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

By

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1.0 ABSTRACT

Climate change will affect both sea level and the temporal and spatial distribution of runoff in California. These climate changes 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. The 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.

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2.0 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 also will accelerate global sea level rise. Current projections suggest a range of mean sea level rise 30 to 45 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 Valleys, 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 5 years with the 2005 versions being the most recent finalized update. 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).

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.

This report 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.

3.0 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, CALVIN, is employed. A large scale optimization model can identify preliminary qualitative management options based on the details of systems operations that can be evaluated in future detailed simulation modeling of individual water supply systems.

3.1 CALVIN

3.1.1 Model

California Value Integrated Network (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).

CALVIN is a generalized network flow model that uses the optimization solver 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% of California's population and 88% 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 as detailed in 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 leaving node i towards node j, c_{ij} = economic costs (ag. or urban), b_j = external inflows 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.

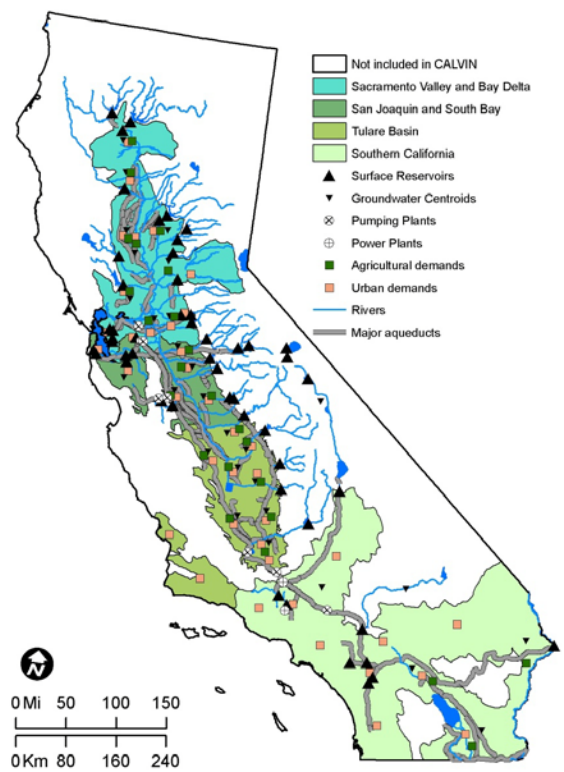


Figure 1. Water supply infrastructure, inflows and demand areas represented in CALVIN.

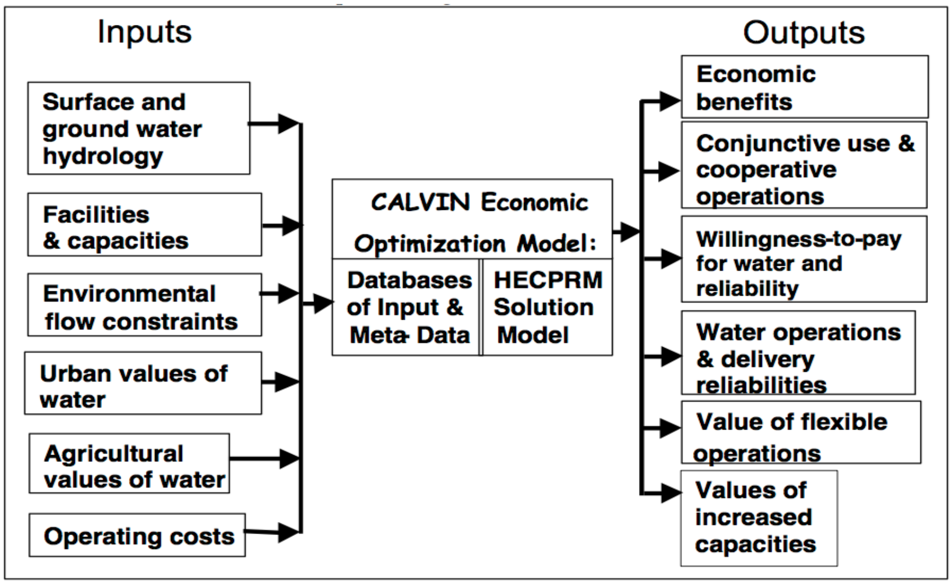


Figure 2. CALVIN data flow.

3.1.2 Operating Costs

Water supply from surface water and groundwater are subject to operating costs of pumping, artificial recharge, and treatment. 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-SFPUC Intertie, and the EBMUD-CCWD Intertie. Urban areas were assumed to be able to recycle a portion of their wastewater flows. 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. 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.

3.1.3 Bay Area Demand Locations

Many water supply wholesalers and retailers (water districts, public utility commissions, irrigation districts, etc.) 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.

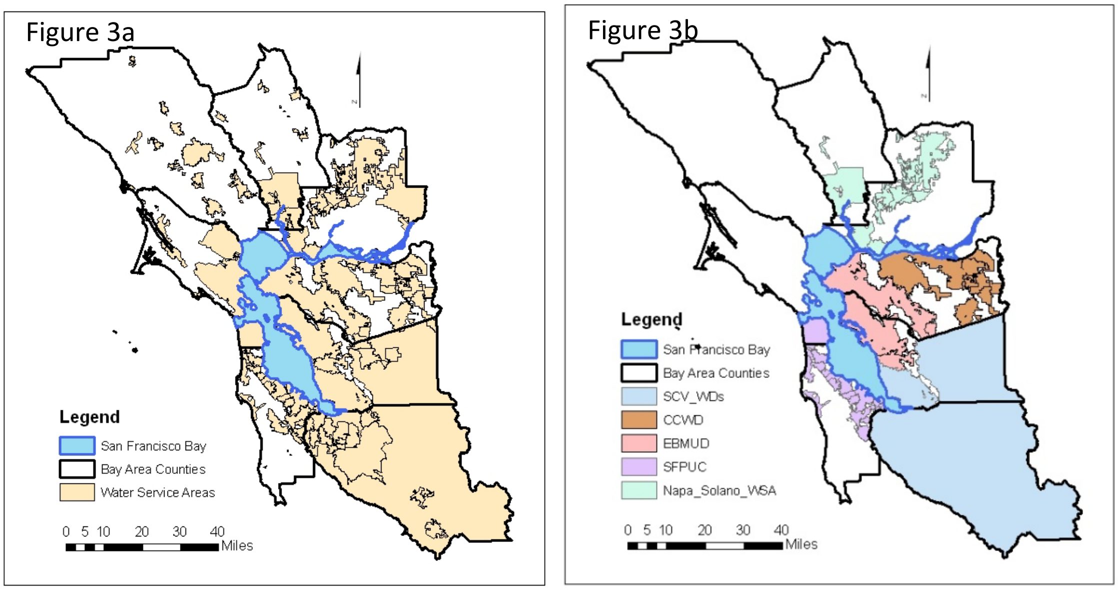


Figure 3. Water supply retailers and wholesalers in the nine San Francisco Bay Area Counties. Figure 3a shows the boundaries of individual water service areas in the San Francisco Bay Area. Figure 3b shows the aggregated CALVIN urban demand locations in the San Francisco Bay Area.

3.1.4 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 (CCWD) has its own water rights and also relies on USBR CVP water. CCWD 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.

East Bay Municipal Utility District (EBMUD) 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 Utility 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. SCV has access to a diverse water supply portfolio. 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. SCV employs conjunctive use of surface and groundwater by banking local, imported and recycled water in overdrafted 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.

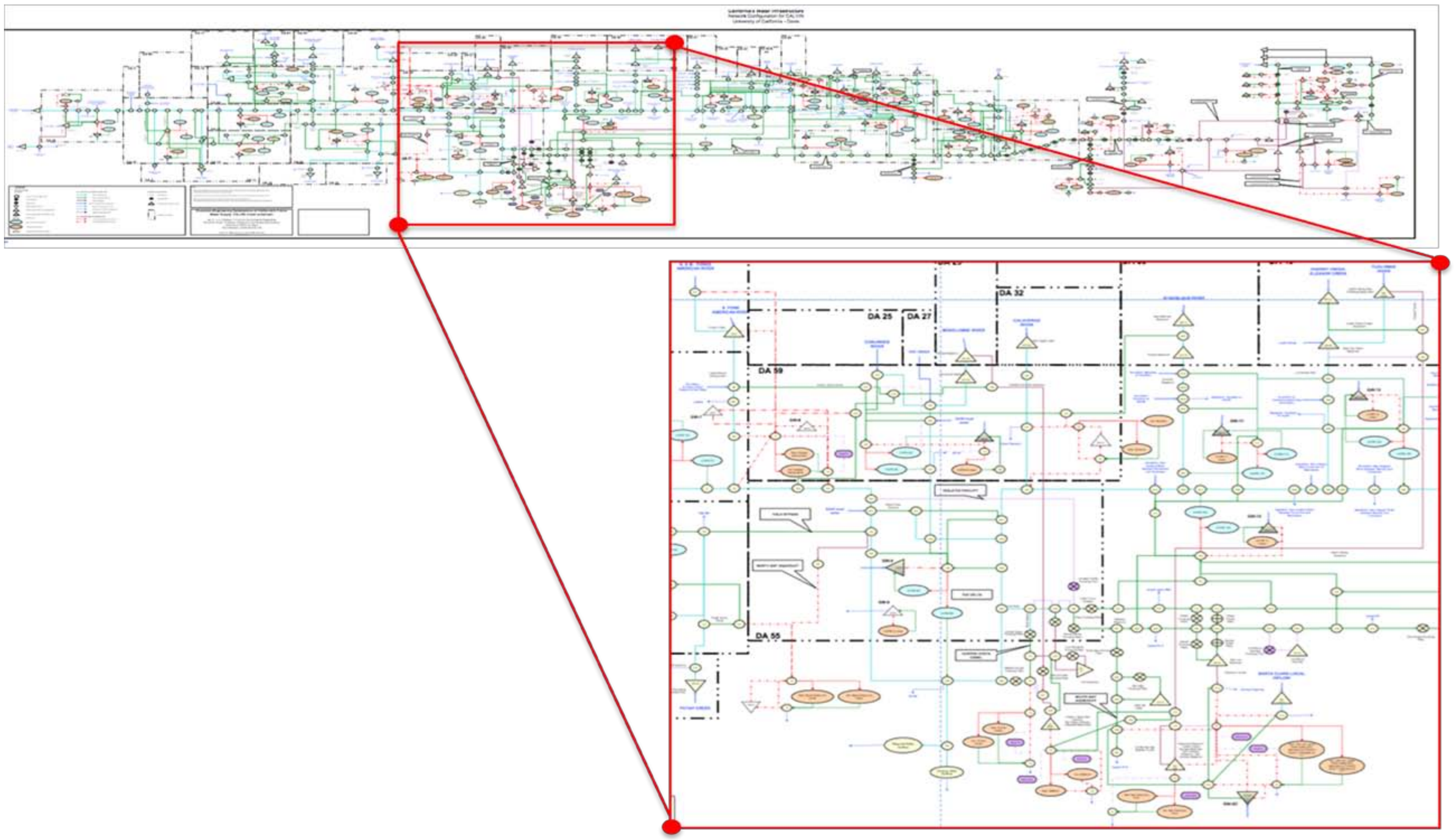


Figure 4. CALVIN schematic.

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

*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

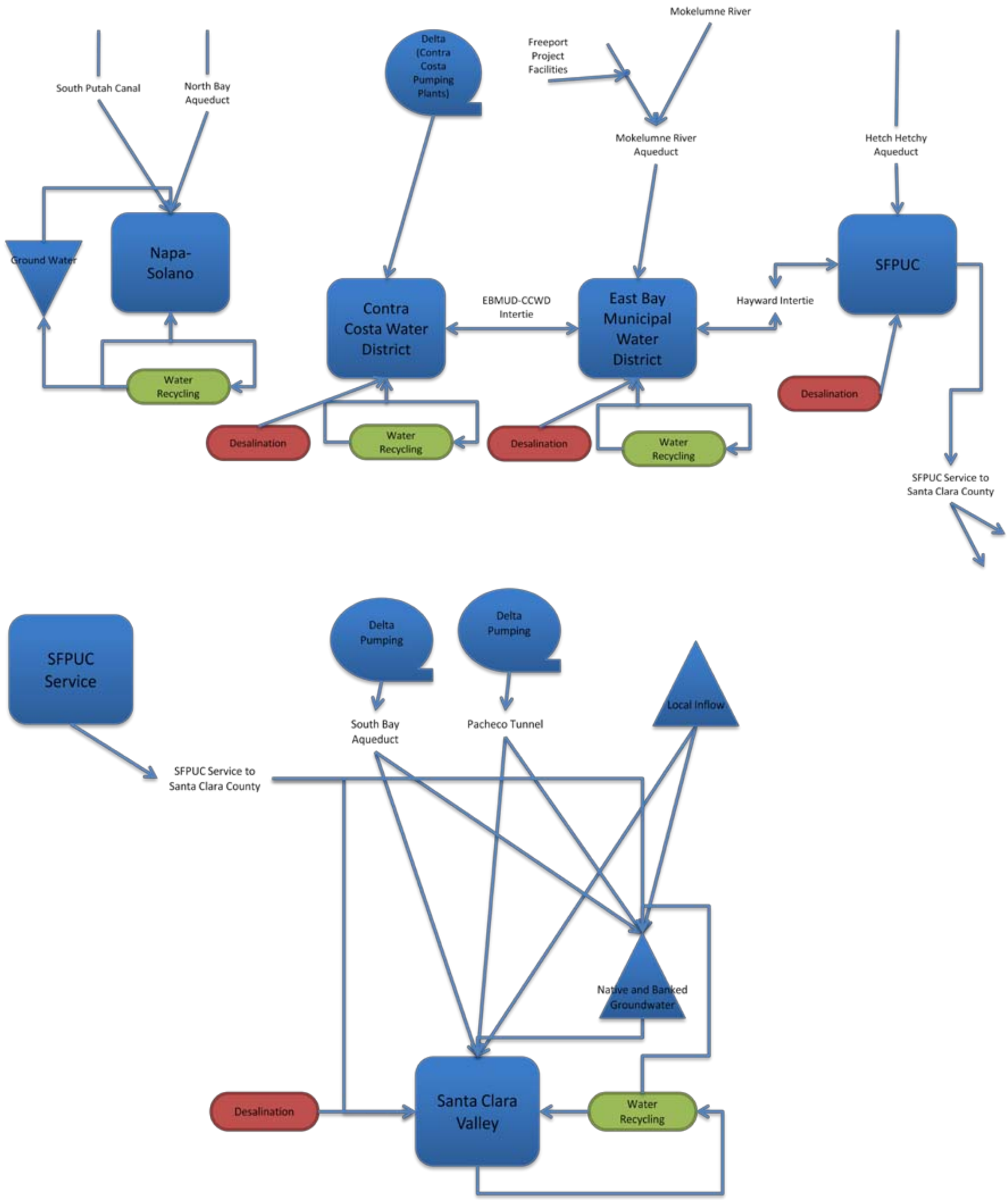


Figure 5. Conceptualization of aggregate demand areas in the San Francisco Bay Area.

