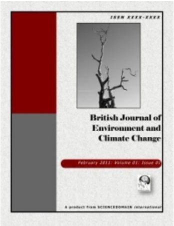

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Climate Change Adaptations for California's San Francisco Bay Area Water Supplies

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Authors' contributions

This work was carried out in collaboration between all authors. All authors read and approved the final manuscript.

Research Article

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ABSTRACT

The impact of climate changes on both sea level and the temporal and spatial distribution of runoff will affect water supply reliability and operations in California. 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, was used to explore the effects on water supply of a severely warmer drier climate and substantial sea level rise, and to identify economically promising long-term adaptations for San Francisco Bay Area water systems. This modeling suggests that Bay Area urban water demands can be largely met, even under severe forms of climate change, but at a cost. Costs are from purchasing water from agricultural users (with agricultural opportunity costs), expensive water recycling and desalination alternatives, and some increases in water scarcity (costs of water conservation). The modeling also demonstrates the importance of water transfer and intertie infrastructure to facilitate flexible water management among Bay Area water agencies. The intertie capacity developed by Bay Area agencies for emergencies, such as earthquakes, becomes even more valuable for responding to severe changes in climate.

Keywords: Water supply; San Francisco Bay Area; engineering economic model; climate change; optimization.

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1. INTRODUCTION

A changing climate will affect California's water supply management. The western United States and California can expect a shift in the temporal and spatial distribution of precipitation, changing streamflow, snowpack accumulation, snowmelt, and evapotranspiration [1,2,3]. These changes will affect the magnitude and timing of inflows into California's water supply system, affecting costs, operations, and allocations of water.

Higher average global temperature also will accelerate global sea level rise. Current projections suggest a mean sea level rise of 30 to 45 centimeters (cm) from year 2000 to 2050 [1]. Sea level rise and inland island failures will shift salinity of the Sacramento-San Joaquin Delta (Delta) inland and threaten the transfer of fresh water from northern California to the San Francisco Bay Area, San Joaquin and Tulare basins, and Southern California [4] [5] [6]. Sea level rise accompanied by a change in the Delta salinity could significantly affect the Delta as a major water supply hub [7].

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 UWMPs every five years. 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 plans call for minimizing reliance on imported water through water conservation, expanded water recycling, desalination, firming up existing water transfer agreements, and entering into water transfer agreements [8,9,10,11,12,13,14,15,16,17]. East Bay Municipal Water District's (EBMUD) new investigation of expanding Contra Costa Water District's (CCWD) Los Vaqueros reservoir indicate the increasing sophistication of water planning in this region and the practical capability to respond to many future changes with considerable flexibility (albeit at some inconvenience and cost), as demonstrated by the results presented here.

This modeling effort explores potential effects of severe climate change on urban water supply in the San Francisco Bay Area and explores management actions to mitigate potential climate change impacts. This paper begins with an overview of the modeling approach used, including the climate change cases 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.

2. MODELING APPROACH

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

2.1 CALVIN Model

CALVIN is an engineering optimization model of California's statewide intertied water supply system. Overall, CALVIN operates and allocates surface water and groundwater resources to minimize scarcity and operating costs, within the physical and environmental constraints of California's water supply system and selected policy constraints [18].

CALVIN has been used 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 [19,20,21,22,23,24,25,26,27,28,29].

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

CALVIN operates the physical infrastructure and allocates water within the system's constraints to minimize statewide water 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 (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. Urban and agricultural water demand functions were scaled to 2050 population, with details of water demand estimation presented in Sicke et al. [30].

Equation 1 is the objective function used in CALVIN, and equations 2 through 4 are the constraints.

$$\text{Minimize:}\quad Z = \sum_i \sum_j c_{ij} X_{ij}, \tag{1}$$

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

$$X_{ij} \leq u_{ij} \quad \text{for all arcs}, \tag{3}$$

$$X_{ij} \geq l_{ij} \quad \text{for all arcs}, \tag{4}$$

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

Although the model does not explicitly include water quality, costs and constraints often are used to represent water quality considerations. Treatment costs for different water sources vary by their water quality and constraints limit the availability of some water sources due to their water quality or their ability to be blended. More detailed representation of water quality concerns are typically examined in later more detailed analyses. Many Bay Area utilities make considerable use of multiple water sources of differing qualities.

For each CALVIN optimization, model results include time series of monthly urban and agricultural water deliveries; stream, canal, and aqueduct flows; 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.

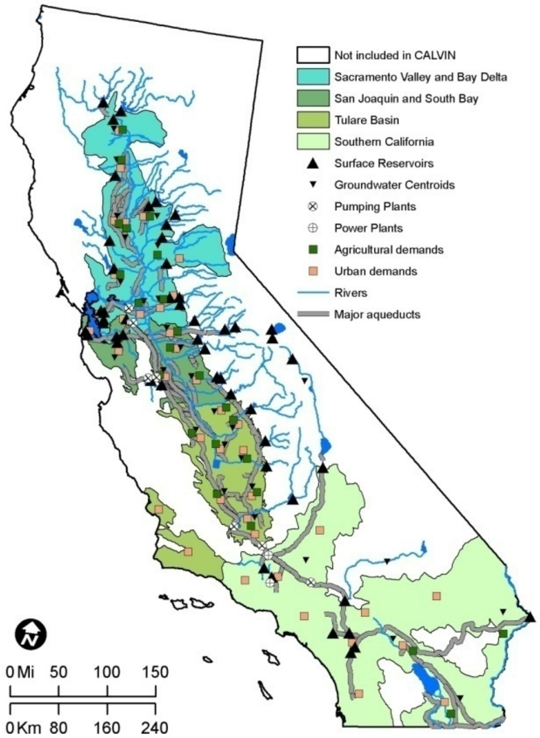

Fig. 1. Water supply infrastructure, inflows and demand areas represented in CALVIN

2.1.1 Operating costs

Operating costs in CALVIN include pumping, treatment, and water quality costs, as well as hydropower benefits (negative costs) [19]. Operating costs are all variable costs for pumping and treatment. The only exceptions are for additions of desalination and wastewater reuse capacity, where a linear average estimated total unit cost is used. CALVIN models most major facilities of California's intertied water supply system including recently completed Bay Area infrastructure such as the Freeport Regional Water Project (FRWP), the EBMUD-Hayward-San Francisco Public Utilities Commission (SFPUC) Intertie, and the EBMUD-CCWD Intertie. Urban areas were assumed to be able to recycle a portion of their wastewater flows (limited to local non-potable use). Urban areas with projected water recycling capacity by 2020 can use this as baseline recycling capacity at $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 $1,500 per acre-foot.

