Regional Groundwater Banking and Water Reuse Potential in the San Francisco Bay Area Water Supply System

By

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ABSTRACT

The San Francisco Bay Area obtains two-thirds of its water supply from imported surface water and only 5% from groundwater. In part due to limited surface water storage, the supply is vulnerable to fluctuations in runoff, as well as reductions and disruptions in imports. This study investigates the potential for local groundwater banking and artificial recharge using recycled water to decrease supply vulnerability and system costs. Groundwater banking with surface water and recycled water was modeled in CALVIN, a hydro-economic model of the California water system. Water-scarce conditions were induced by restricting imports into the Bay Area. The model results showed that groundwater banking and indirect potable reuse could reduce water supply vulnerability in the San Francisco Bay Area. Although there is an increase in operational cost due to groundwater banking and indirect potable reuse, the savings from reduced scarcity (measured in economic loss) offset the increase in operational costs. Groundwater banking was shown to be most effective for reducing short-term scarcity, while indirect potable reuse was effective for reducing the severity of intense, longer-term scarcity. Additionally, the increased operational flexibility from groundwater banking could allow the Bay Area to shift to a more conjunctive-use style of operations, potentially reducing scarcity elsewhere in the state.

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1 INTRODUCTION

A warming climate, greater diversions for environmental needs, and a growing population are exacerbating demands on California's water supply system. The average temperature is forecasted to increase by 2 to 5 °F by mid-century, increasing landscape irrigation demand and likely increasing crop demand, while decreasing the snowpack storage for California's water supply (Hanak et al. 2011). As temperatures increase, sea level rise will increasingly threaten the freshwater transfers through Sacramento-San Joaquin Delta, the hub of California's north-to-south water supply. Additionally, pumping restrictions and instream flow requirements are increasing as scientists and policymakers learn more about impacts of water management on aquatic ecosystems. Meanwhile, on the demand side, California's population is projected to grow by a third to roughly 51 million by 2050, with the San Francisco Bay Area adding approximately 1.5 million people (DWR 2013).

Even before these mounting challenges, the San Francisco Bay Area (the Bay Area) water supply was already vulnerable to droughts and import disruptions. Some agencies lack adequate supplies in dry years (ACWD 2010 UWMP; EBMUD 2010 UWMP). The Bay Area imports two-thirds of its water supply through conveyances subject to seismic disruption. Part of this supply, conveyed in aqueducts from the Sierra Nevada, would likely be restored within weeks to months. The remaining imports are conveyed through the Delta, which could be rendered too saline to use for over a year until freshwater flows flush out the system following levee failure (Lund et al. 2010). Both droughts and disrupted imports could be acutely damaging because the Bay Area has limited local water storage capacity.

There are ten major water agencies of the Bay Area, four in the North Bay and six in the South and Central Bay (Figure 1-1). The water supply portfolios of south and central Bay Area are more vulnerable than the northern Bay Area (Table 1-1). Most of the South and Central Bay water agencies depend on single-source imports, with limited supplemental supplies. In contrast, the North Bay depends more on local supplies, which are less vulnerable to disruption than imported supplies. Additionally, their imports are less vulnerable because they are diverted upstream of the Delta. The lack of diversification in water supplies, the heavy reliance on imports, and the limited within-region storage prompted this investigation into ways to reduce water supply vulnerability in the south and central Bay Area.

Source: SPUR map with data from: California Spatial Information Library ABAG Projections, 2005;
Bay Area Integrated Regional Water Management Plan, November 2006

Figure 1-1. Major water agencies of the San Francisco Bay Area.

Table 1-1. Supply sources for major Bay Area water agencies.

Key: +++++ = >80%; ++++ = 50-80%; +++ = 25-50%; ++ = 5-25%; + = <5%

	Import North of Delta	Import through Delta	Direct import from Sierras	Local runoff	Local groundwater	Other
- North Bay -						
MMWD				+++++		+
Napa	+++			++++		
Solano	++			++++		
Sonoma				+++++	+	+
- South Bay -						
ACWD		+++	++	++	++	
CCWD		+++++				++
EBMUD			+++++	++		+
SFPUC*			+++++	++	+	
SCVWD		+++	++	++	++	+
Zone 7		+++++		++		+