3.1.5 Hydrology

In CALVIN, hydrologic variability is represented using 72 years of monthly hydrology (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.

3.2 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 which results in a 50% reduction diversion capacity from the Delta, (3) a future climate with historical hydrology and sea level rise which results in no exports or diversions from the Delta, (4) a future climate with both warm dry hydrology and sea level rise which results in a 50% reduction in diversion capacity from the Delta, and (5) a future climate with both warm dry hydrology and sea level rise which results in no exports or diversions from the Delta.

3.2.1 Hydrologic Change

Global Circulation Models (GCMs) used to model climate change consider 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 Cyan 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 2009). Connell (2009) used down scaled effects of the Geophysical Fluid Dynamics Laboratory (GFDL) CM2.1 model with A2 emissions scenario to create a warm dry input hydrology for CALVIN. The warm dry climate effectively reduced overall inflows to CALVIN by about 27% on average, but inflow reduction percentages varied over model domain.

For input into CALVIN, the NOAA Geophysical Fluid Dynamics Laboratory (GFDL) CM 2.1 climate scenario with relatively high emissions (A2) were downscaled to capture the effects of warm dry form of climate change by year 2050 (Medellin-Azuara et al., 2009; Medellin-Azuara et al., 2008). The methods described in Zhu et al. (2005) to perturb historical (1921-1993) time series of rim inflows in CALVIN, temperature and precipitation were employed.

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^{o}C increase in temperature and 3.5% decrease in precipitation in California’s Central Valley.

Rim Inflows

Perturbation ratios for surface streamflows 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 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 in Pine Flat Dam. These were employed in Medellin-Azuara et al. (2008) following the methods in Miller et al. (2003). Connell (2009) expanded the number of index rivers to 18, and showed that there were no significant gains in precision from adding more index river streamflows. This study employed the 18 index river information. Roughly a 27% statewide reduction in streamflows 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.

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.

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.

3.2.2 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 (Contra Costa, Old River and Rock Slough) are 16,500 cfs (11.95 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% 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.

3.2.3 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, Medellin-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% 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 Water Resources Control Board’s goal to achieve a 20% 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.

3.2.4 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 Water District, San Francisco Public Utility 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 (30 MGD). The EBMUD-CCWD Intertie is a partnership between East Bay Municipal Water 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.

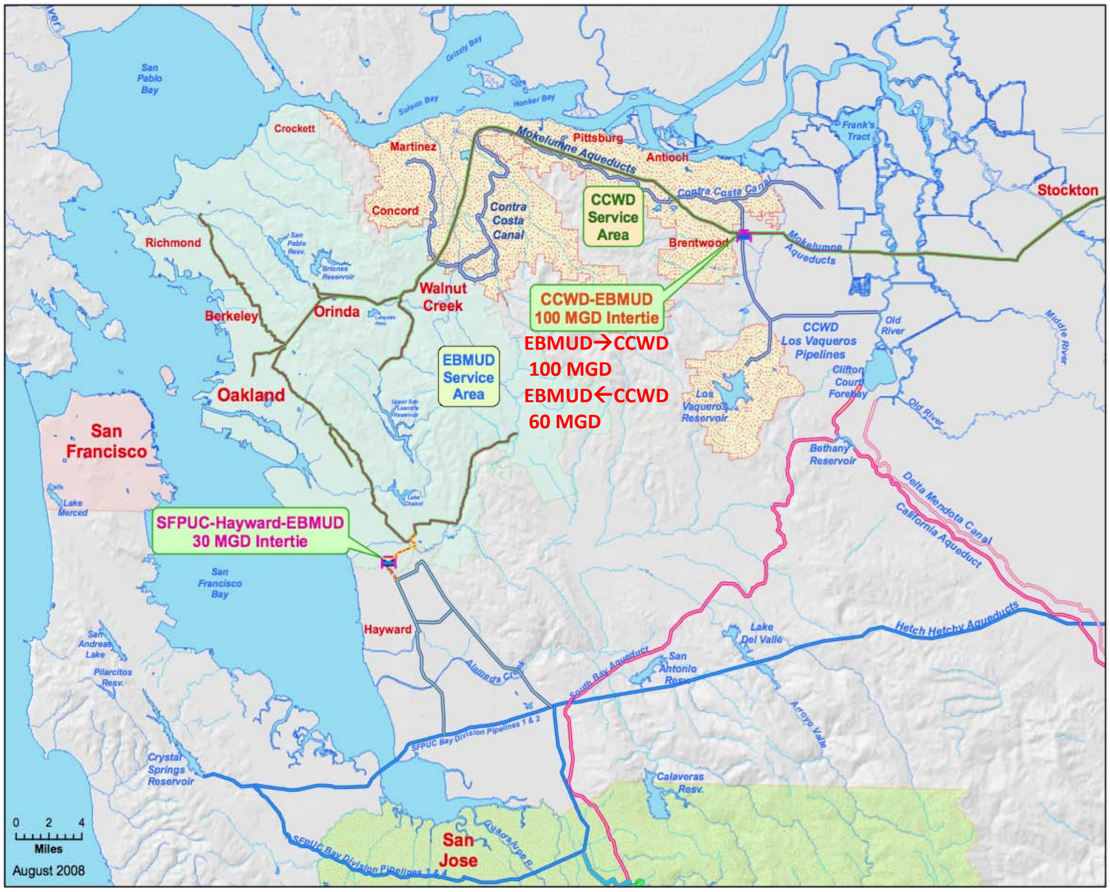


Figure 6. Location and capacity of the EBMUD-Hayward-SFPUC and EBMUD-CCWD Interties. (Modified from EBMUD, 2005)

The Freeport Regional Water Project (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 the 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 functionality of the project was built to provide water to EBMUD during water shortages during droughts. 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.

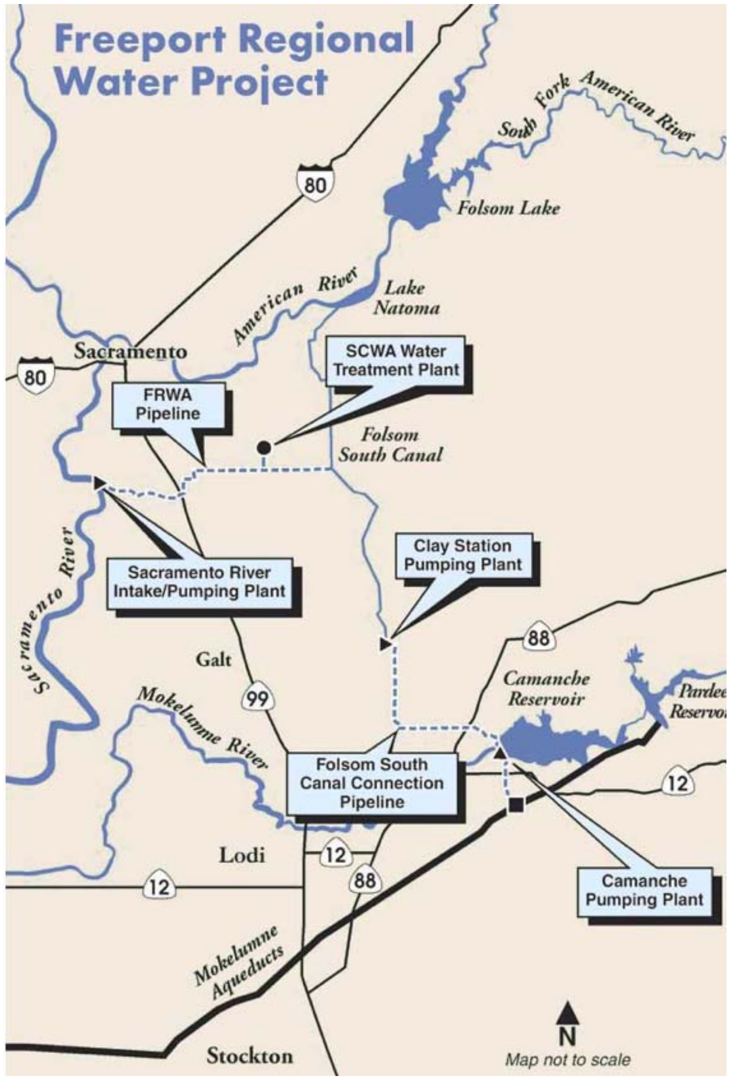


Figure 7. Location of the Freeport Regional Water Project infrastructure
(From Freeport Regional Water Authority, 2011)

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% 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% of physical capacity. The modeled unconstrained and constrained intertie capacities are listed in Table 1.

Table 1. Modeled intertie capacities.

Intertie	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

3.2.5 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%. 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%. 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% of maximum physical capacity. All climate change and policy constrained runs are intended to severely test the system rather than being 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 Long-term Urban Water Conservation		
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 that reduces Delta diversion capacity by 50% (-SLR50) cases do not show different average results from the related historical case or the warm dry case (i.e. H vs. H-SLR50 and WD vs. WD-SLR50, etc.) and therefore are not included separately in the results. This result is likely due to the large amount of storage within the water supply network.

4.0 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.

4.1 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. These 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 (WTP) 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, urban sector water demands are all met. By contrast urban and agricultural users statewide have 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% reduction in Delta exports and diversions shows no increase in scarcity or scarcity costs from the base case.

The agricultural willingness to pay (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 no Delta diversions case and is the highest in the combined reduced stream flow and no Delta diversions case. Achieving 30% 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% 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.

Table 3. Average Bay Area urban water scarcity cost and agricultural opportunity cost.

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
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
Statewide Ag.	297,599	2,105,998	2,654,119	4,359,542	984,891	1,842,245	3,816,988	297,599	2,105,865	4,323,221	4,323,221
Statewide Total	344,416	2,216,271	3,245,850	5,266,876	991,386	1,885,260	3,966,452	344,416	2,152,682	4,910,421	5,210,212

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

4.2 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 Table 13 show the average annual 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. The combination of reduced streamflow and no Delta exports or diversions is the most costly alternative. 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 Table 14 display the total cost of operations and allocations, the sum of the scarcity and variable operating costs.

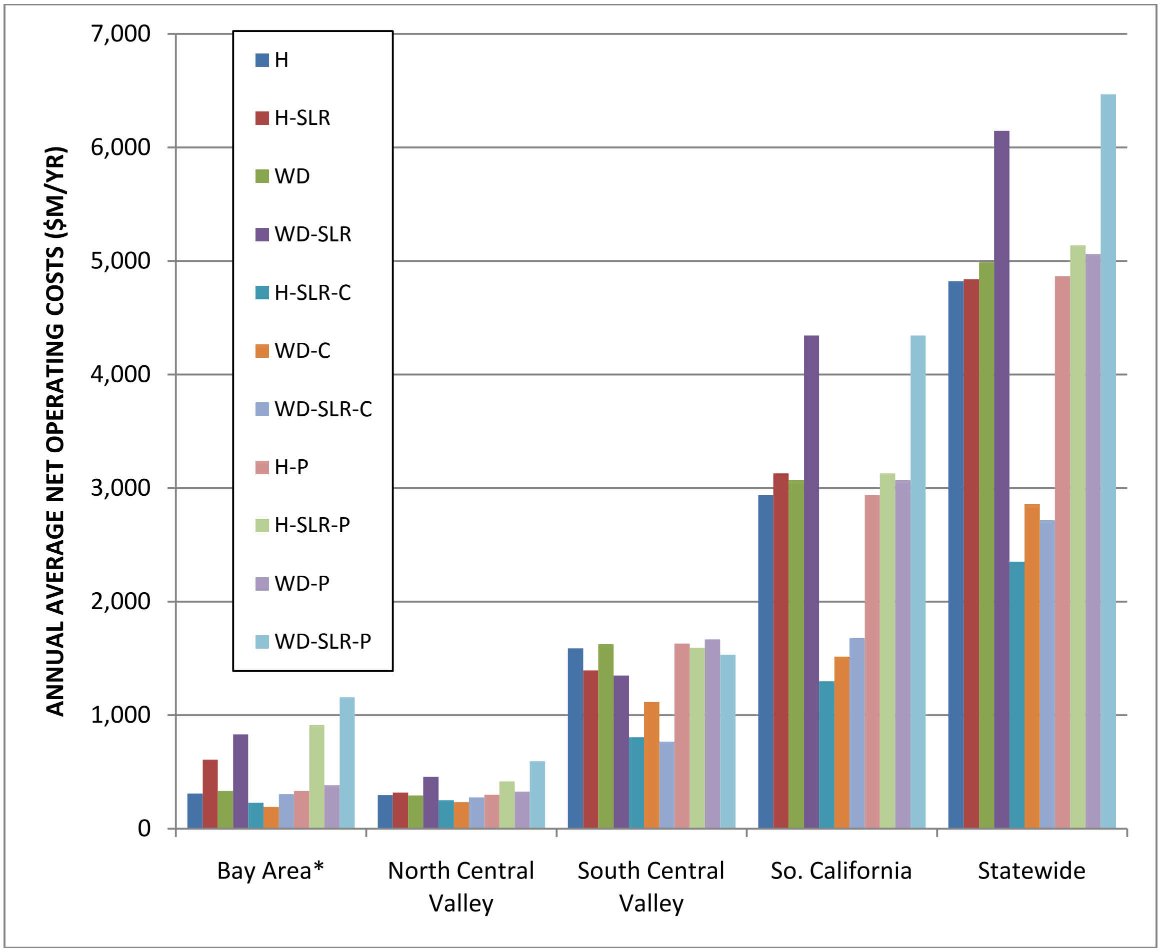


Figure 8. Average annual variable operating costs.