Additionally, urban coastal areas were allowed desalination at $2,100 per acre-foot. Earlier CALVIN water recycling and desalination costs are updated by Bartolomeo (E. Bartolomeo University of California Davis unpublished master's thesis 2011). Water recycling and desalination are capital intensive projects and ideally would be modeled as two-stage optimization with initial capital cost decisions and then operating costs decisions. In this study, we model total average annualized costs as operating costs. All costs are in 2008 dollars.

2.1.2 Bay area demand areas

Fig. 2a shows service areas for major water purveyors in the San Francisco Bay area. CALVIN aggregates purveyors into agricultural and urban demand areas. Aggregation is based on proximity and network connections, shown in Fig. 2b for the Bay Area.

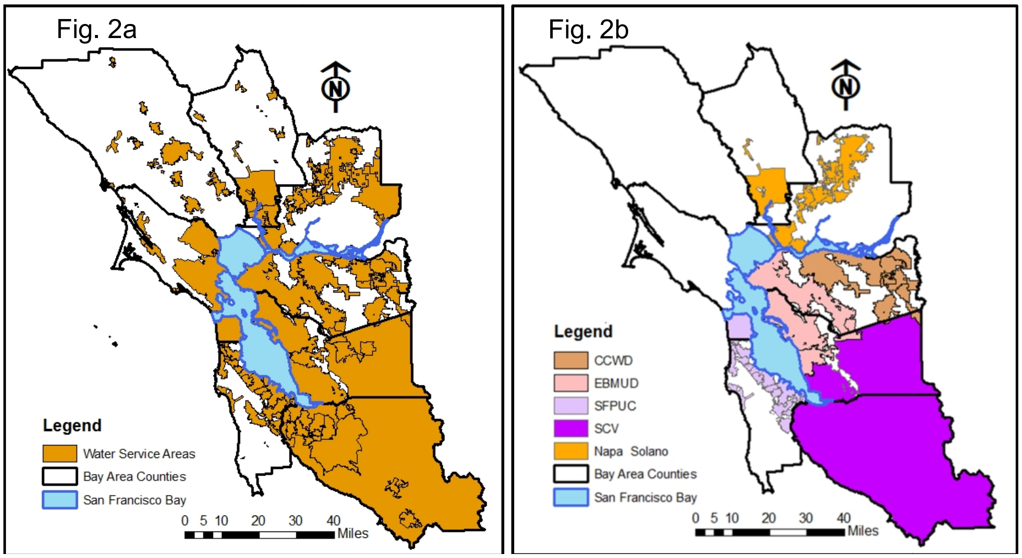

Fig. 2. Water supply retailers and wholesalers in the nine San Francisco bay area counties

Fig. 2a - water service areas boundaries. Fig. 2b - aggregated CALVIN urban demand areas.

2.1.3 Bay area supply sources and infrastructure

Five urban demand areas 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. The overall statewide model schematic appears in Fig. 1, with the Bay Area network shown conceptually in Fig. 3. Seawater desalination is included as a potential future water source for all demand areas, except Napa-Solano, which is farthest upstream in the Delta.

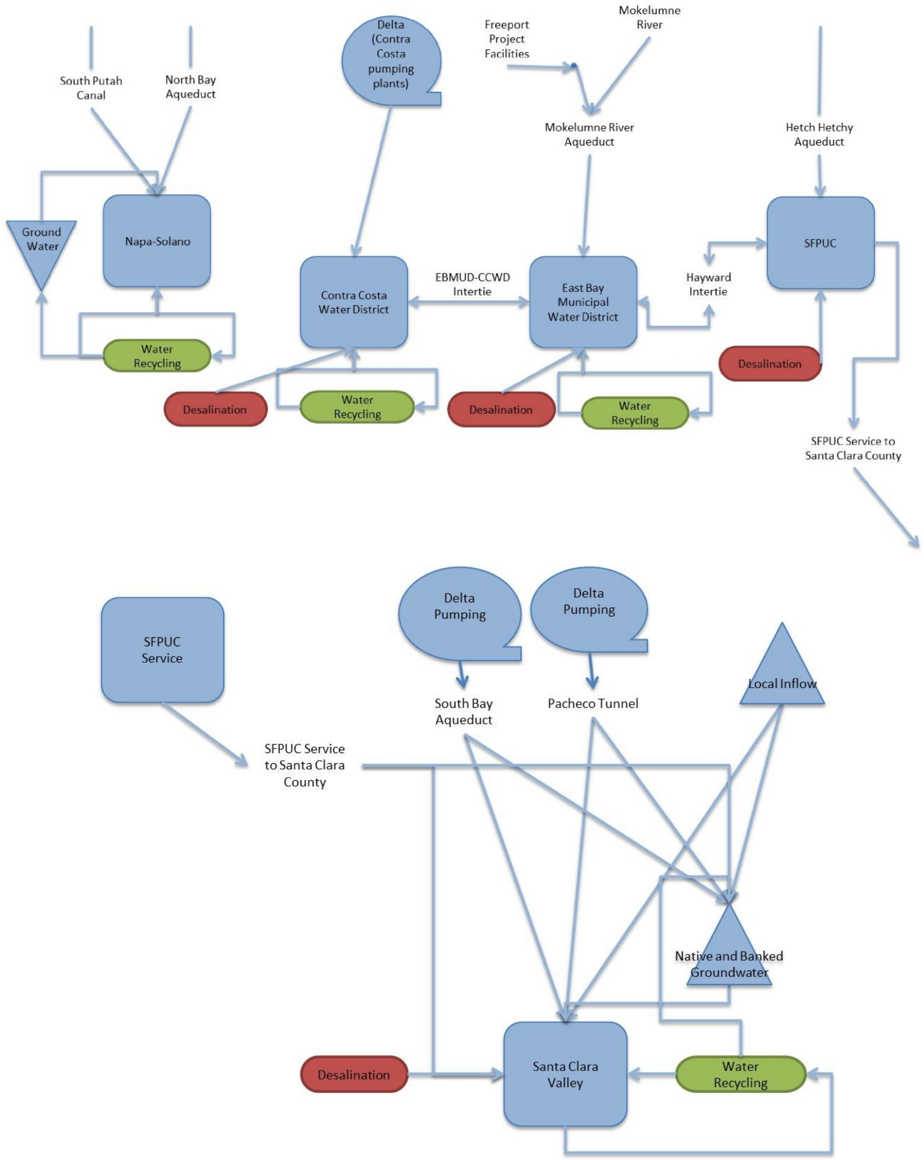

Fig. 3. Conceptualization of aggregate demand areas in the San Francisco bay area