MMWD – Marin Municipal Water District, Napa – City of Napa, Solano – Solano County Water Agency, Sonoma – Sonoma County Water Agency, ACWD – Alameda County Water Agency, CCWD – Contra Costa Water District, EBMUD – East Bay Municipal Utility District, SCVWD – Santa Clara Water District, SFPUC – San Francisco Public Utility Commission, Z7WA – Zone 7 Water Agency
*SFPUC retail plus wholesale to BAWSCA

Options for new water supplies and storage locations are limited, expensive, and tend to have significant drawbacks (Hanak et al. 2011). The main options for new water supply in California's highly (and often over-) allocated system are desalination and wastewater reclamation. Seawater desalination is expensive, energy-intensive, and creates a brine disposal problem, but the end product is fully accepted by the public. Reclaiming wastewater has the same drawbacks as desalination, but less so, because of the lower salt content. However, public perception of even highly purified recycled water currently prevents direct potable reuse. On the storage front, the options are surface storage and in-ground storage. Reservoirs have the advantage of being easier to protect (from contamination and illicit withdrawals) and less expensive to operate than groundwater aquifers, but they have some major drawbacks including high initial costs, sedimentation, which reduces storage capacity, and algae growth, which causes taste and odor issues. Furthermore, finding suitable reservoir sites in an urban region, especially a seismically active area, may be quite difficult.

Given that the Bay Area is highly developed and earthquake prone, groundwater storage has major advantages over developing or expanding surface water storage. Not all Bay Area water agencies have suitable aquifers, but some local aquifers are not used to their full potential – either because demands on the aquifer are smaller than its capacity or because supplies to replenish the aquifer are not currently available. Allowing other agencies to deposit and withdraw water from under-utilized aquifers could improve the local storage problem, reducing potential impacts of import disruption.

Increasing local supplies helps buffer supply interruptions. In Southern California, the Groundwater Replenishment System in Orange County, CA takes treated wastewater and purifies it using a three-step advanced treatment process: microfiltration, reverse osmosis, and ultraviolet light with hydrogen peroxide (Markus and Deshmukh 2010). The extremely high-quality reclaimed water is then used to recharge the local aquifer. The water can be extracted and put in to the treatment system for potable use after a six-month residence time. Such indirect potable reuse could be valuable for the Bay Area. Some agencies are considering it (SCVWD 2012 WSIMP; Zone 7 2011 WSE).

This study explores the potential for within-region groundwater banking and aquifer recharge with reclaimed water to reduce vulnerability of the San Francisco Bay Area's water supply. The potential value of local groundwater banking and indirect potable reuse are assessed under water scarce conditions using hydro-economic modeling.

This report begins with an overview of the modeling approach used, including how water scarce conditions were modeled and how the San Francisco Bay Area infrastructure was expanded to allow groundwater banking and indirect potable reuse. The next section presents the system modeling results comparing regional scarcity, costs, and operations for current and expanded infrastructure under normal and restricted water availability conditions. The following section discusses results for each agency. The final section concludes with implications of the study as well as future research.

2 MODELING APPROACH

2.1 CALVIN

To investigate the potential value of different water supply options in the Bay Area, a hydro-economic model of California's intertied water system, CALVIN, was used. Engineering optimization models can help identify system strengths and weaknesses and explore alternative management ideas, especially for large interdependent systems.

2.1.1 Overview of Model

California Value Integrated Network (CALVIN) model is an economic-engineering optimization model that allocates surface water and groundwater statewide to minimize operating and scarcity costs within the physical and environmental constraints of the water supply system (Draper et al., 2003). CALVIN was developed at UC Davis to organize a quantitative understanding of integrated water supply management in California, examine the economic and supply effects of water management alternatives, and identify economically promising water market, infrastructure, and other water management actions within an integrated water supply management context (Bartolomeo, 2011). An optimization model differs from a simulation model in that it searches for the best solution (to meet a defined objective) as opposed to simply running a single management alternative. This type of optimization model has perfect hydrologic foresight so the model results are best-case outcomes rather than predictions of actual outcomes (Draper 2001).

Previous Uses

CALVIN has been employed to explore water management issues in California, looking at the potential impacts of changes in policy, infrastructure, water use, and climate/hydrology. Studies have included investigating the economic and water management effects of changes in Delta exports (Tanaka and Lund, 2003; Tanaka et al., 2008), water markets in Southern California (Newlin et al., 2002), water management options under extreme drought conditions (Harou et al., 2010) and the potential impacts of climate change on San Francisco Bay Area water supply (Sicke et al. 2013).

