	19,908	2,033	5,832	9,276	276	3,697	7,889	20,139
Owens Lake	237	2,981	3,408	18,925	1,646	2,693	8,059	238	2,986	3,410	18,988
Mono Lake	6,608	12,228	16,764	17,636	7,354	10,391	12,737	6,608	12,228	16,764	17,636

Abbreviations for model runs: H-Historical Hydrology, WD-Warm Dry Hydrology, SLR-Sea Level Rise, and C-Long-term Urban Water Conservation, and P-Policy Constraints on Interties

SECTION 4: Conclusions

The San Francisco Bay Area has the economic and infrastructure potential to weather quite severe forms of climate change, at some costs and assuming operational flexibility by Bay Area water providers and regulators.

- This adaptation potential is largely made possible by a series of system interties completed in recent years for emergency response purposes, but which also can provide longer-term benefits and flexibility.
- Water markets allow urban water users in the Bay Area to operate flexibly and purchase water from agricultural users and each other.
- Water recycling and desalination also can improve water supply reliability by reducing reliance of imported water supply. Under fairly severe climate change conditions, especially with sea level rise ending water diversions from the Sacramento-San Joaquin Delta, purchasing agricultural water becomes more expensive. The CVP and SWP water purchases and transfers wheeled through the Delta become restricted, and urban water users turn to more costly water supply alternatives such as water recycling and desalination, affecting SCV and CCWD the most.
- Long-term urban water conservation is a promising approach to reduce operating costs and reliance on expensive supply alternatives such as water recycling and desalination.
- The SFPUC and EBMUD, with their access to Hetch Hetchy Aqueduct and Mokelumne River Aqueduct water, rely less on the Delta but may see economic benefit from water recycling and desalination under unfavorable climate changes. The SFPUC and EBMUD are not necessarily turning to alternative water supplies because of reduced Hetch Hetchy or Mokelumne River Aqueduct water. The EBMUD-Hayward-SFPUC and EBMUD-CCWD Interties combined with SFPUC service in Santa Clara Valley allows for purchases and transfers of imported water (Hetch Hetchy and Mokelumne River Aqueducts), recycled water, and desalination water to the demand areas that have lost access to CVP and SWP water or suffered reduced regional inflows, thus providing operating and scarcity cost savings.
- The Napa-Solano area stands out because of its access to SWP water through the North Bay Aqueduct and USBR water through Putah South Canal, both of which it can access north of the central Delta. In a functioning water market, the water service agencies in the Napa-Solano area continue to purchase water from the agricultural sector, albeit at higher costs with unfavorable climate changes.
- Like agricultural water users, environmental flows in the Central Valley are affected by climate change. Climate change impacts, especially sea level rise ending Delta diversions, increase competition for environmental flows.
- Overall, adaptation to a warmer drier climate relies primarily on improved system flexibility with investments in water recycling and desalination, at a cost, while adaptation to ending Delta diversions relies on alternative water supply and water

- Challenges to water management will be policies, agreements, and regulations that allow for flexible water transfers, more than mere existence of physical infrastructure.

4.1 Policy Implications

Interties, desalination, and water recycling improve system performance and increase flexibility in managing water supply. As discussed above, CALVIN prescribes least-cost water allocations and operations under physical, hydrologic, and policy constraints. Here, policy constraints were implicitly modeled by reducing capacity along water transfer interties. Some policy implications based on the result of this modeling are related mainly to water markets, system interties, and water conservation.

- Under severe climate change conditions, Bay Area urban water user demand could adapt in part by purchasing water from agricultural water users.
- Another large component of flexibility in system operations is from system interties. Both large water purchases and interties between water purveyors rely on robust institutional capacity to facilitate water transfers. The policy constraint runs showed that reducing intertie capacity increased local shortages and increased both shortage and operational costs in the Bay Area and statewide. The average yearly cost for the intertie policy constraints were $51 million, $297 million, and $896 million for the warm dry, no Delta diversion, and warm dry hydrology with no Delta diversion model runs, respectively. A management policy for intertie cooperative operations can allow large investments in water recycling and desalination to be shared by several agencies.
- Long-term urban water conservation greatly decreases the effects of severe climate change. Expanding water conservation will require extensive planning and some costs.