Of the Bay Area demand areas, water for Napa-Solano is primarily from the United States Bureau of Reclamation's (USBR) Lake Berryessa, conveyed by the South Putah Canal, and State Water Project (SWP) water pumped from the northern Delta through the North Bay Aqueduct. Napa-Solano also uses small amounts of groundwater for Dixon and rural north Vacaville, and some water recycling [8,31].

Contra Costa Water District has its own water rights and also relies on USBR CVP 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 [10]. The EBMUD-CCWD Intertie was built for emergencies.

The East Bay Municipal Utility District relies primarily on imported water from the Mokelumne River Aqueduct, with storage at EBMUD's Pardee Reservoir. Some Sacramento River water can be 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 [11].

San Francisco Public Utilities Commission (SFPUC) relies principally on water from the Hetch Hetchy Reservoir on the Tuolumne River through the Hetch Hetchy Aqueduct. Other sources include water recycling and water transfers using the recently completed EBMUD-Hayward-SFPUC Intertie, and some local area inflows (omitted from the model due to data availability) [14].

In CALVIN, Santa Clara Valley water districts (SCV) include Santa Clara Valley Water District, Alameda County Water District, and Zone 7 Water Agency, the primary water suppliers of Alameda and Santa Clara counties. The SCV has access to a diverse water supply portfolio. SWP and CVP water is exported through Delta pumping and conveyed by the South Bay Aqueduct and San Luis Reservoir-Pacheco Tunnel respectively. SFPUC services the northern Santa Clara Valley to supplement water supply or to recharge groundwater. The SCV conjunctively uses 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 [15,16,17].

Hydrologic variability is represented using 72 years of monthly hydrology data (1921–1993). Hydrologic representation includes surface and subsurface inflows and urban and agricultural return flows. Hydrologic inflows come from existing surface and integrated surface-groundwater models [18,19,32].

2.2 Modeling Climate Change

Two distinct climate changes are expected to affect water supply in California: changes in hydrology and sea level rise. Hydrologic change will be in the form of spatial and temporal distribution precipitation and streamflow. Sea level rise will affect salinity in the Sacramento-San Joaquin Delta [33]. Five severe future climate cases consider these changes: (1) a warm dry hydrology, (2) a historical hydrology and sea level rise that reduces Delta diversion capacity by 50 percent, (3) historical hydrology and sea level rise that ends Delta water diversions, (4) a warm dry hydrology and sea level rise that reduces Delta diversion capacity by 50 percent, and (5) both warm dry hydrology and sea level rise that ends Delta water diversions.

2.2.1 Hydrologic change

Global Circulation Models (GCMs) are often used to model climate change considering a range of emissions, population growth, socio-economic development, and technological progress. The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report 2007 describes these scenarios and summarizes temperature and precipitation climate projections. Regional GCM results and scenarios for California are discussed by Cayan et al. [2]. For input into CALVIN, the NOAA Geophysical Fluid Dynamics Laboratory CM2.1 A2 emissions scenarios were downscaled by Medellín-Azuara et al. [29,27] to capture the effects of a warm dry form of climate change by year 2050. The methods described in Zhu et al. [32] and Connell [28] were employed to perturb historical (1921–

1993) time series of inflows in CALVIN. Temperature and precipitation from the downscaled GFDL CM2.1 A2 scenario for a period of 30 years centered in year 2085 were used, indicating a 2ºC (3.6ºF) temperature increase and 3.5 percent decrease in precipitation.

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. These were employed in Medellín-Azuara et al. [27] following the methods in Miller et al. [3]. Connell ([28] 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 percent statewide reduction in streamflows is expected under the GFDL CM2.1 A2 scenario. 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. [32] 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.

A linear relationship described in Zhu et al. [32] 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 local areas.

2.2.2 Sea level rise

Most of the Delta is currently maintained as a largely fresh water system. This facilitates water movement from Northern California sources and storage to the Bay Area, southern Central Valley, and Southern California using pumping plants. The combined physical pumping capacities for the State Water Project (Banks), Central Valley Project (Jones), and the Contra Costa Water District (Old River and Rock Slough) are 16,500 cubic feet per second (cfs) (11.95 million acre-feet [maf]/year). Increasing sea level will increase Delta salinity to potentially reduce or end diversions from the Delta, by direct sea water intrusion, by collapsing some island levees which foster sea water intrusion, or a combination of both combined with stricter drinking water regulations [34]. Sea level rise is modeled in CALVIN by reducing the capacity of Delta pumping to 50 percent and to zero. This directly affects water users that rely on Delta water diversions.

2.2.3 Long-term urban water conservation

Long-term urban water conservation is implemented in the model to examine its value to reduce water supply related impacts of climate change (R. Ragatz University of California Davis unpublished master's thesis 2013). Thirty percent conservation in CALVIN results in average urban demand of 154 gpcd, similar to the State's 20 percent reduction goal by 2020 [35]. Costs to implement long-term urban water conservation are not addressed in this model, but would include outreach, public announcement campaigns, and efficient water use technologies.

2.2.4 Intertie conveyance policy constraints

Local San Francisco Bay Area water agencies have recently constructed interties to connect neighboring water agencies. Major interties are the EBMUD-Hayward-SFPUC Intertie, the EBMUD-CCWD Intertie, and the FRWP. Although the interties allow for the large water transfers, policy constraints can limit the frequency of use and available capacity.