Model structure

CALVIN is structured as a generalized network flow optimization model where nodes represent network junctions and links represent conveyances, storage, and demands. It operates the physical infrastructure and allocates water within the system's constraints to minimize statewide costs. Costs in the model include 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. The model solution, i.e., the lowest-cost allocation of water, is found using HEC-PRM, the optimization solver developed by the U.S. Army Corps of Engineers. The model formulation is as follows:

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 the flow leaving node i towards node j (arc ij), c_{ij} is the cost associated with arc ij (either operation or scarcity cost), a_{ij} is the loss or gain on arc ij, b_j is the external inflow to node j, u_{ij} is the upper bound on arc ij, and l_{ij} is the lower bound on arc ij.

Model Extent

CALVIN represents the intertied portion of California's intertied water supply network, including 31 groundwater basins, 53 reservoirs, and 32 urban and 24 agricultural economically represented water demand areas (Figure 2-1). It covers 92% of California's populated area and 90% of the 9.25 million acres of irrigated crop area reported in the 2009 California Water Plan Update (Howitt et al. 2010).

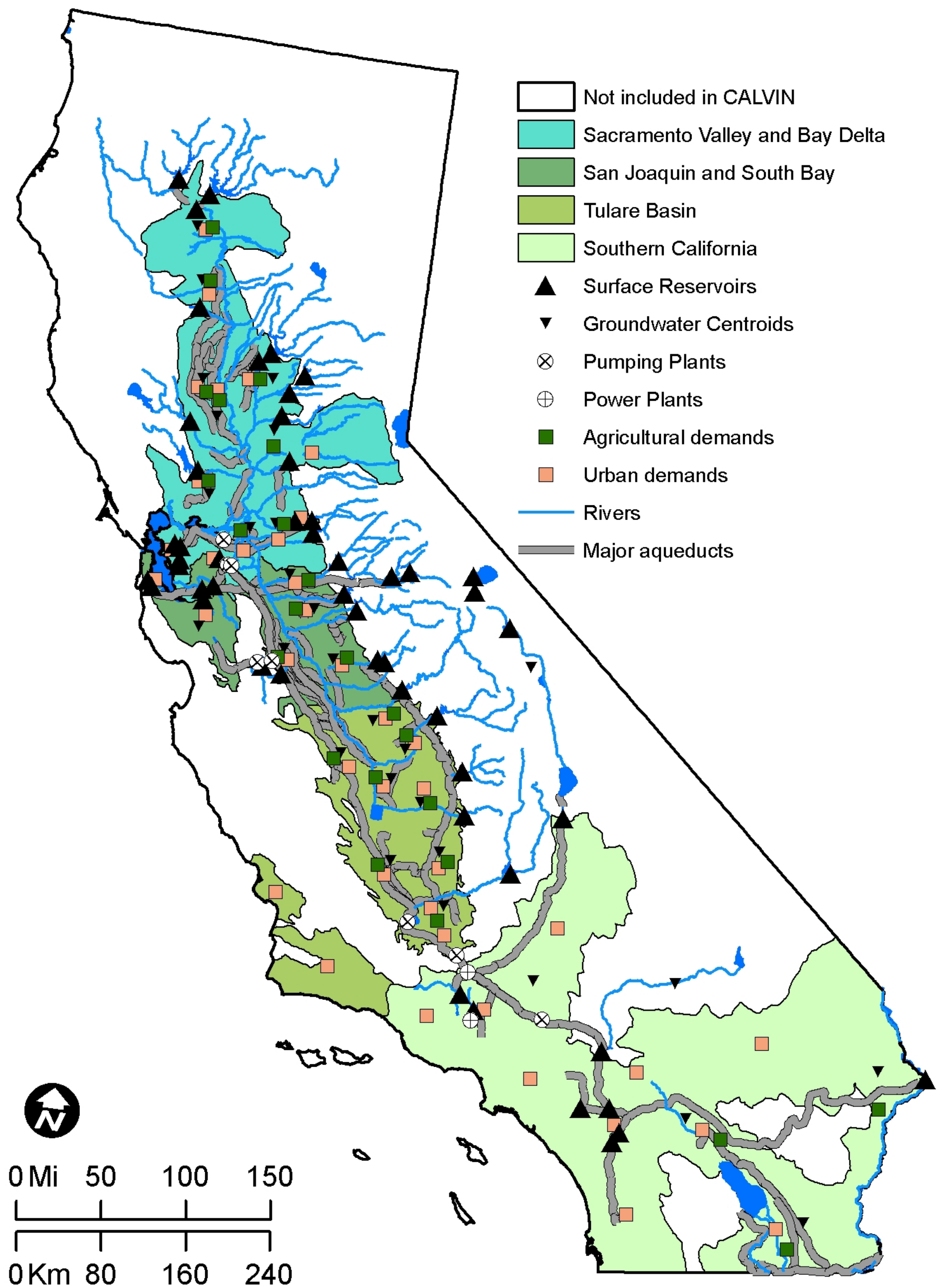

Figure 2-1. Extent of CALVIN: Water supply infrastructure, inflows, and demand areas represented.

2.1.2 Model Inputs

The basis of the model is a network representing the water supply system. The nodes are classified as storage nodes or junctions (pass-through nodes). The storage nodes, e.g., representing groundwater basins, are assigned a storage capacity and an initial volume. The arcs between nodes can be assigned directionality, flow capacity, and costs, e.g., cost of conveying a unit of water. Additionally, links can be assigned constraints, such as seasonally varying minimum flows. Links that represent demands are assigned a penalty function that defines the scarcity cost of not meeting that demand.