4.2 Limitations

CALVIN, like all models, is merely a representation of a real system and suffers from limitations. A comprehensive list of CALVIN limitations are discussed by Jenkens et al. (2001) and Jenkins et al. (2004).

For this particular study, some CALVIN limitations are discussed here. The urban and agricultural demands do not vary by water year type. Similarly, water use efficiencies are fixed values and do not vary by month. Crop water demand and efficiencies will vary between seasons and wet and dry years, as well as with agricultural commodity market conditions. Generally demands and efficiencies increase in dry years due to water availability. Overall, CALVIN may overestimate or underestimate demands in some regions in some years. Additionally, urban water use and scarcity costs are assumed to be constant for all climate conditions. We do not account for changes to conservation measures that could result in response to climate change. Urban housing and agricultural footprint projections are assumed constant and do not account for changes in the housing market, a potential climate change impact.

Environmental flow requirements are difficult to evaluate and describe with an economic demand function. Therefore, the instream environmental flows in CALVIN are modeled as fixed minimum constraints and refuge demands are modeled as fixed deliveries limiting the model flexibility. Additionally, urban and agricultural demands in CALVIN are "normal" year demands.

Another limitation is that CALVIN has perfect foresight. This means that it can perfectly anticipate hydrologic variability in all time steps beyond the current decision step. This will affect the current decision by allowing for perfect hedging of groundwater and surface water storage (Draper 2001).

The model runs used in this analysis included exploring the benefit of long-term urban water conservation. Here, costs to implement 30 percent reduction in demand by 2050 were neglected. Long-term urban water conservation costs will be a function of many things, including the cost of outreach and public service announcement campaigns and efficient water use technologies.

An additional limitation of CALVIN is the pricing of water transfer agreements. This is not a cost in the model, and it is understood that this cost may be a significant barrier to water transfers allowed in the model.

CALVIN operates on a monthly time step delivering water to a demand area's internal water distribution system. CALVIN does not account for the ability of an internal water distribution system to take water from new locations. Additionally, CALVIN does not account for an inter-water distribution system's ability to meet flow rate and pressure requirements within the distribution system within the monthly time step. CALVIN assumes that the internal distribution system has the ability to distribute the bulk water supplied at each monthly time step.

CALVIN results can be improved with updates from the forthcoming 2010 Urban Water Management Plan data, particularly regarding base water demands in the Bay Area. Despite the limitations described, this reconnaissance level modeling analysis highlights many opportunities for the Bay Area's complex water system to adapt to fairly extreme forms of climate change.

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Glossary

CALVIN	California Value Integrated Network
CCWD	Contra Costa Water District
CEC	California Energy Commission
CVP	Central Valley Project
DWR	California Department of Water Resources
EBMUD	East Bay Municipal Water District
FRWP	Freeport Regional Water Project
GCMs	Global Circulation Models
GFDL	Geophysical Fluid Dynamics Laboratory
HEC-PRM	Hydrologic Engineering Center's Prescriptive Reservoir Model
IPPC	Intergovernmental Panel on Climate Change
MGD	Million gallons per day
PIER	Public Interest Energy Research
SCV	Santa Clara Valley Water District
SCWA	Sacramento County Water Authority
SFPUC	San Francisco Public Utility Commission
SWAP	Statewide Agricultural Production model
SWP	State Water Project
TAF	Thousand acre-feet
USBR	United States Bureau of Reclamation
UWMP	urban water management plans
WTP	Willingness-to-pay

Model run acronyms are described in Table 2: Model Runs
H
H-SLR50
H-SLR
WD
WD-SLR50
WD-SLR
H-SLR50-C
H-SLR-C
WD-C
WD-SLR50-C
WD-SLR-C
H-P
H-SLR50-P
H-SLR-P
WD-P
WD-SLR50-P
WD-SLR-P

APPENDIX A

Table A-1: Average Water Supply Portfolio for SCV Demand Area (% Use)