The EBMUD-Hayward-SFPUC Intertie connects East Bay Municipal Utility District, San Francisco Public Utilities Commission, and the City of Hayward with a capacity of 30 million gallons per day (MGD) (Fig. 4). The EBMUD-CCWD Intertie connects East Bay Municipal Utility District and Contra Costa Water District with a capacity of 60 MGD to CCWD or 100 MGD to EBMUD (Fig. 4). Both the EBMUD-Hayward-SFPUC and the EBMUD-CCWD Interties were constructed for emergency response to catastrophic events such as an earthquake. The interties can boost water supply when needed and, under current policy agreements, are not intended for regular service.

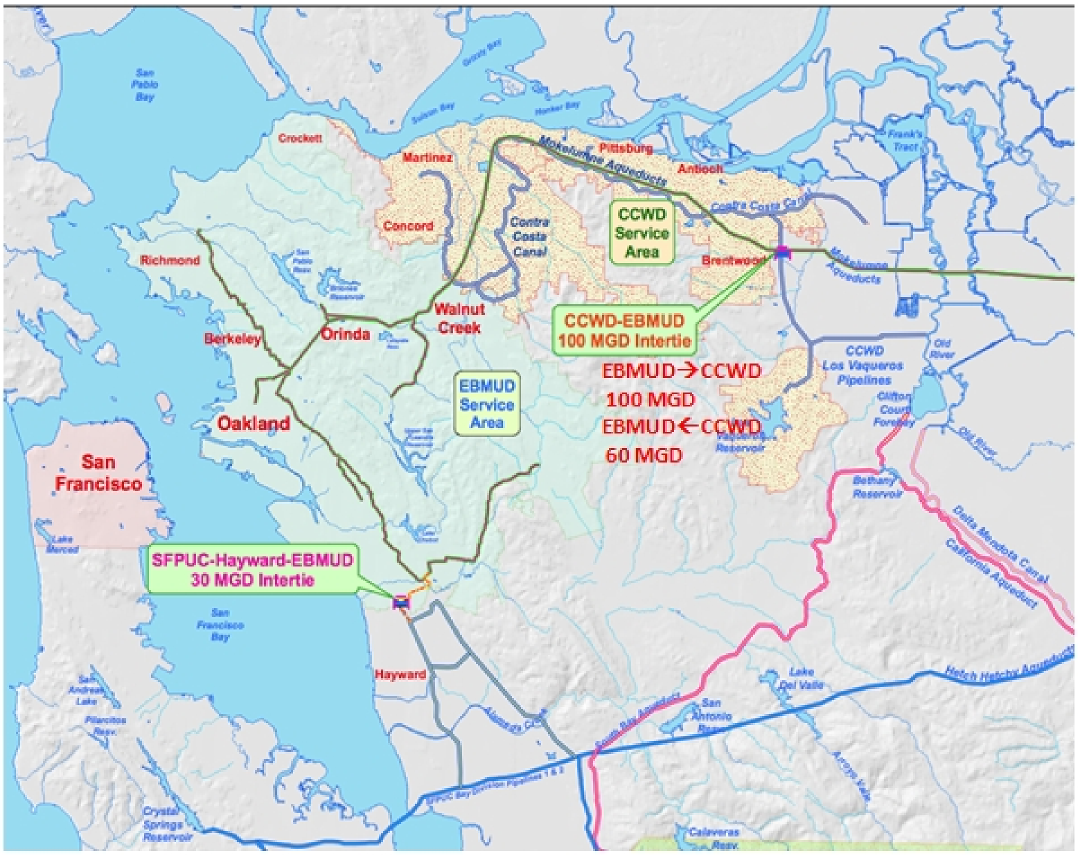

Fig. 4. Location and capacity of the EBMUD-hayward-SFPUC and EBMUD-CCWD Interties
(from EBMUD 2005 [11])

The Sacramento County Water Authority (SCWA) and East Bay Municipal Utility District joint project connects an intake at Freeport on the Sacramento River to the South Folsom Canal, and ultimately to EBMUD's Mokelumne River Aqueduct below Camanche Reservoir. The project can supply SCWA users with 85 MGD, with a 100 MGD intertie to EBMUD. Freeport operation is restricted to dry years or drought periods as defined by EBMUD's CVP contract. The effects of policy constraints on the interties were investigated by reducing the intertie capacities in the model to 20 percent of maximum capacity. The modeled unconstrained and constrained intertie capacities are listed in Table 1.

Table 1. Modeled intertie capacities (TAF = thousand acre-ft)

Intertie	Physical capacity TAF/Month	Policy constraint capacity TAF/Month
EBMUD-Hayward-SFPUC	2.8	0.56
EBMUD→CCWD	9.3	1.87
EBMUD←CCWD	5.6	1.12
Sacramento → EBMUD	9.3	1.87
SFPUC → Santa Clara Valley	13.5	2.7

2.2.5 Model runs

Eleven model runs were completed with CALVIN to evaluate three climate cases (Table 2). All runs use 2050 estimated population and land use. Specific urban land use responses to climate change are not included. Model run H is a base case for comparison with climate change scenarios, using historical hydrology to represent the spatial and temporal variability of inflows. 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, but sea level rise reduces Delta diversion capacity by 50 percent. Model run H-SLR represents a future climate with unchanged hydrology, but sea level rise and other changes end major Delta water diversions. As modeled here, the sea level rise (combined with other Delta problems) is severe enough to significantly reduce or preclude all major Delta diversions [7]. Model run WD-SLR50 includes effects of a warm dry future climate combined with sea level rise that reduces Delta diversion capacity by 50 percent. Model run WD-SLR shows effects of a warm dry future climate combined with sea level rise that ends Delta diversions. Model runs “-C” explore effects of long-term urban water conservation on the impacts of climate changes. Model runs, “-P,” evaluate the system flexibility gained by relaxing policy constraints on intertie operations. All climate change and policy constrained runs severely test the system, and do not individually represent likely futures.

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

3. RESULTS

The results presented here, while preliminary, provide some perspective and insights on how the Bay Area could adapt to some fairly severe forms and consequences of climate change. Results from the model runs include water scarcity and scarcity costs, system operating costs, water supply portfolio, infrastructure importance and expansion opportunities, and environmental flow costs. Here we present a subset of these results. More detailed results on changing water supply portfolios, infrastructure importance and expansion opportunities, and environmental flow costs can be found in Sicke et al. [30].