***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.

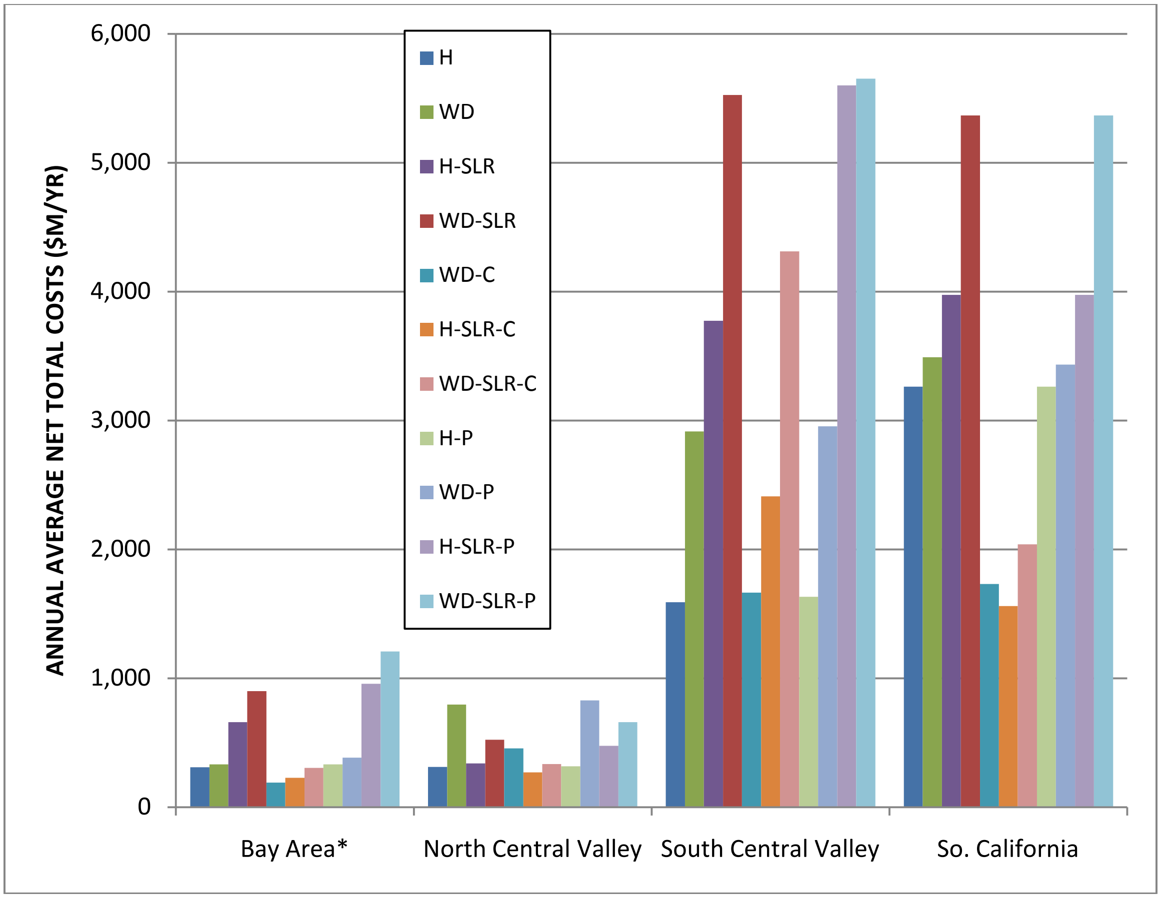


Figure 9. Average annual total costs (scarcity and operating) ($M/yr).

***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.

4.3 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 5 shows the marginal costs of environmental flows statewide. 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 the most illustrate 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 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 5. Average marginal costs of environmental flows ($/af/yr).

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.

Environmentally Sensitive Areas	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
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
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

4.4 Supply 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 given a functional water market.

4.4.1 Santa Clara Valley Water Districts Demand Area

Santa Clara water districts (SCV) is the largest Bay Area urban demand area in CALVIN with a projected demand of 715,000 acre-ft/year by 2050. 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 Table 6 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 taf/year or 36% of water delivered on average. Groundwater pumping, local sources and SFPUC service account for about 17% each or 125 taf/year average. Water recycling is about 2% of water supply, 16 taf/year, 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% reduction in Delta diversion capacity (SLR50) shows 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% of supply in both the sea level rise (H-SLR50) and warm dry and sea level rise (WD-SLR50) cases respectively. Desalination accounts for 9% and 14% of supply in the sea level rise (H-SLR50) and warm dry and sea level rise (WD-SLR50) cases respectively.

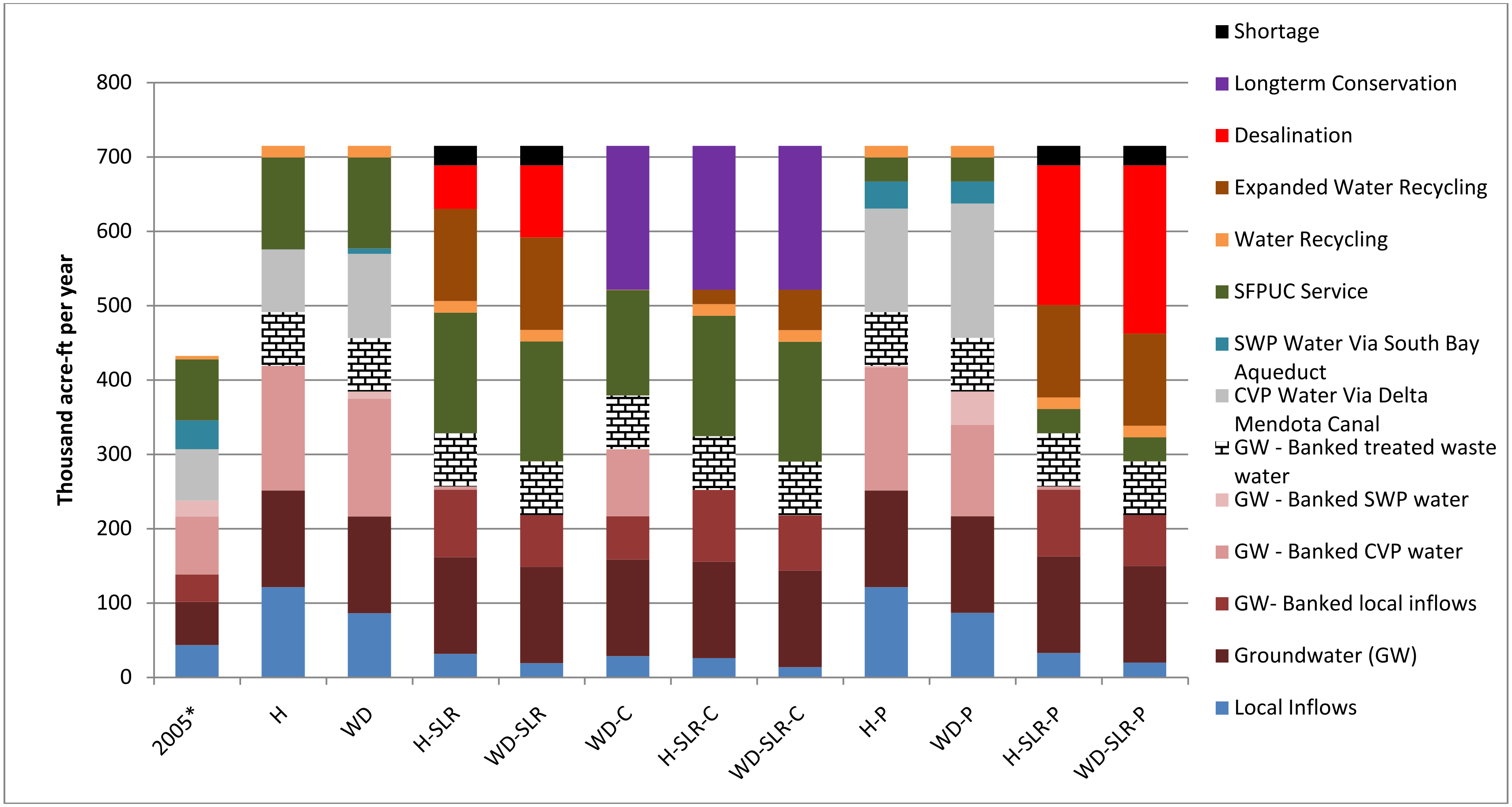


Figure 10. Average Santa Clara Valley demand area water supply portfolio.

*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

Table 6. Average water supply portfolio for SCV demand area (% use).

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

	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

Water conservation of 30% 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 Table 6 show that under sea level rise, the total groundwater banking/conjunctive use drops.

4.4.2 San Francisco Public Utility Commission Demand Area

The San Francisco Public Utility Commission (SFPUC) demand area has access to water from the Hetch Hetchy Aqueduct, the Hayward Intertie, water recycling and desalination. Figure 11 and Table 7 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.

4.4.3 Contra Costa Water District Demand Area

Contra Costa Water District (CCWD) 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 Table 8 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% 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% 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.

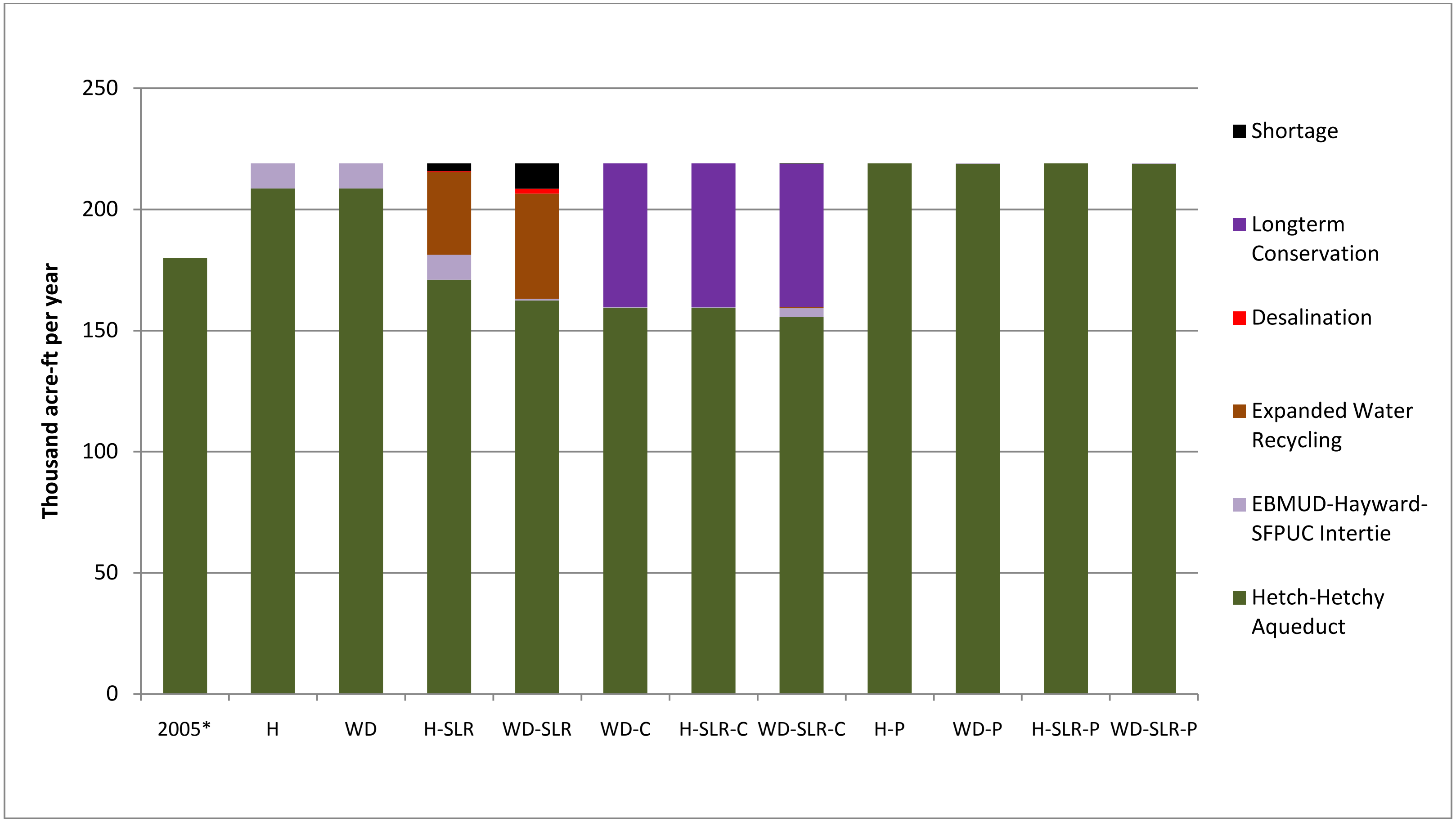


Figure 11. Average SFPUC demand area water supply portfolio.
*2005 water use estimates based on 2005 urban water management plans and State Water Plan
Abbreviations for model runs: H-Historical Hydrology, WD-Warm Dry Hydrology, SLR-Sea Level Rise, and C-Long-term Urban Water Conservation, and P -Policy Constraints on Interties

Table 7. Average water supply portfolio for SFPUC demand area (% use).