The model is driven by 72 years of monthly hydrologic data. Every time step, estimated surface water and ground water flows enter and leave the model. These flows represent, for example, unimpaired river inflows at the model boundary and native vegetation taking up groundwater. Additionally, evaporative losses from lakes and reservoirs are calculated each time step.

Operating costs assigned to the network links can be either simple values, e.g., dollar/acre-foot, or functions of flow volume through the link, e.g., marginal cost increases with flow. Most costs are based on statewide averages for treatment, delivery, water quality, hydropower, etc. (Jenkins et al. 2001). However, some local costs were changed where data was available.

The demands in the model are forecasted for the year 2050. The agricultural demands and associated penalty functions were developed using the Statewide Agricultural Production model (SWAP) (Howitt et al. 2012). The original urban demands in CALVIN were calculated from the 1998 State Water Plan. San Francisco Bay Area urban demands were updated using agencies' 2010 Urban Water Management Plans (ACWD 2010 UWMP, CCWD 2010 UWMP, EBMUD 2010 UWMP, SFPUC 2010 UWMP, SCVWD 2010 UWMP, Zone 7 2010 UWMP). The urban demands are split into two sectors: industrial use and residential/commercial use. Additionally, residential/commercial use is subdivided into indoor and outdoor use. The interior use is constant over time, while the exterior use varies seasonally.

2.1.3 Model Outputs

For the conditions simulated, CALVIN outputs an optimized physical allocation of water throughout the supply network over the time period simulated and the marginal value of water throughout the network over the same period. The model's allocation of water can be used to determine usage of infrastructure, operating and scarcity costs, optimized water supply portfolios, and supply reliability. The marginal value of water throughout the network provides the value of expanding infrastructure, of reducing flow or storage constraints, and of increasing any particular supply. This marginal value of water is also referred to as willingness-to-pay (WTP). By comparing the results of different scenarios (e.g., changes in operating and scarcity costs), one can assess the value of different water management alternatives, including changes in infrastructure and supply options.