3.1 Water Scarcity and Scarcity Cost

Under the climate change scenarios, water scarcity increases because of reduced inflows and reduced water diversions from the Delta. Scarcity costs represent the economic costs to water users from agricultural water shortages or costs of short-term conservation by households and businesses.

Table 2. Model runs

Run	Hydrology	Sea level rise	Long-term urban conservation	Intertie policy constraint
H (Base case)	Historical	None	None	None
Climate change				
H-SLR50	Historical	50% reduction	None	None
H-SLR	Historical	No Delta exports	None	None
WD	Warm Dry	None	None	None
WD-SLR50	Warm Dry	50% reduction	None	None
WD-SLR	Warm Dry	No Delta exports	None	None
Climate change and long-term urban water conservation				
H-SLR50-C	Historical	50% reduction	30% of Demand	None
H-SLR-C	Historical	No Delta exports	30% of Demand	None
WD-C	Warm Dry	None	30% of Demand	None
WD-SLR50-C	Warm Dry	50% reduction	30% of Demand	None
WD-SLR-C	Warm Dry	No Delta exports	30% of Demand	None
Climate change and policy constraints				
H-P	Historical	None	None	20% of Capacity
H-SLR50-P	Historical	50% reduction	None	20% of Capacity
H-SLR-P	Historical	No Delta exports	None	20% of Capacity
WD-P	Warm Dry	None	None	20% of Capacity
WD-SLR50-P	Warm Dry	50% reduction	None	20% of Capacity
WD-SLR-P	Warm Dry	No Delta exports	None	20% of Capacity

Table 3 shows scarcity, scarcity cost, and willingness-to-pay for additional deliveries for Bay Area urban water users and statewide urban and agricultural water users. Bay Area urban water demands are all met in the base case with the historical hydrology, although statewide users have annual average scarcity of 32 and 871 thousand acre-ft (taf) respectively. Water shortages in the base case reflect variability in water supply availability, infrastructure capacity, environmental flow constraints, and water supply costs that preclude some users from purchasing their full demand. Climate change impacts of reduced hydrology and sea level rise (no Delta exports) have little or no increased water scarcity for Bay Area water users, while statewide water users suffer more scarcity. Water shortages and shortage costs affect Santa Clara Valley districts the most under no export cases, as Santa Clara and Alameda counties rely on SWP and CVP imports. Table 3 shows that agricultural water users sell water and bear additional shortage costs of Bay Area and statewide urban users continuing to receive deliveries. Reduced water availability puts the agricultural sector in the position to sell water to the urban sector (spot, short-term or long-term transfers). The sea level rise case that reduces Delta diversion capacity by 50%s shows very small increases in scarcity or scarcity costs from the base case for the Bay Area. The scarcity and scarcity costs increase for agricultural demand. This result suggests there is an incentive for water transfers from agriculture to urban to meet urban demand.

Table 3. Average bay area urban water scarcity and scarcity cost

	Base case	**Climate change**			**Climate change with long-term urban 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 Urb	0	0	29	40	0	0	0	0	0	26	29
State Urb.	32	116	417	636	8	50	142	32	32	414	616
State Ag.	871	7,666	5,539	9,132	4,366	4,027	8,301	871	7,656	9,061	9,061
State 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 Urb	0	0	51,026	70,047	0	0	569	0	0	46,495	52,325
State Urb.	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
Average Marginal Willingness-to-Pay for additional water, $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 Urb	0	0	229	376	0	0	12	0	0	195	280
State Urban	25	86	263	420	23	52	106	25	25	241	378
State Ag.	33	230	186	301	148	162	285	33	230	299	299

H-Historical hydrology, WD-Warm dry hydrology, SLR-Sea level rise, C-Long-term urban Conservation, and P-Policy intertie constraints

The agricultural WTP for additional water listed in Table 3 is the average value of an additional unit of water to agricultural water users, representing the opportunity cost of transferring agricultural water to urban users. The agricultural opportunity cost is lowest under the no Delta diversions case and highest in the combined reduced streamflow and no Delta diversions case. Achieving 30 percent urban conservation alleviates all Bay Area urban shortages even under severe climate changes. Long-term urban water conservation also decreases 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 prohibiting Delta diversions. However, CCWD increases desalination to meet demand. With the EBMUD-CCWD Intertie constrained to 20 percent of its capacity, CCWD has no alterative water source when it cannot pump water from the Delta. Again, the scarcity and scarcity costs increase for agricultural demand. Urban demand in the Bay Area is met by agricultural to urban water transfers and increases in alternative water supply such as desalination. Operating costs include groundwater and surface water pumping, water treatment, waste water recycling, and desalination. Sicke et al. [30] show the average annual net operating variable costs. The most costly case is the combination of reduced streamflow and no Delta diversions. South of the Delta operating costs decrease because reduced water availability and no Delta exports reduces costly pumping. But other operating costs increase as urban water users turn to water recycling and desalination. Urban water conservation greatly reduces operating costs. Intertie policy constraints increase operating costs as expensive alternative water supply options such as much more expensive desalination are needed to meet high-value urban demand.

3.2 Supply Portfolios

Each Bay Area demand area relies on water supplies from a variety of local resources, imported water and water transfers, groundwater pumping, water recycling, and desalination sources. Climate change often shifts the mix of supplies as water becomes less available generally, as agricultural opportunity costs raise the cost of water transfers, and as water imports from the two large water projects (SWP and CVP) through the Delta are reduced. These factors can increase use of more costly options such as recycled water, desalination, groundwater banking, and pumping. Water supply portfolios add operational efficiency, and are often facilitated by a functional water market.

Santa Clara Valley Water District is the largest Bay Area urban demand area in CALVIN with a projected annual demand of 715,000 acre-ft by 2050. The SCV relies on imported SWP and CVP water from the Delta, local supplies, recycled water, and groundwater. Some of this area is supplied by SFPUC, represented as a water transfer to SCV in CALVIN. SCV also banks surface water in its aquifer. Fig. 5 and Sicke et al. [30] show how the supply portfolio for SCV shifts due to climate changes, long-term urban water conservation, and policy constraints on intertie operations.