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

	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

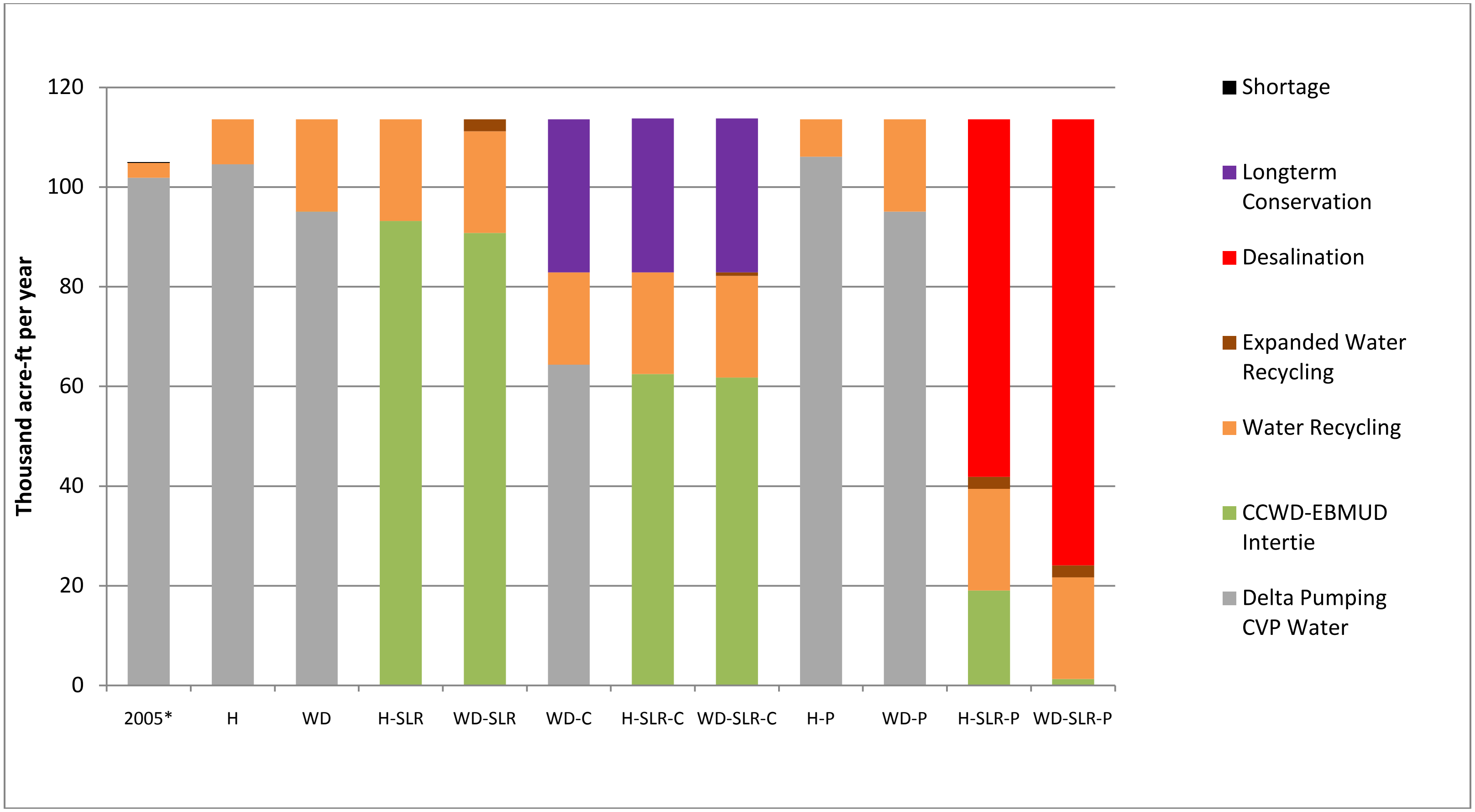


Figure 12. Average CCWD demand area water supply portfolio.

*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

Table 8. Average water supply portfolio for CCWD demand area (% use)

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

	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

4.4.4 East Bay Municipal Utility District Demand Area

The East Bay Municipal Utility District (EBMUD) 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 Table 9). Reduced Delta exports and diversion capacity does not significantly change the water supply portfolio from historical. With ending Delta exports or diversions, water recycling makes up 3% of the total water supply. With a warm dry climate, Freeport Project diversions become 31% of supply and water recycling expands to 9%. 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.

4.4.5 Napa-Solano Demand Area

The Napa-Solano demand area water supply portfolio appears in Figure 14 and Table 10. 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 north of the Delta eliminates problems from reduced south-of-the-Delta diversions.

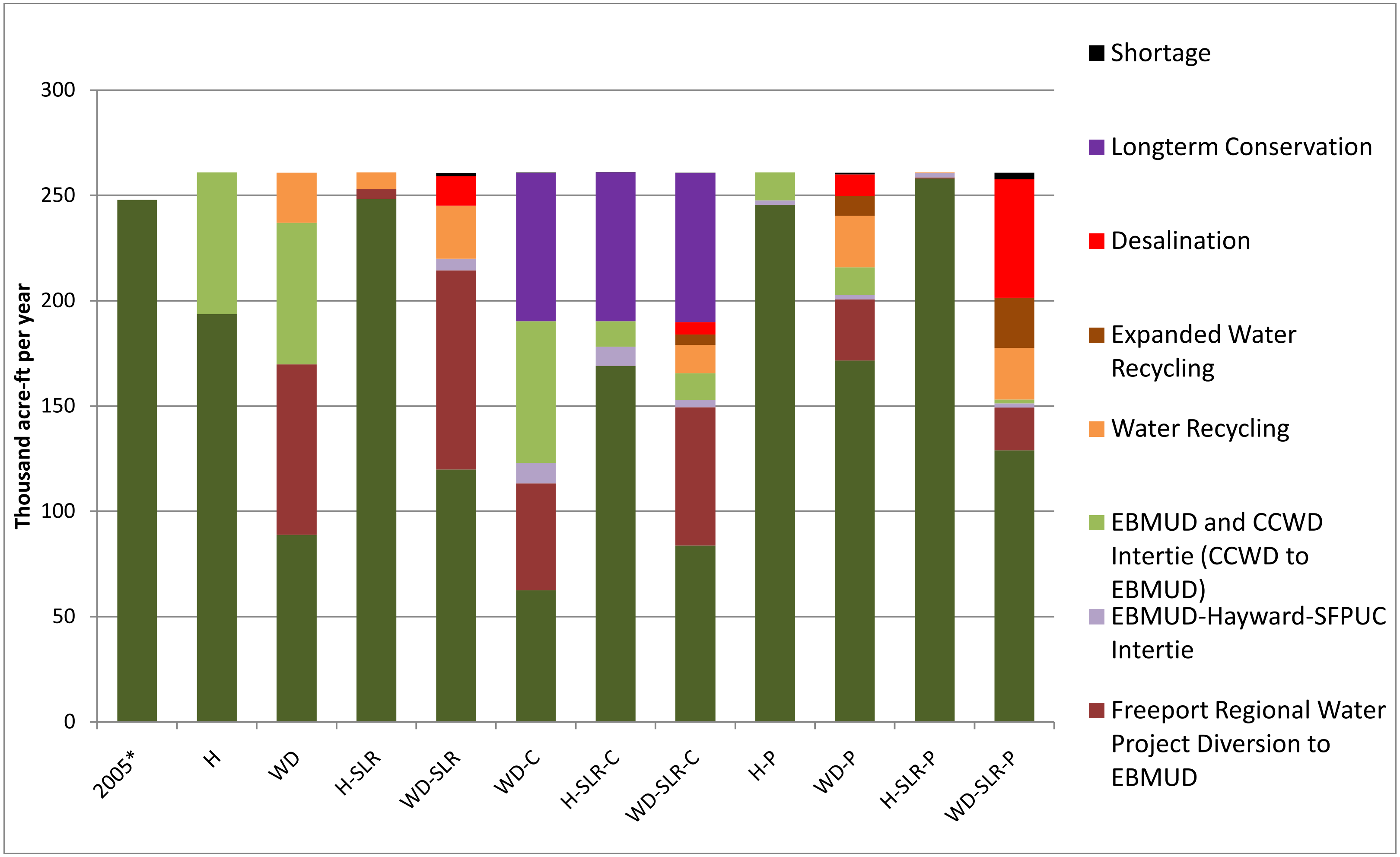


Figure 13. Average EBMUD demand area water supply portfolio.

*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

Table 9. Average water supply portfolio for EBMUD demand area (% use).

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

	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

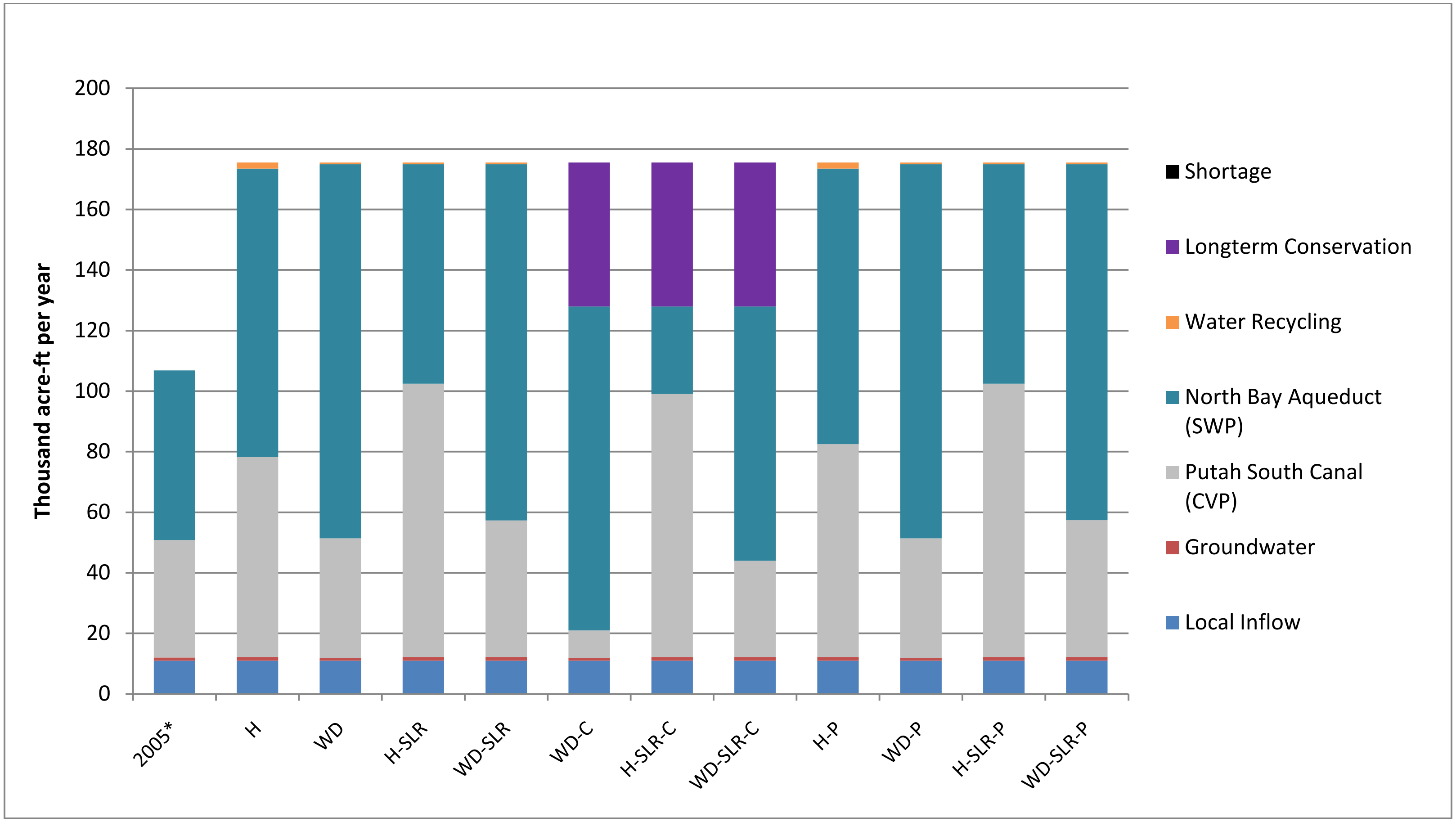


Figure 14. Average Napa-Solano demand area water supply portfolio.

*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

Table 10 **Average water supply portfolio for Napa-Solano demand area (% use)**

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

	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

4.5 Infrastructure Importance and Expansion Opportunities

Lifeline systems provide a network for stable delivery of services and resources of modern economies and civilization. Examples of lifeline systems are electrical power, liquid and gas fuels, telecommunications, transportation, waste removal, and water supply. Increasing attention has been given to evaluating the performance of such systems in the wake of natural disasters and for homeland security. Evaluations of lifeline systems are generally focused on identifying system vulnerabilities and prioritizing system components. Identification of vulnerabilities and prioritizing system components allows managers to target fortification efforts toward vulnerable and important components or to plan for emergency response following a failure.