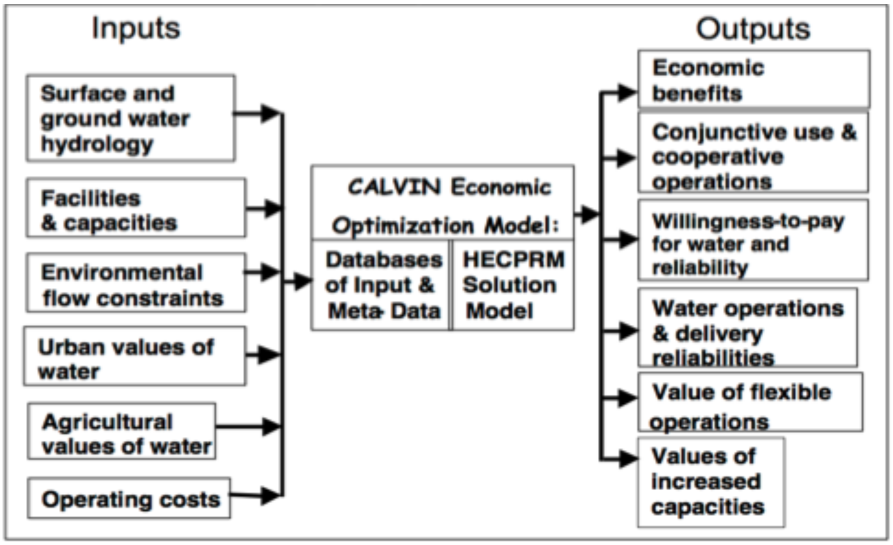

Figure 2-2. CALVIN data flow.

2.1.4 Model Representation of San Francisco Bay Area

As a statewide model, CALVIN aggregates water purveyors by location in the supply network, rather than attempting to represent the thousands of utilities, water districts, water companies, etc. operating in California. The Bay Area is aggregated into seven demand nodes (one North Bay demand node and six South-Central Bay demand nodes). The following Bay Area service areas are represented in CALVIN:

- Alameda County Water District (ACWD)
- Contra Costa Water District (CCWD)
- East Bay Municipal Utility District (EBMUD)
- Napa-Solano, representing the City of Napa and Solano County Water Agency
- San Francisco Public Utility Commission (SFPUC), including wholesale service to part of San Mateo County
- Santa Clara Valley Water District (SCVWD)
- Alameda County Flood Control & Water Conservation District Zone 7 (Zone 7)

Only agencies that are intertied into the statewide water infrastructure are represented in CALVIN. Marin and Sonoma Counties, which rely solely on local water sources, are not represented in CALVIN.

Interconnected Bay Area

The schematic (Figure 2-3) shows the major water supply infrastructure for the area focused on in this study. Napa-Solano was not included because it is not directly connected to the main Bay Area water supply system and it does not have the same vulnerabilities with its water source being upstream of the Delta.