	Base Case	Climate Change			Climate Change with Long-term Urban Water Conservation			Historical Hydrology and Climate Change with Intertie Policy Constraints			
Source	**H**	**WD**	**H-SLR**	**WD-SLR**	**WD-C**	**H-SLR-C**	**WD-SLR-C**	**H-P**	**WD-P**	**H-SLR-P**	**WD-SLR-P**
Local Inflows	17	12	5	3	4	4	2	17	12	5	3
CVP Water Via Delta Mendota Canal	12	16	0	0	0	0	0	19	25	0	0
SWP Water Via South Bay Aqueduct	0	1	0	0	0	0	0	5	4	0	0
Desalination	0	0	9	14	0	0	0	0	0	27	33
GW - Banked treated waste water	10	10	10	10	10	10	10	10	10	10	10
GW- Banked local inflows	0	0	13	10	8	13	10	0	0	13	10
GW - Banked CVP water	24	22	1	0	13	0	0	23	17	1	0
GW - Banked SWP water	0	1	0	0	0	0	0	0	6	0	0
Groundwater (GW)	18	18	19	19	18	18	18	18	18	19	19
SFPUC Service	17	17	23	23	20	23	23	5	5	5	5
Expanded Water Recycling	0	0	18	18	0	3	8	0	0	18	18
Water Recycling	2	2	2	2	0	2	2	2	2	2	2

Abbreviations for model runs: H-Historical Hydrology, WD-Warm Dry Hydrology, SLR-Sea Level Rise, and C-Long-term Urban Water Conservation, and P-Policy Constraints on Interties

Table A-2: Average Water Supply Portfolio for SFPUC Demand Area (% Use)

	Base Case	Climate Change			Climate Change with Long-term Urban Water Conservation			Historical Hydrology and Climate Change with Intertie Policy Constraints			
Source	**H**	**WD**	**H-SLR**	**WD-SLR**	**WD-C**	**H-SLR-C**	**WD-SLR-C**	**H-P**	**WD-P**	**H-SLR-P**	**WD-SLR-P**
Hetch Hetchy Aqueduct	95	95	79	78	73	73	71	100	100	100	100
Desalination	0	0	0	1	0	0	0	0	0	0	0
EBMUD-Hayward-SFPUC Intertie	5	5	5	0	0	0	2	0	0	0	0
Expanded Water Recycling	0	0	16	21	0	0	0	0	0	0	0

Abbreviations for model runs: H-Historical Hydrology, WD-Warm Dry Hydrology, SLR-Sea Level Rise, and C-Long-term Urban Water

Table A-3: Average Water Supply Portfolio for CCWD Demand Area (% Use)

	Base Case	Climate Change			Climate Change with Long-term Urban Water Conservation			Historical Hydrology and Climate Change with Intertie Policy Constraints			
Source	**H**	**WD**	**H-SLR**	**WD-SLR**	**WD-C**	**H-SLR-C**	**WD-SLR-C**	**H-P**	**WD-P**	**H-SLR-P**	**WD-SLR-P**
Delta Pumping CVP Water	92	84	0	0	78	0	0	93	84	0	0
CCWD-EBMUD Intertie	0	0	82	80	0	75	75	0	0	17	1
Desalination	0	0	0	0	0	0	0	0	0	63	79
Expanded Water Recycling	0	0	0	2	0	0	1	0	0	2	2
Water Recycling	8	16	18	18	22	25	25	7	16	18	18

Abbreviations for model runs: H-Historical Hydrology, WD-Warm Dry Hydrology, SLR-Sea Level Rise, and C-Long-term Urban Water Conservation, and P-Policy Constraints on Interties

Table A-4: Average Water Supply Portfolio for EBMUD Demand Area (% Use)

	Base Case	Climate Change			Climate Change with Long-term Urban Water Conservation			Historical Hydrology and Climate Change with Intertie Policy Constraints			
Source	**H**	**WD**	**H-SLR**	**WD-SLR**	**WD-C**	**H-SLR-C**	**WD-SLR-C**	**H-P**	**WD-P**	**H-SLR-P**	**WD-SLR-P**
EBMUD-Hayward-SFPUC Intertie	0	0	0	3	4	3	1	1	1	1	1
Desalination	0	0	0	20	0	0	2	0	4	0	22
Mokelumne River Diversion to EBMUD	74	34	93	31	24	65	32	94	66	99	50
Freeport Regional Water Project Diversion to EBMUD	0	31	2	24	19	0	25	0	11	0	8
EBMUD and CCWD Intertie (CCWD to EBMUD)	26	26	2	2	26	5	5	5	5	0	1
Expanded Water Recycling	0	0	0	9	0	0	2	0	4	0	9
Water Recycling	0	9	3	10	0	0	5	0	9	0	9