Historically the performance of a water supply system has been evaluated by how well the system meets water demand by water delivery given variability of inflow to the water system. Using simulation or optimization tools, systems are evaluated by their ability to meet current and future water demands given inflow magnitudes and sequences equivalent to the historical record or a stationary stochastic representation of possible future inflows based on historical records. In a series of papers published in Water Resources Research in 1982 (Cohon, 1982; Hashimoto et al. 1982a, 1982b; Moy et al. 1982), performance indicators were presented for evaluating a water supply system in the context of variability of water inflow and demands.

These performance indicators can provide a risk assessment of the water supply system evaluating system capacity, configuration, and operating policies. These quantitative performance indicators are reliability, resiliency and vulnerability. Reliability is the probability that the system performance meets demand at any given time during the period of evaluation. Resiliency and vulnerability both describe the possible severity of failures. Resiliency is how quickly a system will recover from a failure once it has occurred. Vulnerability indicates the likely magnitude of the failure if it occurs. Hashimoto et al. (1982a) show that a system cannot be optimized for all of these measures. For example, it is often cost prohibitive to build redundant conveyance or a reservoir large enough to make failure impossible which leaves the system less robust. However, in such a case, effort should be spent minimizing vulnerability to minimize the impact of a failure event (Hashimoto et al. 1982a). The definitions presented in these papers provide a useful basis for discussing the performance of a water supply system. Historically these indicators have been used to optimize system operations. Techniques that are used focus on minimizing the occurrence or economic impact of water shortages (Jenkins and Lund 2000). Shortages are defined as the difference between water demanded and water delivery.

Infrastructure importance in a systems performance and ranking of system components has been performed using risk assessment methods and network reliability methods. Examples of the former are seen in the analysis of transportation systems, and examples of the latter are seen in the analysis of electrical networks and water distribution networks.

4.5.1 Risk Assessment

Following earthquake related damage of transportation systems in California and elsewhere in the last 30 years, managers and engineers have sought to fortify their systems by upgrading bridges to withstand earthquake related forces. One challenge has been how to allocate limited resources to bridge strengthening. This has resulted in various methods for systematically ranking/prioritizing bridges (Basoz 1996). All methods to prioritize bridges have relied on a network level evaluation of the system, with the bridges ranked based on a weighted vulnerability factor and a weighted importance factor. The common form of the ranking is in equation 5.

$$Rank = \sum_{i=1}^{n} w_i F_i \qquad (5)$$

where *i* is the individual factor (vulnerability or importance or more up to *n* factors) w_i is a weight and F_i is the factor value. The vulnerability factor is a function of the ability to resist earthquake forces and large relative movement, age and state of repair, and seismic velocity maps. The importance factor is a measure of the bridge's importance to the performance of the system. The importance factor is a function of route types that cross the bridge, detour lengths in the absence of the bridge, average daily traffic, utility lines carried by the bridge, and importance of the bridge as a public asset.

Many researchers have used this general ranking form with small differences in weighting and functional parameters (Basoz 1996). Other researchers have suggested that the summation of factors is insensitive to relative risk and favor using a ranking system based on the product of the factors, or suggest breaking out seismicity as its own factor for a three factor evaluation (Caltrans 1993, Gilbert 1993). However, all authors emphasize the value of the importance factor in evaluation. Basoz and Kiremidjian (1996) developed a comprehensive systematic method for establishing the importance factor of a system component using network analysis and decision analysis. They use decision models to integrate engineering, economic, and social factors.

4.5.2 Network Reliability

Network reliability analysis provides a robust method to evaluate reliability which includes system performance aspects discussed above of variation in supply and demand and includes infrastructure failure which will result in changes to network configuration. Reliability is the complement of probability of system failure. System reliability has implications for system design, operations and maintenance, and planning and management. Network reliability theory is particularly important for evaluating lifeline systems such as electrical grids, transportation systems, and water distribution systems that have varying degrees of network redundancy. This importance stems from the stochastic nature of system failures and that lifeline system failure not only results in lost revenue and repair costs to the agency managing the system but can also impact a region's public health, safety, economy, and environment.

Reliability of active redundancy in a network consists of two parts: topological reliability and performance reliability (Savage and Carr 1990). Failure of a system component results in a new topological configuration of the system. There will be a probability that the new topology is functional and a probability that the new topology will provide adequate system performance. A reliable system should perform in as many new topological configurations as possible. These general statements about network reliability allow for application to many systems, and require an engineer to clearly define a functional system and performance metrics.

A reliable water distribution network must supply water to demand nodes at required quantities and desired residual heads through connected and redundant conveyance networks (Gupta

1993). Electrical power networks similarly must supply power between generating stations such as hydropower and nuclear power and substation grids and distributed demand locations (Holmgren, 2002). In both network types the initial approaches to reliability explore topological reliability of the network. Analytical techniques are used to determine the interconnectedness and the redundancy of the network. Node isolation probability, minimum cut set, reachability and connectivity are all examples of changing the network topology in a simulation software package and observing the resulting performance of the system. Node isolation probability calculates the probability that a system node will be isolated given the probability of failure of each conveyance arc connected to the node. Minimum cut set is the minimum set of system components whose combined failure results in the failure of the entire system (Yang, 1996b). Reachability measures that each demand node is connected with at least one source node while connectivity measures that each source node is connected with at least one demand node for each topological configuration (Yang, 1996a). The applications in electrical power networks draw upon graph theory concepts of average path length and degree distribution. Average path length is the number of edges, links or arcs between a supply and demand. A degree is the number of edges connected to a source or demand node, and when applied to all source and demand nodes in a network results in the networks degree distribution. In structural vulnerability analysis of an electrical power network, failures are modeled by removing edges and recalculating the average path length or degree distribution.

Although these techniques can identify unsatisfactory topologies, the main limitation of these techniques is that they presume that if a node is connected to a source, demand is met. They are unable to identify unsatisfactory topologies that result from the combination of the topological configuration and infrastructure capacity constraints. Regardless of this limitation, these initial approaches could be applied to California's intertied water supply system to identify the level of network redundancy and to provide an indication of system vulnerabilities.

California's large and complex water supply system has features of a redundant network. Network redundancy is especially evident in the San Francisco Bay Area where water service agencies have constructed interties and implemented water recycling to expand and diversify their water supply portfolios. CALVIN provides a platform for evaluating the importance of system components drawing on the examples from transportation system infrastructure importance ranking and electrical and water distribution network reliability theory. The output from the network flow optimization solver provides output commonly used for a sensitivity analysis (Hillier and Lieberman 2005). Linear optimization solvers provide shadow value (marginal value or marginal cost) matrices (Lagrangian multipliers) 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 two very different climate change cases and looking at uncertainty and variability within each case using 72 year time series. Additionally, the topology of the network is significantly altered in sea level rise model runs by removing a network component (the ability of the Delta to act as a high flow network hub).

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 the system are indicators of the importance of the system component, the value of expanding the component's capacity, or the flexibility provided by the system component to deal with hydrologic uncertainty or topological changes. Viewing these data can indicate the vulnerabilities and system resiliency. Figure 15 shows the annual flow through an example system component for each year of model time. The data in this format are very hard to read. However, recalling that the hydrologic time series is strictly used to represent the variability in hydrology, it is useful to plot the flow volume through a system component as a non-exceedance probability (Figure 16). The next sections evaluate the sensitivity analysis results and display non-exceedance probability plots of system components to indicate system vulnerabilities and resiliencies that impact the San Francisco Bay Area.

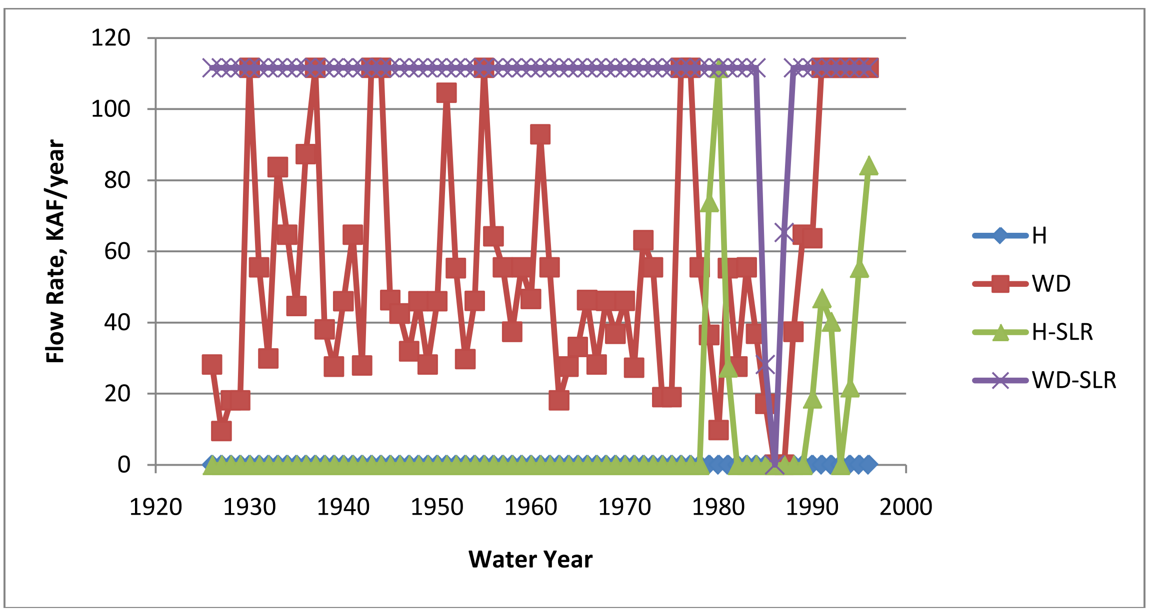


Figure 15. Flow rate through the Freeport Regional Water Project.

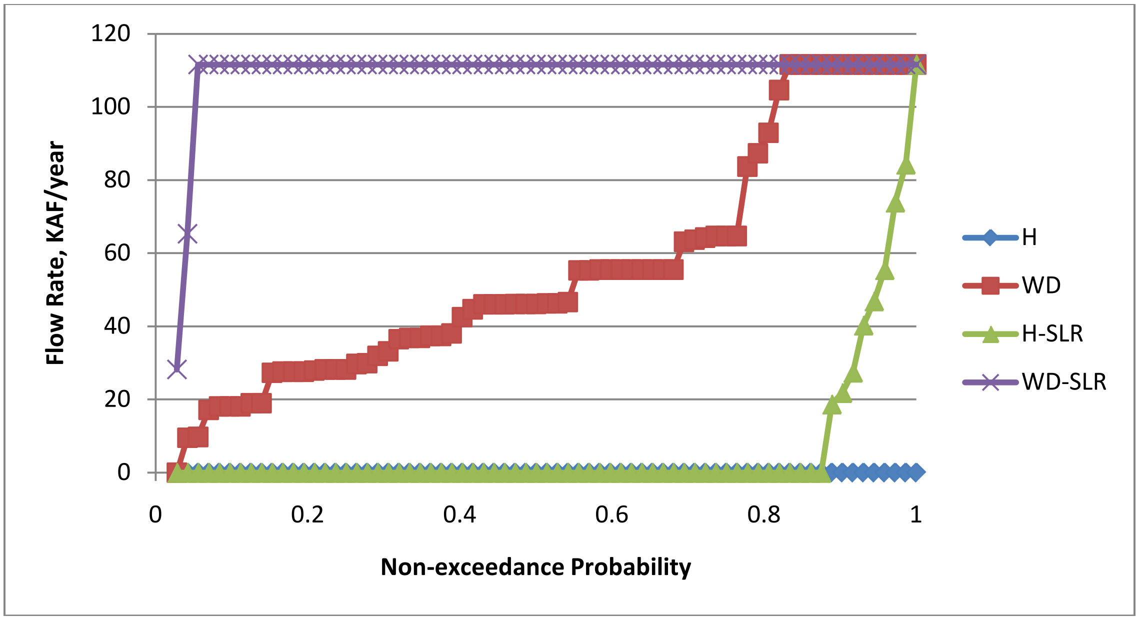


Figure 16. Non-exceedance probability of yearly flow through the Freeport Regional Water Project.

4.5.3 Marginal Cost of Infrastructure Expansion and Policy Relaxation

Table 11 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. The review of the water supply portfolios in the previous sections indicated the importance of the EBMUD's Freeport Project and Mokelumne River Aqueduct and SPFUC's Hetch Hetchy Aqueduct under climate change conditions. Figure 17 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 don't 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.

Table 11. Average marginal value of conveyance and water recycling capacity ($/af).