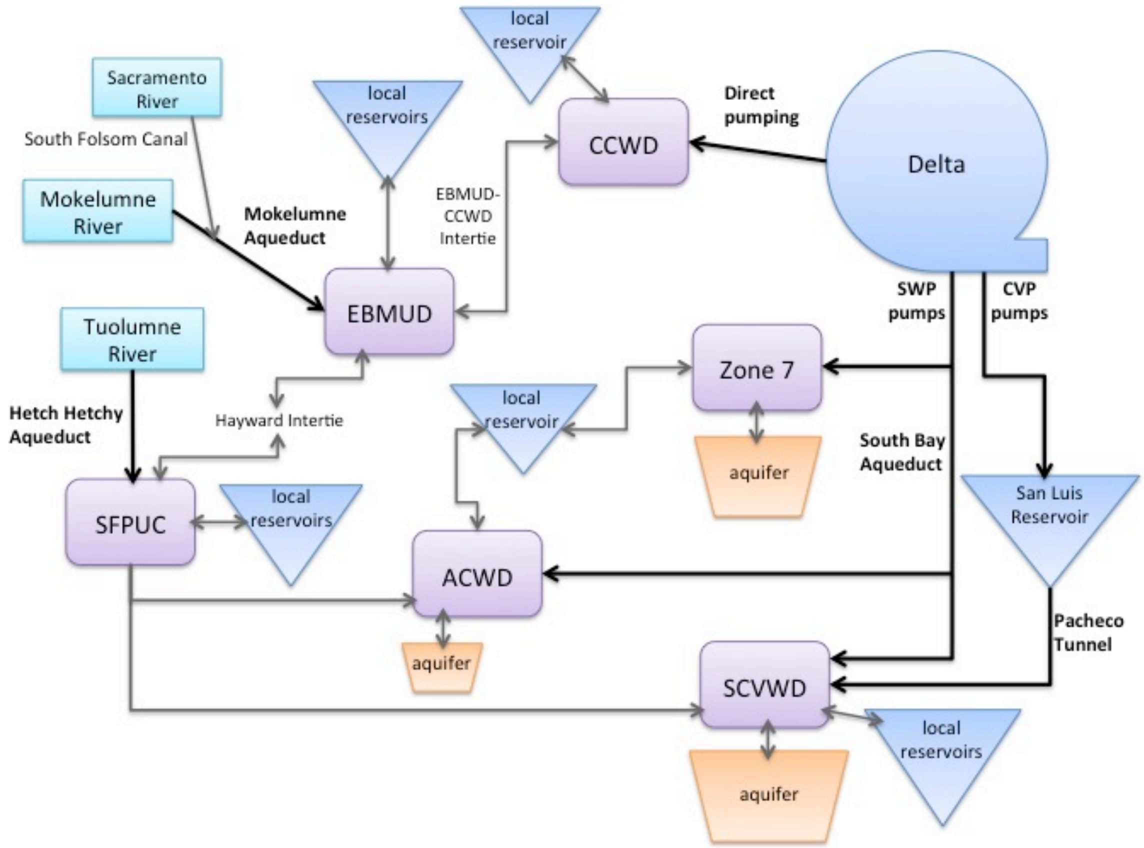

Figure 2-3. Intertied portion of San Francisco Bay Area's water supply system.

Most of the Bay Area's water supply comes from outside the region, so the import infrastructure is central to meeting water needs. SFPUC and EBMUD both import water from the Sierra Nevada via lengthy pipelines: Hetch Hetchy aqueduct and Mokelumne aqueduct, respectively. SFPUC, in turn, serves much of this imported water to other agencies in the region. CCWD pumps water directly from the Delta using four different intake locations. ACWD, SCVWD, and Zone 7 import water via the South Bay Aqueduct, which is fed by large State Water Project (SWP) pumps in the South Delta. SCVWD also imports water using the Pacheco Tunnel, fed with Delta water from San Luis Reservoir and Central Valley Project (CVP) Delta pumps. Local surface water and groundwater provides a portion of the supply, but the water demands have grown far past the sustainable water yield of the region. Some of the water agencies have developed water reuse programs, but the end product has been limited to non-potable use thus far. The specific water supply portfolios for each of these demand areas are discussed in the Results section.

2.2 Scenario Runs

This study explored the value of groundwater banking and indirect potable reuse under water scarce conditions in the Bay Area. Accordingly, model scenarios were developed to represent historic (current or recent) water availability and constrained water availability with and without groundwater banking and recycled water aquifer recharge infrastructure. The outcomes, such as usage of expanded infrastructure and regional scarcity and operating costs, can indicate whether groundwater banking and indirect potable reuse may provide economically sensible ways to hedge against water scarcity.

2.2.1 Scenario description

Water scarcity was induced in the model by reducing import capacity into the Bay Area in dry years[1]. Figure 2-4 shows the choke points on the major import infrastructure. The constrained water availability scenario runs coarsely represent a variety of situations that could reduce water availability: increased environmental restrictions on diversions; more extreme droughts; catastrophic flood or earthquake resulting in water infrastructure failure (Delta levees and aqueducts). The water availability reduction had to be fairly extreme to induce scarcity because the model solver has perfect hydrologic foresight and can prepare for the dry years by storing up water.

For the expanded groundwater infrastructure runs, Bay Area aquifers were examined for banking suitability in terms of size, water quality, and present usage level. Two suitable aquifers were identified:

- Livermore Valley aquifer
- Santa Clara Valley aquifer

Livermore Valley aquifer's operational storage is estimated to be 130 TAF (Zone 7 Groundwater Management Plan 2012) and Santa Clara Valley aquifer's operational storage is estimated to be 530 TAF (SCVWD Groundwater Management Plan 2012). The combined aquifer storage of 660 TAF corresponds to approximately half the volume of the forecasted year 2050 demand for the area (1,300 TAF/year).

Both aquifers were set up as groundwater banks in the model. The Livermore Valley aquifer, managed by Zone 7 water agency, was linked up to the neighboring service areas of CCWD and EBMUD, who could contribute and extract groundwater for a cost. The Santa Clara Valley aquifer, managed by SCVWD, was connected to its nearest neighbors, SFPUC and ACWD, who were then allowed to deposit and withdraw water.

As further expansion of the infrastructure, indirect potable reuse was set up for the groundwater banking host agencies. SCVWD and Zone 7's recycled water plants were each linked up to their respective aquifers to allow recharge, as was ACWD, which manages a small aquifer. The other agencies had their own non-potable recycling programs, but these were not connected to the groundwater banks due to prohibitive conveyance costs (would need to lay dedicated non-potable pipe between neighboring agencies).