Today, SCV relies heavily on SWP and CVP water from the Delta, averaging 253 thousand acre-feet/year (36 percent of water delivered). Groundwater pumping, local sources, and SFPUC account for about 17 percent each or 125 taf/year average. Water recycling averages about 2 percent of water supply, 16 taf/year. Water recycling has already reached capacity under the base case. A warm dry climate produces less local inflow, but increases Delta water imports slightly, suggesting water purchases from agricultural users to cover decreased local supplies. It is more economical to pay the agricultural opportunity cost than to expand desalination or wastewater reuse. The cases with a 50 percent reduction in Delta diversion capacity (SLR50) show little change in the water supply portfolio from the base case. The sea level rise cases (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 and water purchases from agricultural users become more restricted. Fig. 5 shows that in these cases scarcity and scarcity cost reach a point where SCV urban users are willing to pay to expand water recycling and desalination. Expanded water recycling capacity accounts for 18 percent of supply in both the sea level rise (H-SLR50) and warm dry and sea level rise (WD-SLR50) cases.

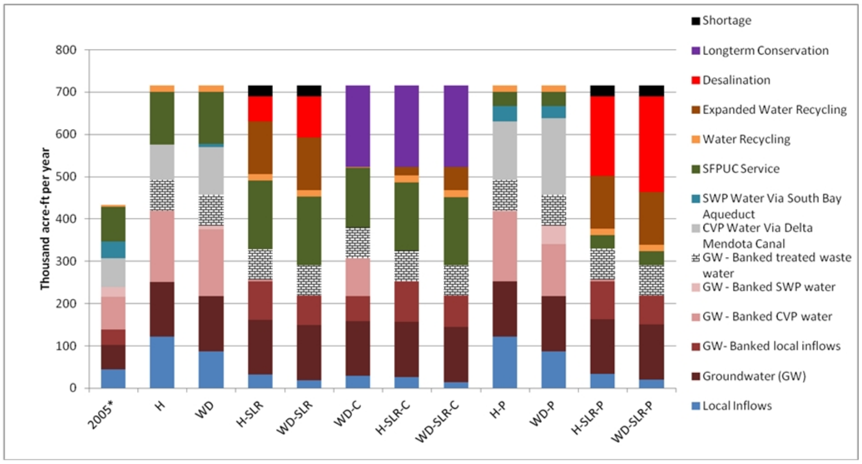

Fig.5. Average santa clara valley demand area water supply portfolio

*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

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. Water conservation of 30 percent in the warm dry climate case (WD-C) reduces dependence on imported SWP and CVP supplies. In the sea level rise (H-SLR50-C) and warm dry climate sea level rise cases (WD-SLR50-C), water conservation reduces the use of 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 supplies through the Delta and reduction in water from SFPUC. Under sea level rise, total groundwater banking/conjunctive use also drops.

Water management portfolios for other Bay Area demand areas are detailed in Sicke et al. [30]. The SFPUC demand area has access to water from the Hetch Hetchy Aqueduct, the Hayward Intertie, water recycling, desalination, and some local supplies. The policy constrained runs show that under all climate change 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 suggests operational cost savings through flexible operations of interties and water transfer agreements. SFPUC did not provide local inflow estimates to their system, so these were conservatively neglected in the model.

Contra Costa Water District demand area relies mainly on CVP water and its own water rights from the Delta conveyed through the Contra Costa Canal and Los Vaqueros Reservoir. In the base case model run, CVP water from the Delta is 92 percent of CCWD water supply, with the remainder from water recycling. In the warm dry climate, water recycling increases. Reducing Delta diversion capacity by 50% does not change the water supply portfolio. Ending Delta diversions affects the water supply portfolio differently, depending on the hydrology and intertie policy. With the historical hydrology, there may be sufficient water in the Mokelumne River system for the EBMUD-CCWD Intertie to offset the loss of Delta pumping. This would require purchasing water from other Mokelumne River diverters. Under limited water transfers through EBMUD-CCWD Intertie (H-SLR50-P and WD SLR50-P) desalination becomes cost effective in the absence of Delta diversions. In all warm dry climate cases combined with no Delta diversions, water recycling and desalination are expanded. Long-term urban water conservation reduces the need for costly desalination and water recycling.

The East Bay Municipal Utility District demand area relies mainly on water from the Mokelumne River Aqueduct. In the base case, Mokelumne River Aqueduct and transfers from CCWD account for all supplies [30]. Reduced Delta exports and diversion capacity do not significantly change the water supply portfolio. With ending Delta exports or diversions, water recycling makes up 3 percent of total water supply. With a warm dry climate, Freeport Project diversions become 31 percent of supply and water recycling expands to 9 percent. Sea level rise ends CCWD transfers of Delta water and reliance shifts heavily to Mokelumne River water. Combining a warm dry hydrology and sea level rise (ending Delta exports), EBMUD suffers small shortages on average, and must rely on all portfolio elements. With diversions from the Sacramento River north of the Delta reduced, EBMUD must rely on costly desalination.

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

3.3 Infrastructure Importance and Expansion Opportunities

CALVIN provides a platform for evaluating the importance of system components. The output from the network flow optimization solver provides shadow values (marginal value or cost) for each constraint in the model. Shadow values indicate the sensitivity of performance to capacity, flow, and availability uncertainty. The shadow value, in the case of storage capacity or conveyance capacity, represents the marginal value of that resource. The model runs for this analysis consider uncertain hydrology by looking at different climate change scenarios and looking at uncertainty and variability within each using the 72-year time series. Conveyance, water recycling, and storage capacities are represented in CALVIN as upper bounds on conveyance and storage links. Sensitivity output from CALVIN includes the marginal values of additional conveyance and storage capacity. When a conveyance or storage capacity is not reached in a time step, the marginal value of additional capacity is zero. 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.

Table 4 contains the average value of one additional unit of increased capacity for selected conveyance and water recycling components in the Bay Area's water system.

Table 4. Average marginal value of conveyance and water recycling capacity ($/af)

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

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

Fig. 6 shows the marginal values of infrastructure capacity expansion. 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 values, because there is so little water in the system that the conveyance components rarely flow at capacity. The "-SLR50" cases results were omitted in the tables and figures because the results on average did not differ from the related historical and warm dry cases (e.g., H vs. H-SLR50 and WD vs. WD-SLR50).

The Hetch Hetchy Aqueduct constrains 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. The Hetch Hetchy Aqueduct adequately meets demand under the policy-constrained intertie cases. These data suggest operational cost savings from intertie conveyance capacity. Ending exports or diversions from the Delta begins to stress the capacity of infrastructure as the model relies on conveyance through these remaining components to meet demand. Long-term urban water conservation reduces stress on these system components and reduces the value of increased capacity under climate change.