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

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

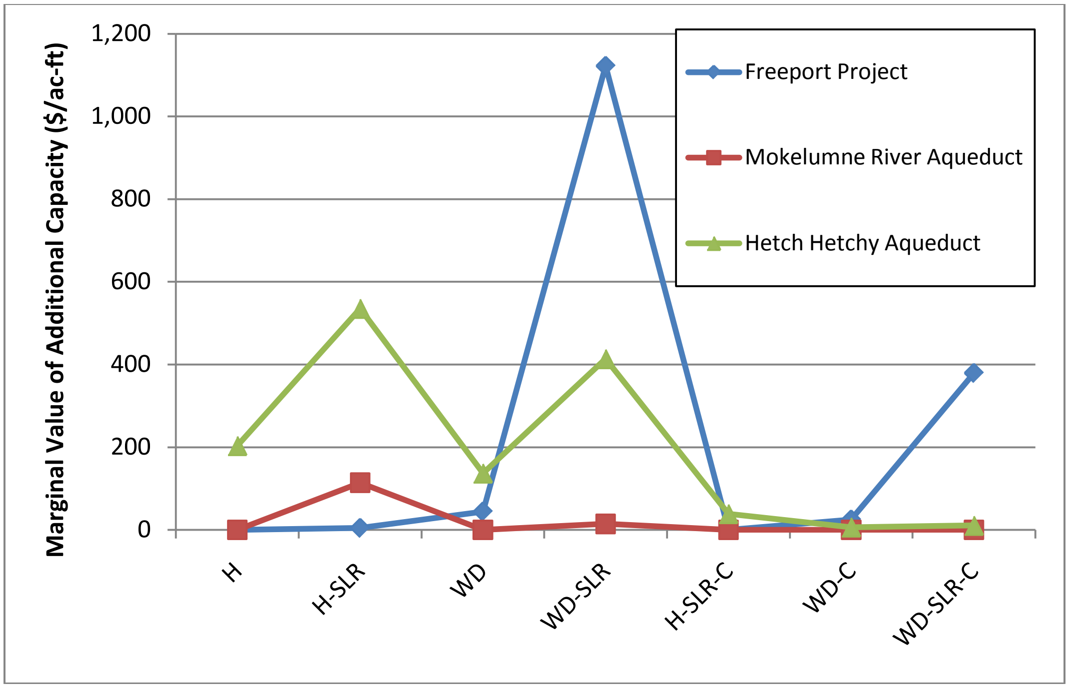


Figure 17. Average marginal value of additional aqueduct conveyance capacity.
Abbreviations for model runs: H-Historical Hydrology, WD-Warm Dry Hydrology, SLR-Sea Level Rise, and C-Long-term Urban Water Conservation.

Figure 18 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 19 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 12). 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%). 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 (i.e. H vs. H-SLR50 and WD vs. WD-SLR50, etc.). 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 12. Average marginal value of storage capacity ($/af).

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

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 Res	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
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 Res	12	106	11	13	60	11	12	2	32	7	0

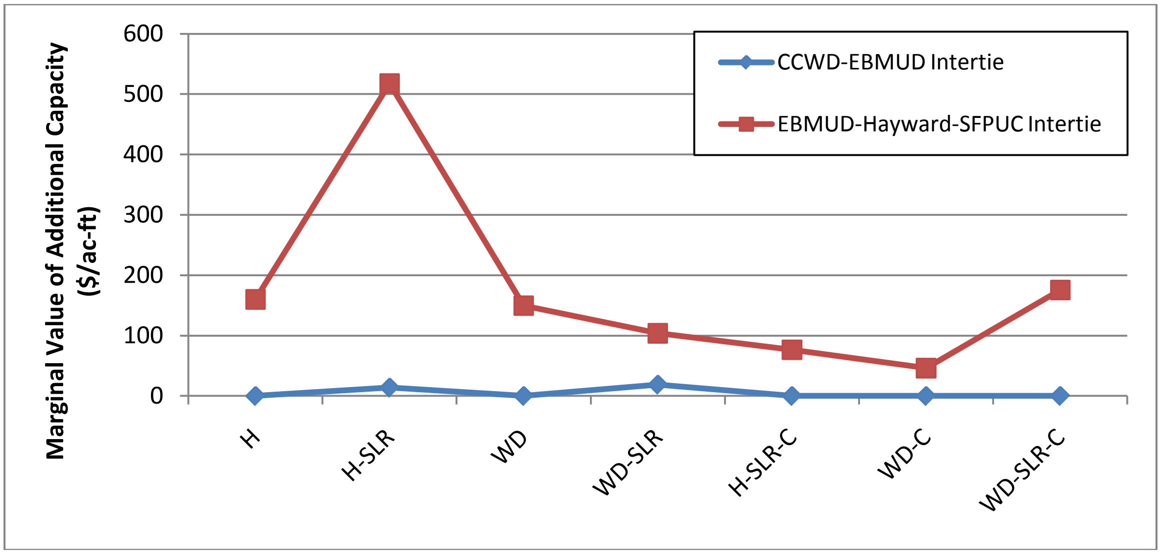


Figure 18. Average marginal value of additional intertie conveyance capacity.
Abbreviations for model runs: H-Historical Hydrology, WD-Warm Dry Hydrology, SLR-Sea Level Rise, and C-Long-term Urban Water Conservation.

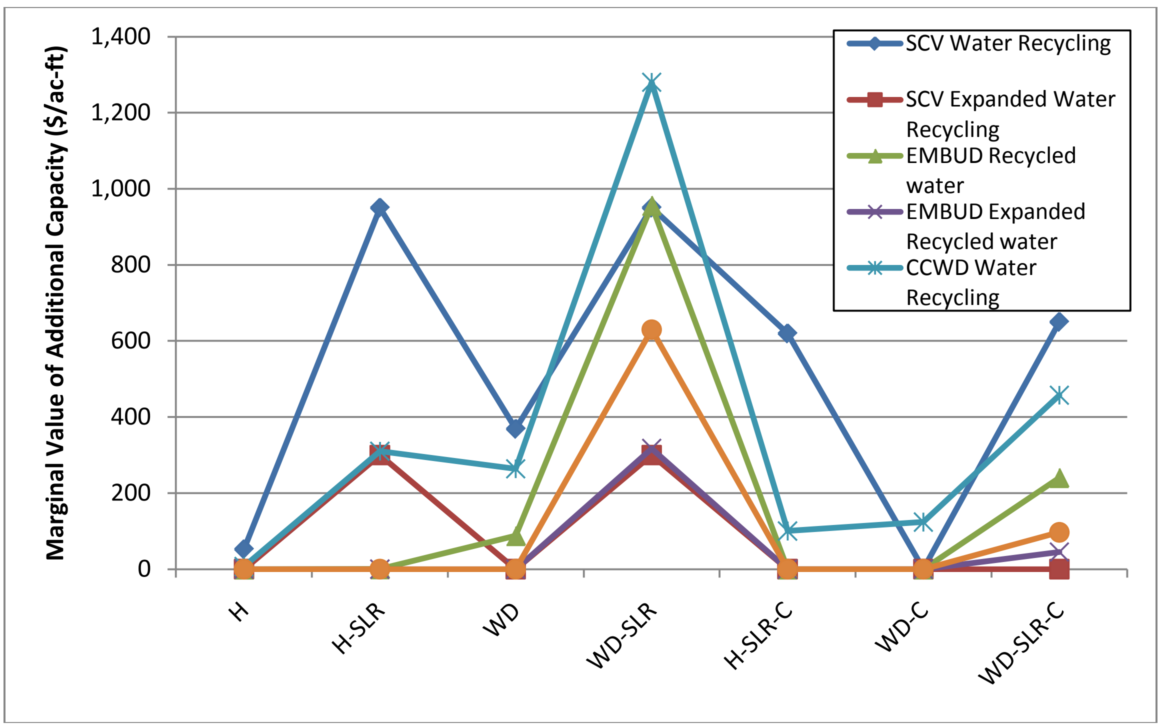


Figure 19. Average marginal value of additional water recycling capacity.
Abbreviations for model runs: H-Historical Hydrology, WD-Warm Dry Hydrology, SLR-Sea Level Rise, and C-Long-term Urban Water Conservation.

Figure 20 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 agencies water supply portfolio, they allow for wheeling of water between agencies, and allow agencies to cooperate on water supply alternatives such as water recycling and desalination. Figure 20 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 results in no Delta exports or diversions when the overall water supply portfolio of the Bay Area is reduced by eliminating SWP and CVP water.

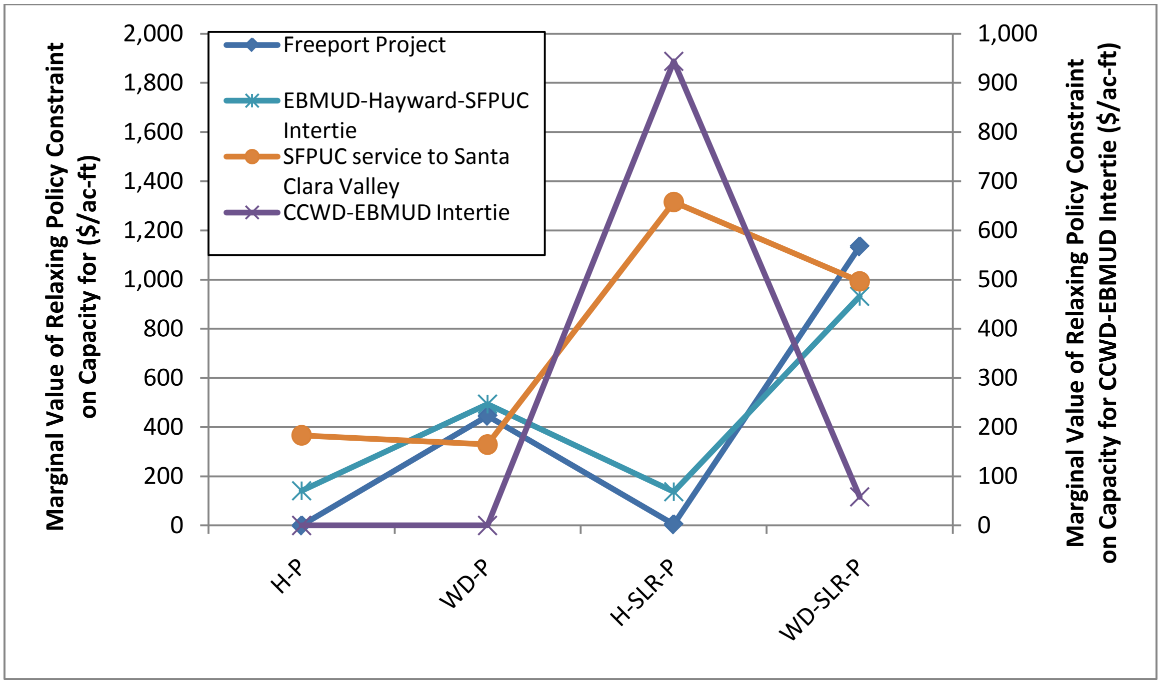


Figure 20. Average marginal value of relaxing policy constraints on intertie capacity.

4.5.4 Non-exceedance Probabilities

The yearly non-exceedance probability of flow through a system component is a useful way to evaluate the importance of infrastructure. The frequency with which a system components' capacity is utilized given changes in climate and network topology and given hydrologic uncertainty indicates the degree to which infrastructure allows for flexible operations, and the degree to which it limits the system. Non-exceedance probability plots were generated for water recycling, desalination, groundwater banking (conjunctive use), and emergency intertie infrastructure. The non-exceedance probabilities of flow through infrastructure components appear in the figures below for each of the model cases. The plots in each figure overlap making it difficult to distinguishing the individual model cases; therefore, for clarity, the cases have been grouped in each figure. Additionally, the plots only show the sea level rise case that results in no Delta exports or diversions because the sea level rise case that results in a 50% decrease in Delta exports and diversions showed very little change on average from the historical and warm dry cases.

Desalination

Figure 21 shows the non-exceedance probability of annual flow for desalination links in the Bay Area. Desalination as an alternative water supply option becomes increasingly important under to EBMUD and SCV in all cases which end Delta exports (sea level rise). Little economic gain is made by desalination at SFPUC. Additionally, CCWD only employs desalination under intertie policy constraint model runs where it cannot benefit from alternative water supply water developed in other areas wheeled through interties. As expected, long term urban water conservation reduces the value of desalination. However, intertie policy constraints increase the value of water supply from desalination.

Water Recycling

Figure 22 and Figure 23 show the non-exceedance probability of annual flow for expanding water recycling links in the Bay Area. Like the desalination links, expanded water recycling is more valuable and used more frequently under sea level climate change conditions. Water recycling is less valuable and used less frequently under base case conditions. Long term urban water conservation reduces the frequency of use of water recycling. The results from SFPUC water recycling are significantly different from the other demand locations. SFPUC only uses water recycling with frequency when there are no policy constraints on operations of intertie conveyance. With policy constraints in place, SFPUC transfer less Hetch Hetchy Aqueduct water along the interties; therefore, no water recycling is used to meet demand.

Conveyance Interties

Figure 24, Figure 25, and Figure 26 show the probability of non-exceedance for annual flow of the conveyance interties. Figure 24 shows little pattern between the frequency of water transfer along the EBMUD-Hayward-SFPUC Intertie and model run. This is likely due to both EBMUD's and SFPUC's water supply portfolios containing Mokelumne River Aqueduct water and Hetch Hetchy Aqueduct water, imported water supply that are reliable in reduced hydrology and sea level rise (no Delta exports) conditions. This intertie is used to wheel water to demand areas with less reliable water supply portfolios. The Freeport Regional Water Project is used to full capacity nearly 100% of years for sea level rise cases, but under warm dry only climate change conditions the project is used to full capacity only 20% of the time (Figure 25). In Figure 26, the direction of water transfers along the CCWD-EBMUD Intertie depends on the climate change scenario. For a warm dry only climate change conditions, water is transferred from CCWD to EBMUD, but for all sea level rise scenarios water is transferred at full capacity from EBMUD to CCWD.

The probability of non-exceedance for annual flow of the Hetch Hetchy and Mokelumne River Aqueducts appear in Figure 28. The aqueducts which import high quality water into the San Francisco Bay Area are important in all model cases. Their importance increases under sea level rise (no Delta exports) conditions.