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[1] Water scarcity had to be artificially induced because water was economically allocated in this model and thus the high-value urban demands of the Bay Area were fully met under historic water availability (i.e., base case). In reality, the Bay Area has experienced water scarcity, such as mandatory rationing during droughts, because the system is not perfectly economically efficient and allocations are beholden to water rights and contracts (water does not simply go to the highest bidder as it would in an economically efficient market).

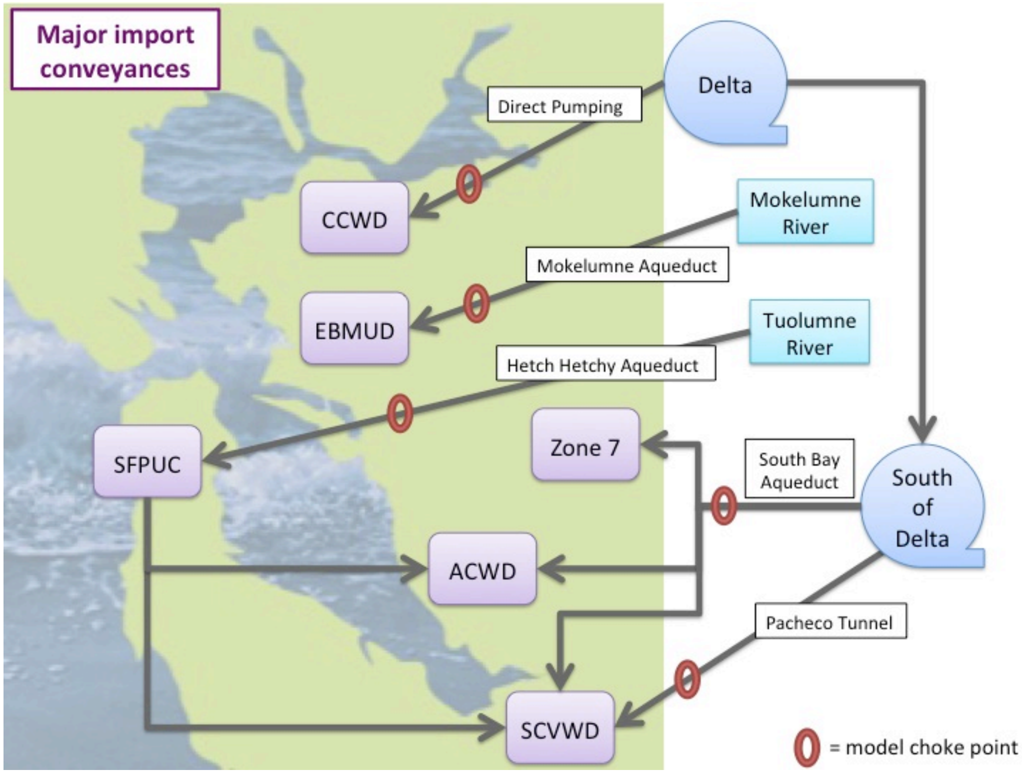


Figure 2-4. Major water import infrastructure for south and central Bay Area.

Using these scenarios, the following model runs were performed (Table 2-1). The base run represents current water supply infrastructure with historical water availability. The *HE* run checks if any of the expanded infrastructure (for groundwater banking and artificial recharge with recycled water) under consideration would be valuable under historical water availability. The *CC* run represents current water supply infrastructure with constrained water availability; this run represents what might happen under extreme drought or other water scarce conditions if no modifications are made to the present water supply system. Finally, the *CE* run shows if the expanded infrastructure is valuable under constrained water availability, and if it can reduce water scarcity economically.

Table 2-1. Model runs.

Run ID	Run name	Water Availability	Infrastructure
S07I20	Base	Historic	Current
S07I20HE	HE	Historic	Expanded
S07I20CC	CC	Constrained	Current
S07I20CE	CE	Constrained	Expanded

2.2.2 Details of scenarios

The constrained water availability case was set up as a tiered reduction on import capacity (Figure 2-5). It was developed by sorting the 72 years of input hydrology from wettest to driest, allowing full import capacity in the above normal years, and restricting import capacity in the below normal years. The import capacity was restricted to a quarter of the full capacity in the driest 25% of years and was restricted to half capacity in the 25th to 50th percentile years.