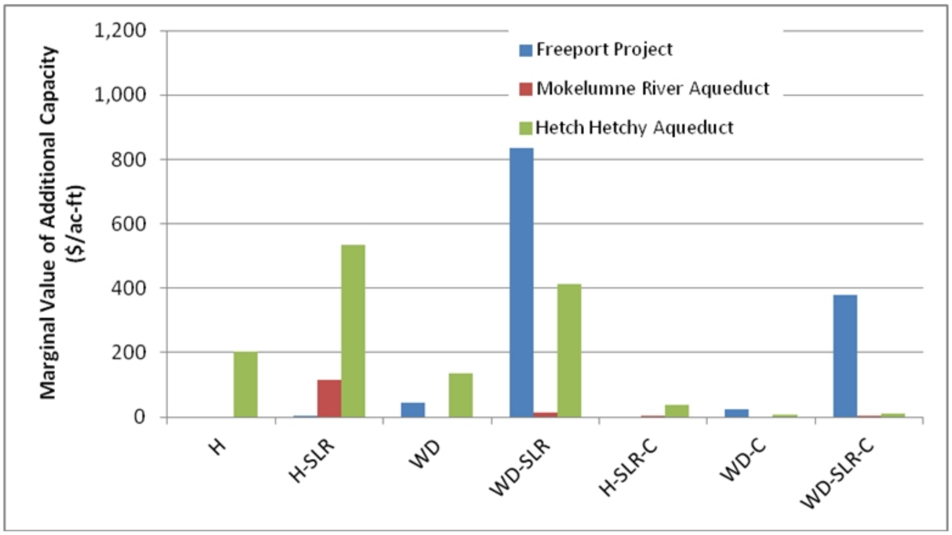

Fig. 6. Average marginal value of additional aqueduct conveyance capacity

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

Fig. 7 shows the marginal value of intertie conveyance capacity. The CCWD-EBMUD Intertie's capacity is only slightly stressed on average under all climate changes. However, the EBMUD-Hayward-SFPUC Intertie increases in value under climate change conditions as more water users depend on the intertie to transfer and wheel water from various sources. Long-term urban water conservation reduces the marginal value of increased intertie capacity.

Fig. 8 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 uses base water recycling capacity before expanding water recycling capacity. The marginal values indicate the importance of water recycling capacity in increasing system flexibility for all climate changes. The marginal value of expanded water recycling capacity suggests the opportunity for infrastructure expansion mainly under a warm dry hydrology with reduced Delta supplies.

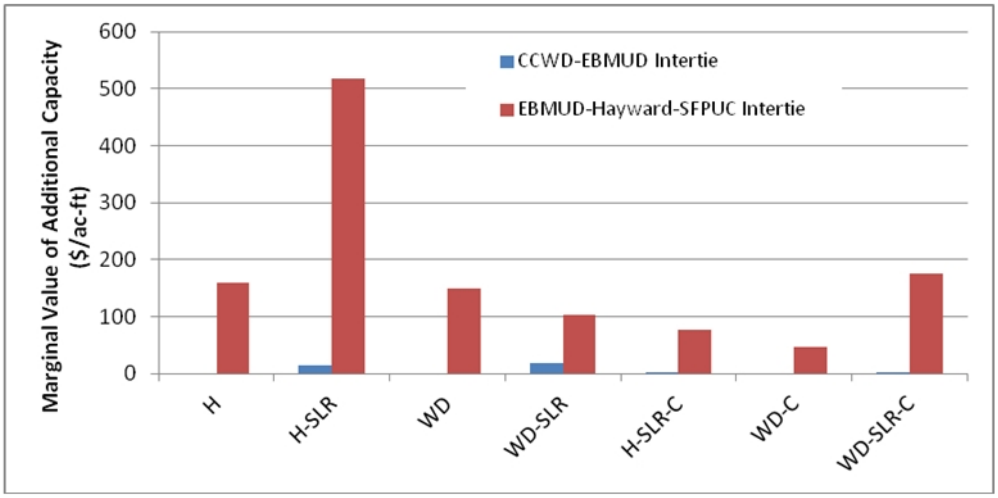

Fig. 7. Average marginal value of additional intertie conveyance capacity
Abbreviations for model runs: H-Historical Hydrology, WD-Warm Dry Hydrology, SLR-Sea Level Rise, and C-Long-term Urban Water Conservation

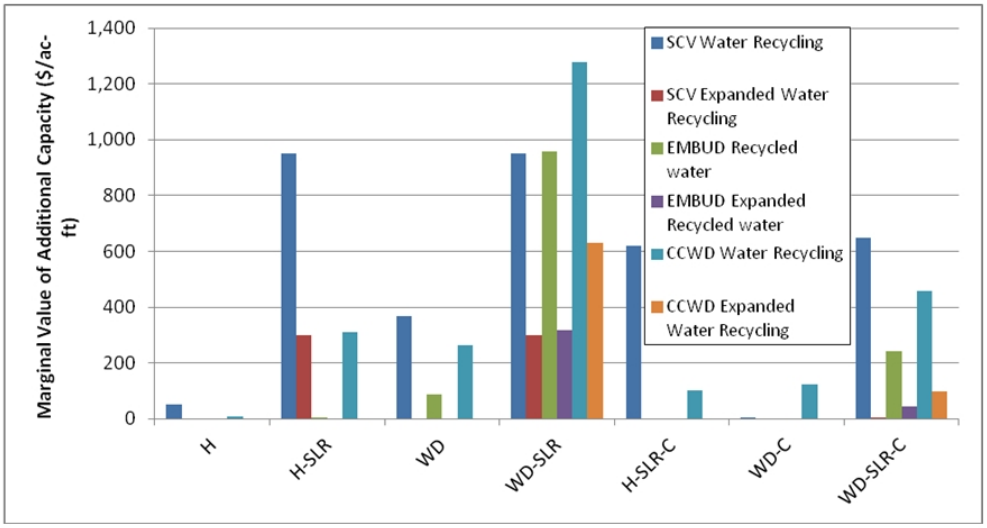

Fig. 8. Average marginal value of additional water recycling capacity
Abbreviations for model runs: H-Historical Hydrology, WD-Warm Dry Hydrology, SLR-Sea Level Rise, and C-Long-term Urban Water Conservation

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 5).