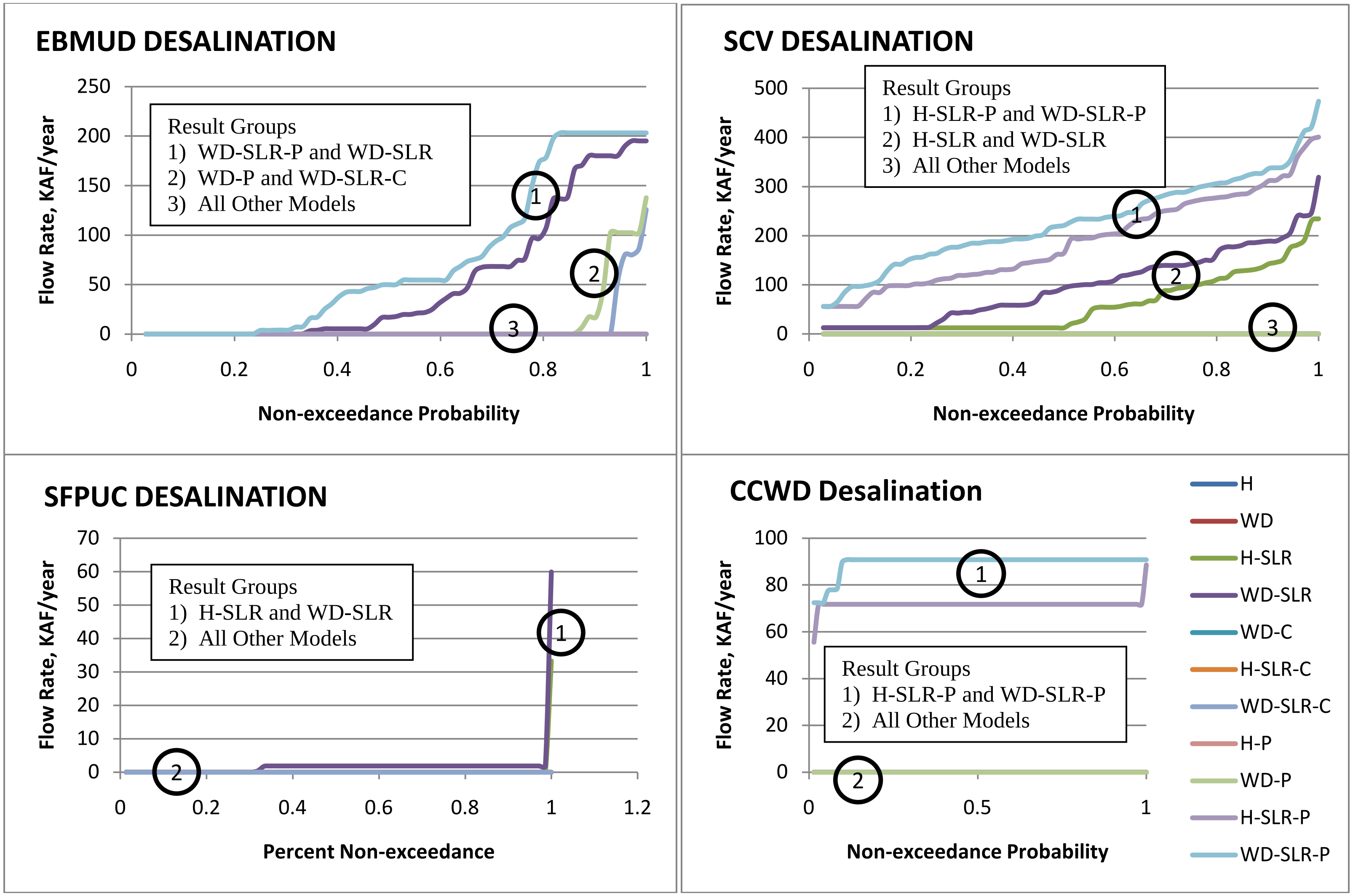
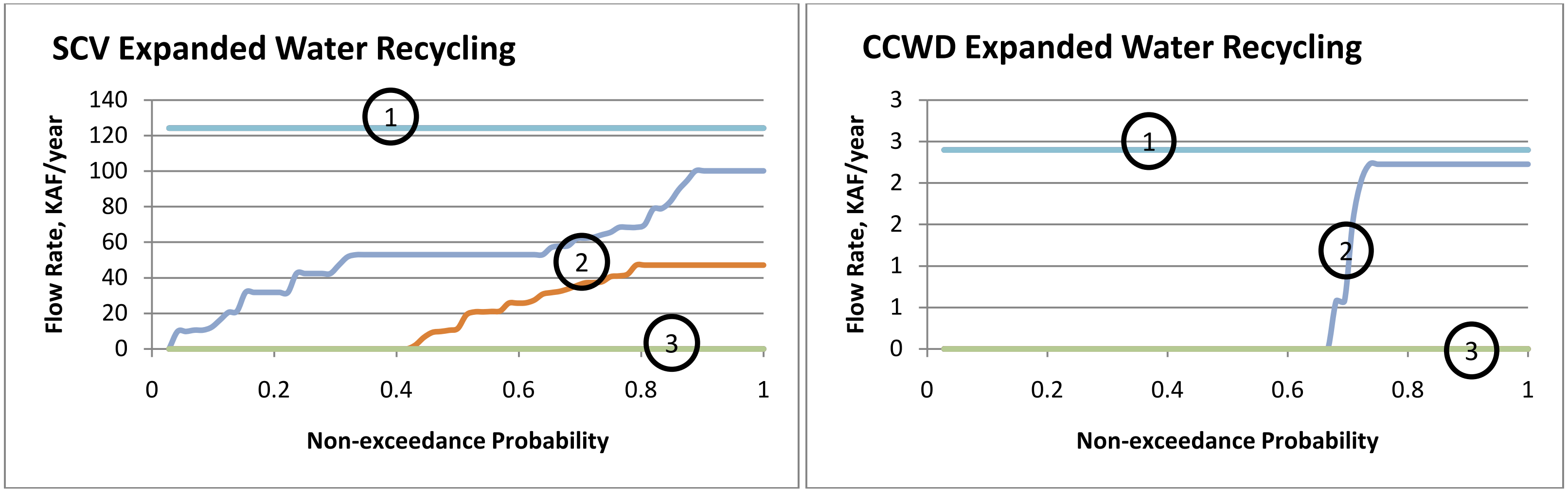
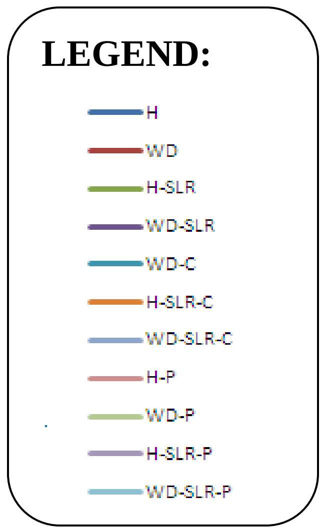


Figure 21. Desalination non-exceedance probability.

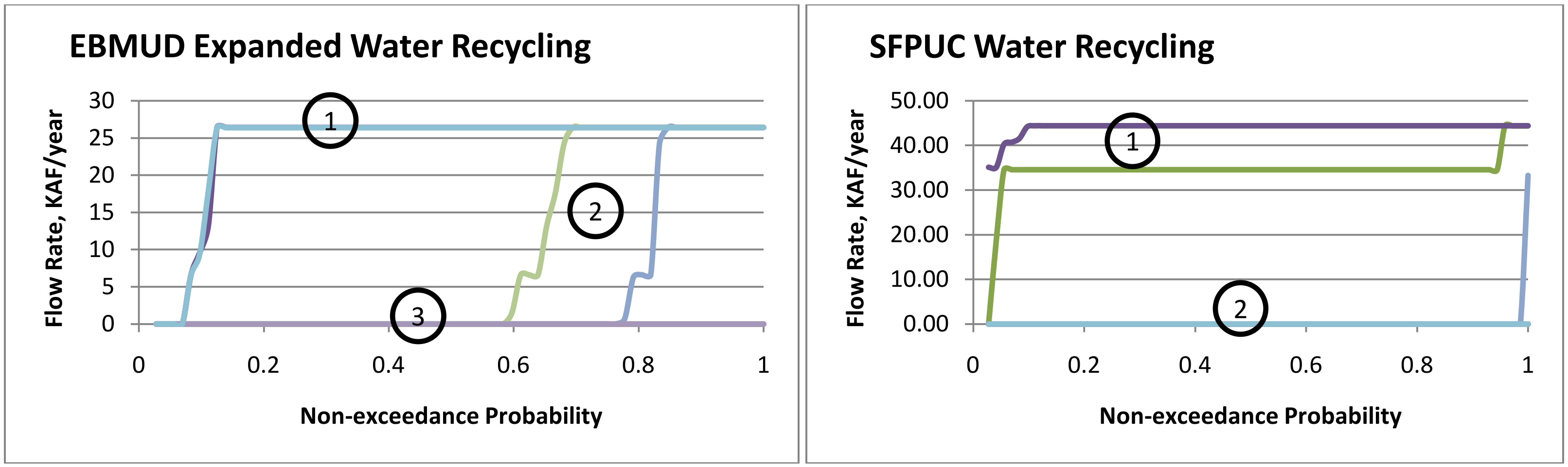


Result Groups
1) H-SLR, WD-SLR, H-SLR- P, and WD-SLR-P
2) H-SLR and WD-SLR-C
3) All Other Models

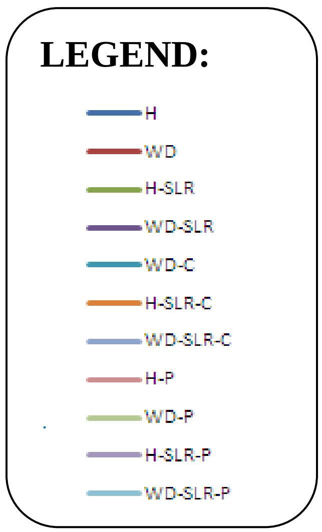


Result Groups
1) WD-SLR, H-SLR- P, and WD-SLR-P
2) WD-SLR-C
3) All Other Models

Figure 22 Water recycling non-exceedance probability (A).

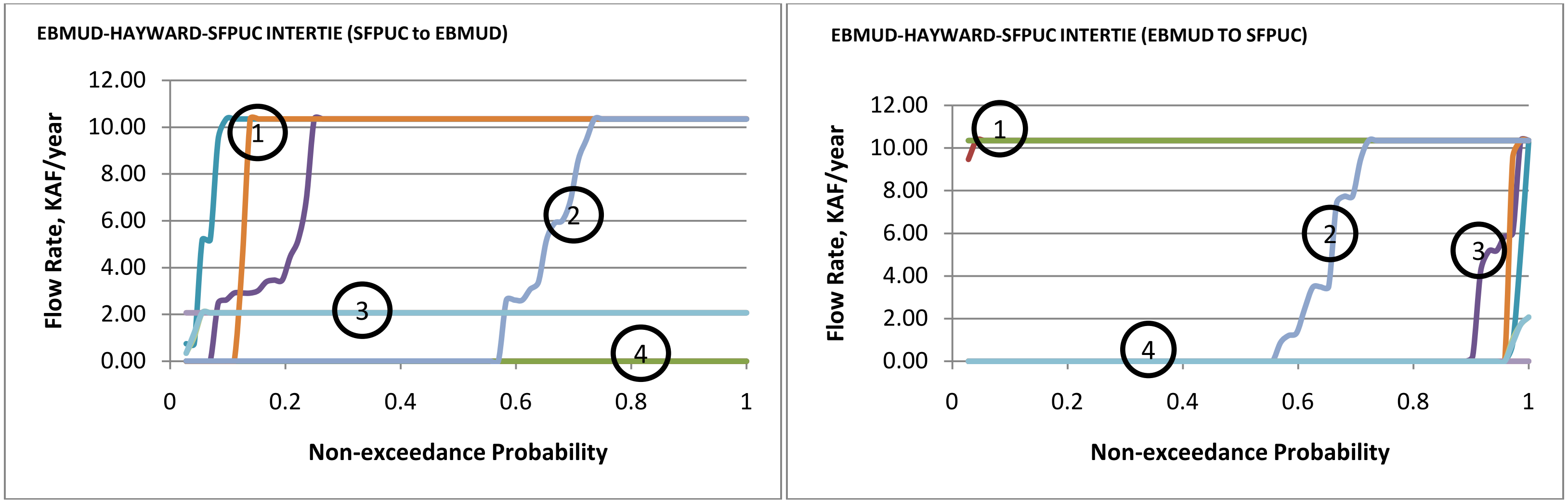


Result Groups
1) WD-SLR and WD-SLR-P
2) WD-P and WD-SLR-C
3) All Other Models

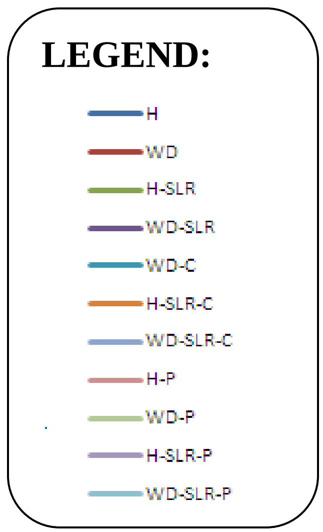


Result Groups
1) H-SLR and
2) All Other Models

Figure 23 Water recycling non-exceedance probability (B).