Abbreviations for model runs: H-Historical Hydrology, WD-Warm Dry Hydrology, SLR-Sea Level Rise, and C-Long-term Urban Water Conservation, and P-Policy Constraints on Interties

Table A-5: Average Water Supply Portfolio for Napa-Solano Demand Area (% Use)

	Base Case	Climate Change			Climate Change with Long-term Urban Water Conservation			Historical Hydrology and Climate Change with Intertie Policy Constraints			
Source	**H**	**WD**	**H-SLR**	**WD-SLR**	**WD-C**	**H-SLR-C**	**WD-SLR-C**	**H-P**	**WD-P**	**H-SLR-P**	**WD-SLR-P**
Putah South Canal (CVP)	38	22	51	26	5	49	18	40	22	51	26
North Bay Aqueduct (SWP)	54	70	41	67	61	16	48	52	70	41	67
Groundwater	1	1	1	1	1	1	1	1	1	1	1
Water Recycling	1	0	0	0	0	0	0	1	0	0	0
Local Inflow	6	6	6	6	6	6	6	6	6	6	6

Abbreviations for model runs: H-Historical Hydrology, WD-Warm Dry Hydrology, SLR-Sea Level Rise, and C-Long-term Urban Water Conservation, and P-Policy Constraints on Interties

Table A-6: Average Annual Net Variable Operating Costs ($M/yr)

	Base Case	Climate Change			Climate Change with Long-term Urban Water Conservation			Historical Hydrology and Climate Change with Intertie Policy Constraints			
	H	**WD**	**H-SLR**	**WD-SLR**	**WD-C**	**H-SLR-C**	**WD-SLR-C**	**H-P**	**WD-P**	**H-SLR-P**	**WD-SLR-P**
Bay Area*	310	332	609	829	190	227	303	332	383	910	1,156
North Central Valley	294	292	318	456	232	250	274	298	325	414	592
South Central Valley	1,588	1,625	1,394	1,347	1,114	803	765	1,631	1,666	1,594	1,531
So. California	2,938	3,070	3,128	4,342	1,513	1,299	1,677	2,938	3,070	3,128	4,342
Statewide	4,820	4,986	4,839	6,145	2,859	2,352	2,716	4,867	5,062	5,136	6,466

*Bay Area includes the portion of costs of operating south Delta pumps that deliver water through the South Bay Aqueduct and Pacheco Tunnel.

Abbreviations for model runs: H-Historical Hydrology, WD-Warm Dry Hydrology, SLR-Sea Level Rise, and C-Long-term Urban Water Conservation, and P-Policy Constraints on Interties.

Table A-7. Average Annual Net Total Costs (Scarcity and Operating) ($M/yr)

	Base Case	Climate Change			Climate Change with Long-term Urban Water Conservation			Historical Hydrology and Climate Change with Intertie Policy Constraints			
	H	**WD**	**H-SLR**	**WD-SLR**	**WD-C**	**H-SLR-C**	**WD-SLR-C**	**H-P**	**WD-P**	**H-SLR-P**	**WD-SLR-P**
Bay Area*	310	332	660	899	190	227	304	332	383	957	1,208
North Central Valley	313	796	339	523	456	269	333	317	827	476	659
South Central Valley	1,589	2,915	3,774	5,524	1,664	2,410	4,311	1,632	2,954	5,598	5,652
So. California	3,263	3,491	3,973	5,365	1,730	1,559	2,039	3,263	3,433	3,973	5,365
Statewide	5,165	7,203	8,136	11,482	3,851	4,237	6,683	5,211	7,214	10,093	11,728

*Bay Area includes the portion of costs of operating south Delta pumps that deliver water through the South Bay Aqueduct and Pacheco Tunnel.

Abbreviations for model runs: H-Historical Hydrology, WD-Warm Dry Hydrology, SLR-Sea Level Rise, and C-Long-term Urban Water Conservation, and P-Policy Constraints on Interties.