Table 5. Selected average marginal values of storage capacity ($/af)

Conveyance, water recycling, and desalination infrastructure	Base case	Climate change			Climate change with long-term urban water conservation			Historical hydrology and climate change with intertie policy constraints			
	H	WD	H-SLR	WD-SLR	WD-C	H-SLR-C	WD-SLR-C	H-P	WD-P	H-SLR-P	WD-SLR-P
Shasta Lake	5	45	5	23	35	5	23	6	53	2	14
Clair Engle Lake	2	27	2	20	21	2	22	5	47	3	12
Black Butte Lake	6	169	3	43	98	3	42	10	77	7	13
Lake Oroville	10	53	7	12	38	7	11	6	103	1	1
New Bullards Bar Reservoir	12	106	11	13	60	11	12	2	32	7	0
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

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

However, the robust existing water storage capacity raised system resiliency in the "-SLR50" cases (sea level rise cases that model reduced Delta diversion capacity by 50 percent). The "-SLR50" cases results were excluded here because the results on average did not differ from the related historical and warm dry cases (e.g., H vs. H-SLR50 and WD vs. WD-SLR50). Future work could include model cases that look at the performance of the reservoir systems in managing seasonal changes Delta salinity that could seasonally affect diversion capacity.

Fig. 9 shows marginal values for relaxing policy constraints on intertie operations. The interties increase the variety of an agency's water supply portfolio, allow for wheeling of water among agencies, and allow agencies to cooperate on alternatives such as water recycling and desalination. The CCWD-EBMUD intertie is very important for reducing shortages at CCWD. Overall, the interties are most valuable with Delta diversion restrictions.

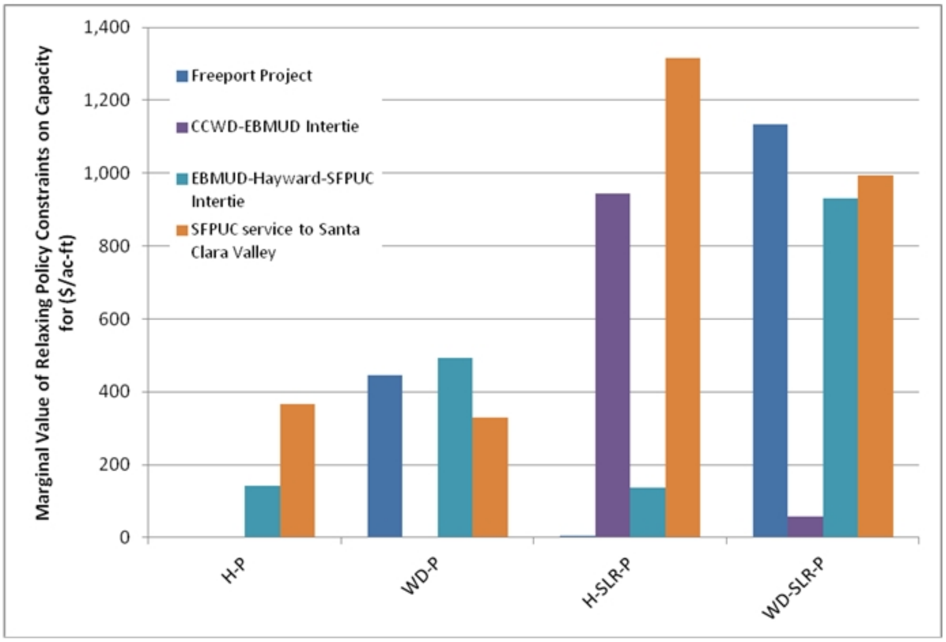

Fig. 9. Average marginal value of relaxing policy constraints on intertie capacity

4. LIMITATIONS

CALVIN, like all models, is merely a representation of a real system and suffers from limitations. A comprehensive list of CALVIN limitations are discussed by Jenkins et al. [19] [23]. For this particular study, CALVIN limitations are discussed in more depth in Sicke et al. [30]. These limitations include: water demands and efficiencies do not vary by water year type, other uncertainties in water demands arising from urban water conservation efforts and their costs, long-term changes in environmental requirements, the hydrologic foresight of the modeled operations, the pricing of water transfer agreements, localized water distribution system constraints, and operations occurring on a time scale less than one month.

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

5. 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. The SFPUC and EBMUD, with their access to Hetch Hetchy Aqueduct and Mokelumne River Aqueduct water, rely less on the Delta but may see economic benefit from water recycling and desalination under unfavorable climate changes. The SFPUC and EBMUD are not necessarily turning to alternative water supplies because of reduced Hetch Hetchy or Mokelumne River Aqueduct water. The EBMUD-Hayward-SFPUC and EBMUD-CCWD Interties combined with SFPUC service in Santa Clara Valley allows for purchases and transfers of imported water (Hetch Hetchy and Mokelumne River Aqueducts), recycled water, and desalination water to the demand areas that have lost access to CVP and SWP water or suffered reduced regional inflows, thus providing operating and scarcity cost savings.

Water recycling and desalination also can improve water supply reliability by reducing reliance of imported water supply. Under fairly severe climate change conditions, especially with sea level rise ending water diversions from the Sacramento-San Joaquin Delta, purchasing agricultural water becomes more expensive. The CVP and SWP water purchases and transfers wheeled through the Delta become restricted, and urban water users turn to more costly water supply alternatives such as water recycling and desalination, affecting SCV and CCWD the most.

Long-term urban water conservation greatly decreases the effects of severe climate change, and reduces operating costs and reliance on expensive supply alternatives such as water recycling and desalination. However, expanding water conservation will require extensive planning and some costs.

Overall, adaptation to a warmer drier climate relies primarily on improved system flexibility with investments in water recycling and desalination, at a cost, while adaptation to ending Delta diversions relies on alternative water supply and water 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 mere existence of physical infrastructure. The average yearly cost for the intertie policy constraints were $51 million, $297 million, and $896 million for the warm dry, no Delta diversion, and warm dry hydrology with no Delta diversion model runs, respectively. A management policy for intertie cooperative operations can allow large investments in water recycling and desalination to be shared by several agencies.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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