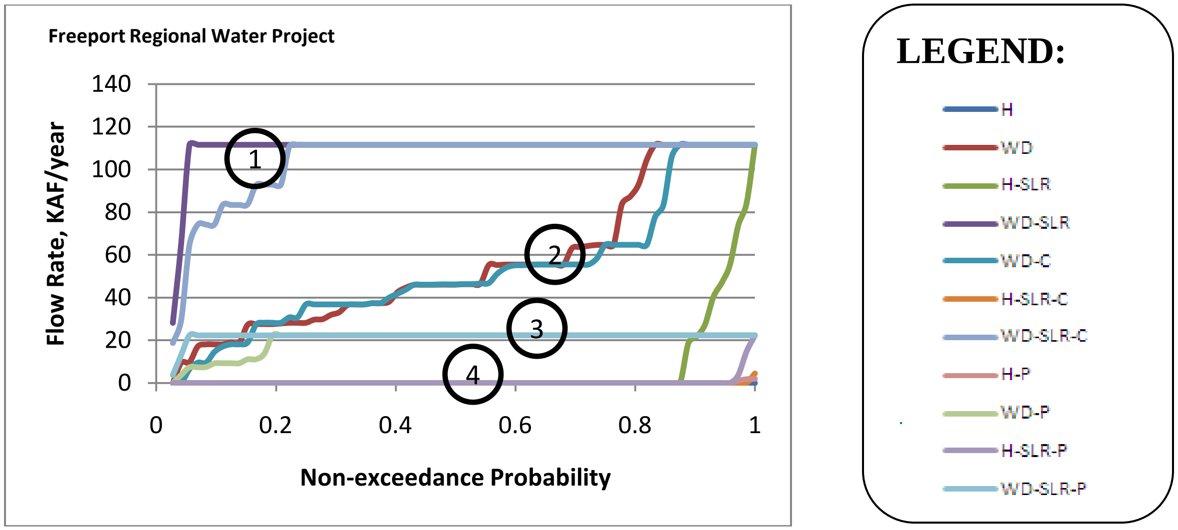


Result Groups
1) WD-C and SLR-C
2) WD-SLR-C
3) WD-P, SLR-P, and WD-SLR-P
4) All Other Models



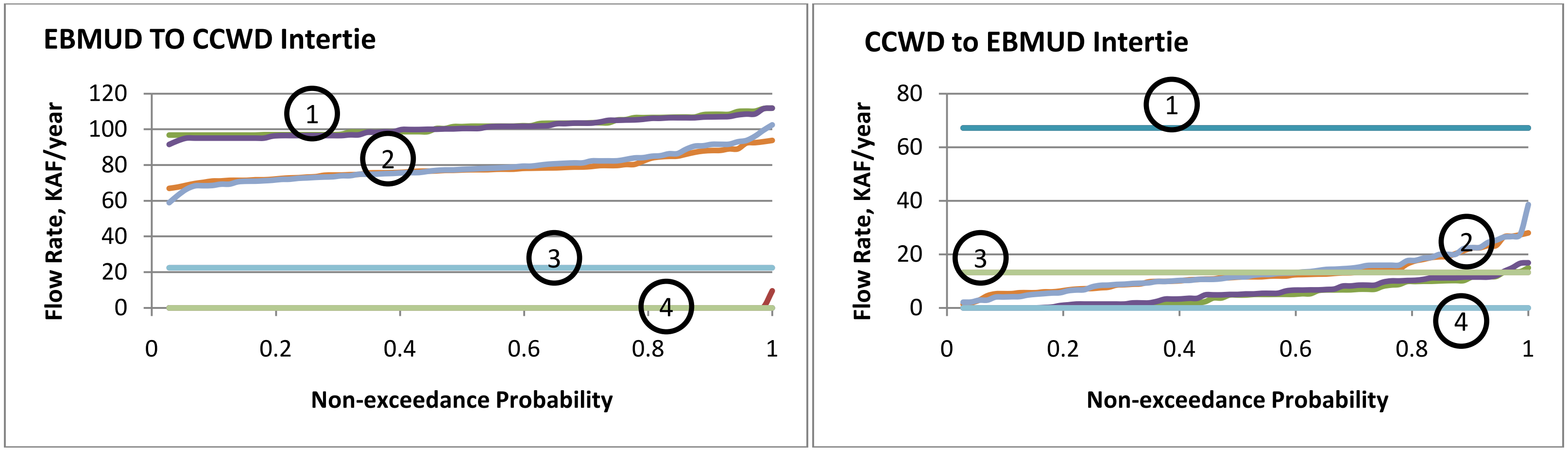
Result Groups
1) H, WD, H-SLR
2) WD-SLR-C
3) WD-SLR, WD-C, WD-SLR-C
4) All Other Models

Figure 24 Intertie non-exceedance probability (A).

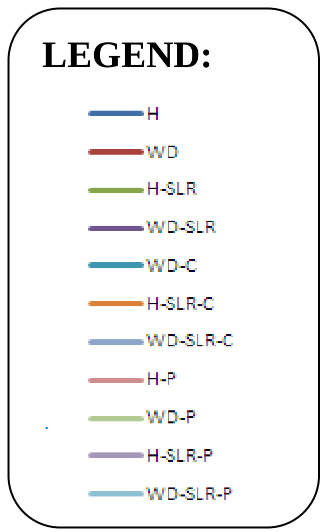


Result Groups
1) WD-SLR and WD-SLR-C
2) WD and WD-C
3) WD-P and WD-SLR-P
4) All other models the intertie was unused

Figure 25 Intertie Non-exceedance probability (B).



Result Groups
1) H-SLR and WD-SLR
2) H-SLR-C and WD-SLR-C
3) H-SLR-P and WD-SLR-P
4) All other models the intertie was unused



Result Groups
1) WD and WD-C
2) H-SLR, WD-SLR, H-SLR-C, and WD-SLR-C
3) WD-P
4) All other models the intertie was unused

Figure 26 Intertie non-exceedance probability (C).

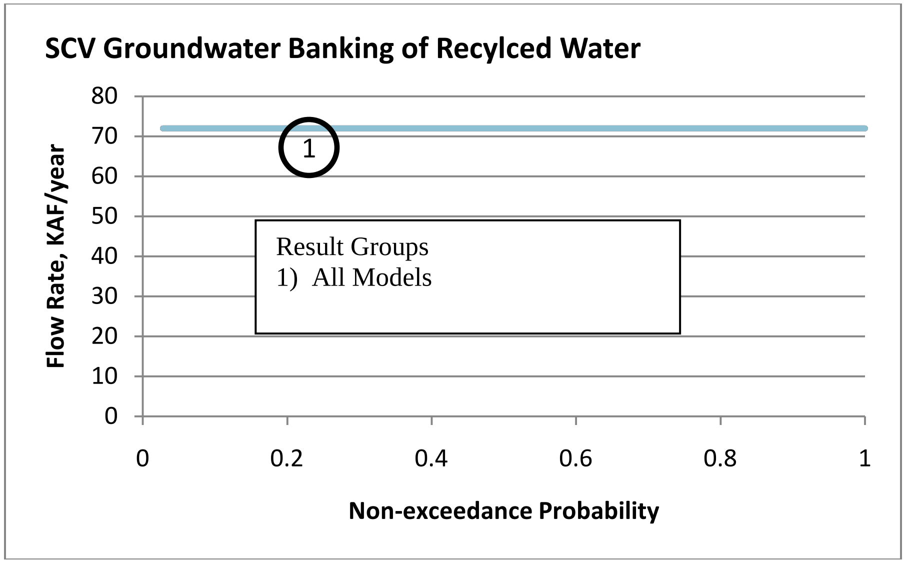


Figure 27 SCV groundwater banking of recycled water non-exceedance probability.

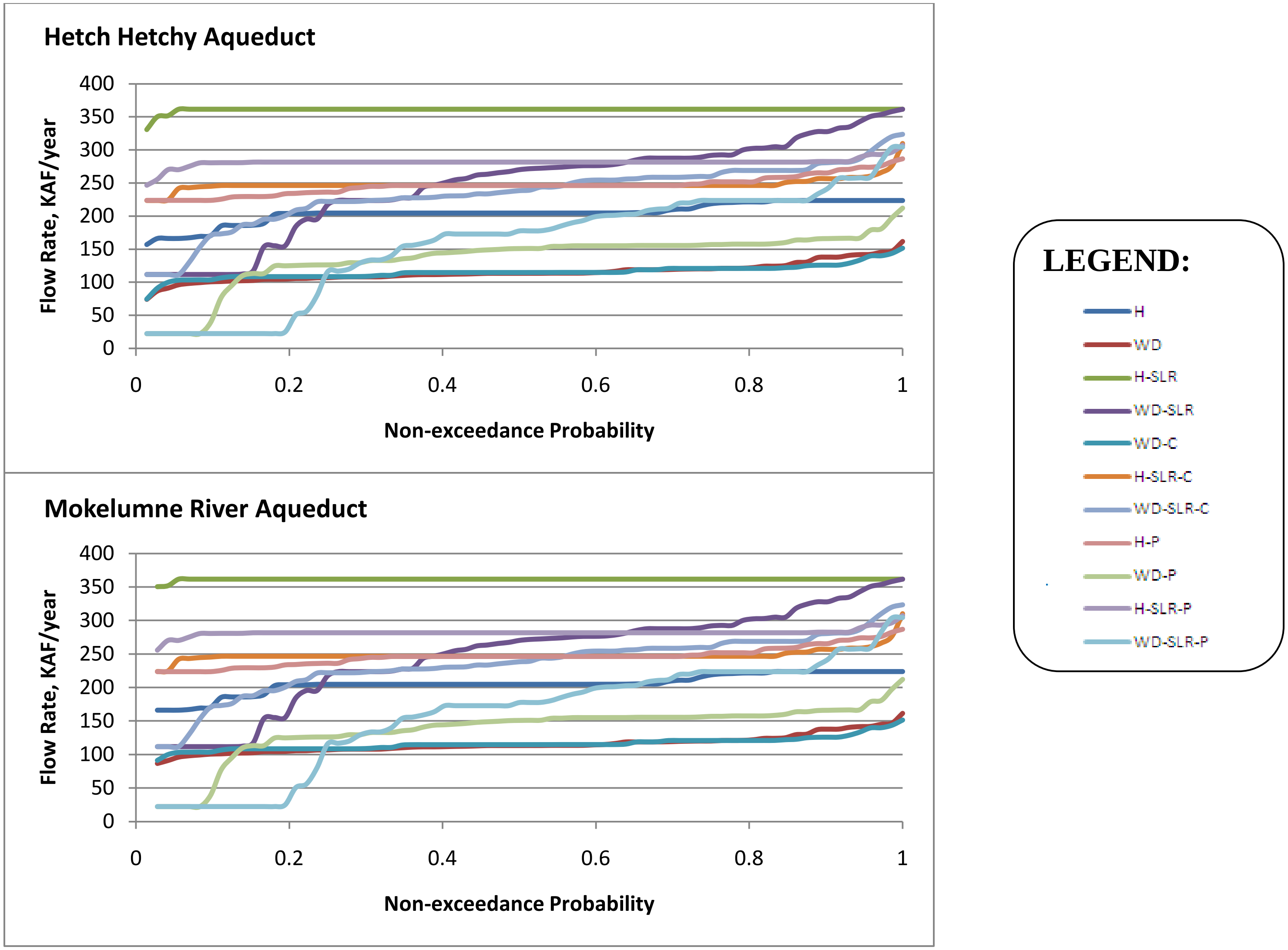


Figure 28 Hetch Hetchy and Mokelumne River Aqueducts non-exceedance probability.

5.0 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 exports from the San Francisco-San Joaquin Delta, purchasing agricultural water becomes more expensive. 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.
- 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. 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 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, 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 sea level rise relies on alternative water supply and water transfers along the existing emergency interties which are important to system flexibility.
- Challenges to water management will be policies, agreements and regulations that allow for flexible water transfers, more than infrastructure.

5.1.1 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, sea level rise only, and warm dry with sea level rise model runs. 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.

5.1.2 Limitations

CALVIN, like all models, is merely a representation of a real system and suffers from limitations. 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. The 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 agricultural commodity market conditions. Generally demands and efficiencies increase in dry years due to water availability. Overall, CALVIN may over or under estimate demands in some regions in some years.

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% 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 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 systems 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 forth coming 2010 Urban Water Management Plan data, particularly regarding base water demands in the Bay Area. Despite these limitations this work should offer orientation and qualitative insights and guidance to promising strategies for adapting Bay Area water management to severe forms of climate change.

5.1.3 Future Work

Methods of evaluating risk and vulnerability costs from the network reliability literature were discussed in Section 3.5 (page 37). However, due to the model size, length of computational time, and length of post-processing time, network reliability approaches as described above have not been used with the CALVIN model. The main cause of the computational and post-processing time requirement is the use of 72 years of hydrologic record to represent variability of inflow into the system. The approach to date has been the one employed in this analysis: to change the hydrologic inflows into the network and to change specific infrastructure components resulting in a changed network topology. Model results can then be analyzed to provide insight into the economic impacts of uncertain hydrology and identify infrastructure limitations or promising new infrastructure. An interesting approach to investigate the value that may be added to decision making by applying network reliability analysis approaches would be to choose a representative five to ten year record of hydrology and create model runs that systematically remove infrastructure components. This approach would be analogous to minimum cut set or reachability approaches. From this, we could observe the level of degradation of system performance with each component removed. Applying network reliability analysis methods in this way could provide a way to identify and rank critical system infrastructure. Additionally, knowing information about the probability of failure of a system component due to earthquake, flood or other failure mechanism can further rank system vulnerabilities. The network analysis method of identifying system performance or conversely performance degradation due to a topological change is a measure of the cost of the topological change. The vulnerability or risk from the change in topology is defined as the product of the probability of failure multiplied by the cost of failure. Where probability is an exogenous measure of the system component failure likelihood obtained from outside work and the cost is the performance cost of losing the system component.

6.0 APPENDIX

Table 13. Average annual variable operating costs ($M/yr).
***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.

	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*	0	0	51	70	0	0	1	0	0	46	52
North Central Valley	19	505	21	67	224	19	59	19	502	61	67
South Central Valley	1	1,290	2,380	4,177	550	1,606	3,546	1	1,288	4,004	4,120
So. California	325	421	845	1,023	217	260	362	325	363	845	1,023
Statewide	344	2,216	3,297	5,337	991	1,885	3,967	344	2,153	4,957	5,263

Table 14. Average annual total costs (scarcity and operating) ($M/yr).
***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.

	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

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