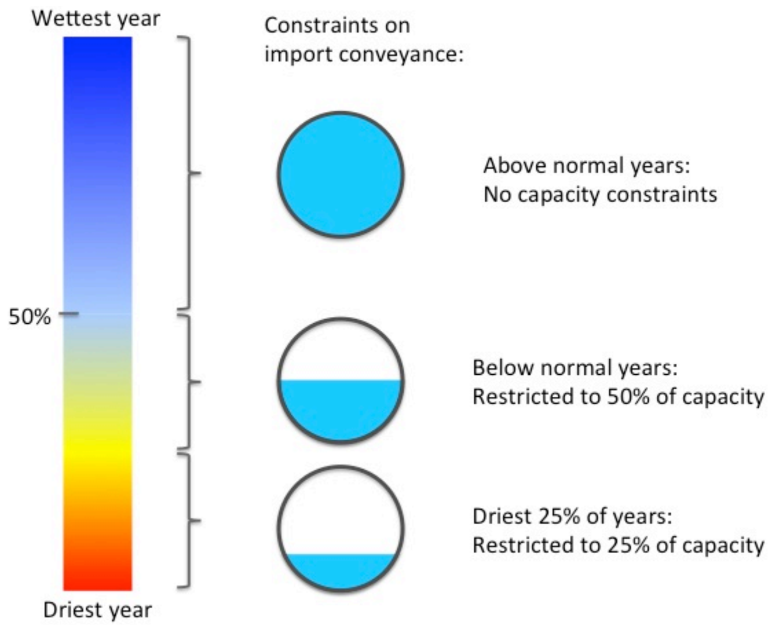


Figure 2-5. Tiered constraints for modeling water scarcity.

All agencies were affected by import restrictions (Table 2-2), but the impact of the restrictions depends on the ratio of capacity to demands, as well access to other supply sources. For example, CCWD's pumping capacity is about three times greater than the projected 2050 service areas demands, so the agency can meet most of the demand even with 25% capacity. Meanwhile, EBMUD has projected 2050 service areas demands that fall midway between full and half capacity. Given that EBMUD has limited alternative supply options, their import capacity being restricted causes scarcity in the service area.

Table 2-2. Forecasted demands and modeled import capacities.

Agency	Year 2050 Demand (TAF)	Infrastructure	Full capacity (TAF/year)	50% capacity (TAF/year)	25% capacity (TAF/year)
CCWD	190	Combined Delta intakes	623	311	156
SFPUC*	240	Hetch Hetchy Aqueduct	336	168	84
EBMUD	280	Mokelumne Aqueduct	362	189	90
SCVWD	420	Pacheco Tunnel	348	174	87
ACWD	90	South Bay Aqueduct	217	109	54
SCVWD	420				
Zone 7	80				

*Also impacts ACWD and SCVWD, who are wholesale customers of SFPUC.

In the expanded infrastructure scenario, network links were added to allow neighboring agencies to deposit and withdraw groundwater from host agencies' groundwater banks (Figure 2-6). Based on proposed and existing interties in the Bay Area water supply system, the capacity on these links was set to 20 MGD (2 TAF/month). Additionally, connections were set up to allow agencies to recharge their own aquifer with recycled water. The recycled water recharge capacities depended on the amount of wastewater produced (the supply) and the size of the aquifer. SCVWD's recharge capacity was set to 100 MGD (9 TAF/month), Zone 7's was set to 30 MGD (3 TAF/month), and ACWD's was set to 10 MGD (1 TAF/month). A limitation in modeling groundwater banking in CALVIN is the inability to track water "ownership" in communal storage. As a result the model cannot constrain withdrawals to be equal or less than water deposits by depositor, as an actual groundwater bank might operate. However, the results still can show the benefit of pooling resources in this manner, even if the exact operations cannot be modeled.

The expanded infrastructure was assigned operating costs based on local estimates when available and values from elsewhere in California when not (Table 2-3). To put these costs in context, local groundwater costs about $200-$400/AF to pump, treat, and distribute and water imports to the Bay Area cost vary from $200/AF to $600/AF. In the model, existing and expanded non-potable recycled water capacities are assigned costs of $518/AF and $1480/AF, respectively. On the priciest end, agencies with ocean or bay access can use seawater desalination[2] for $2072/AF.

[2] There currently is no ocean or bay desalination in the Bay Area (although a feasibility study for a regional desalination plant is underway). The model provides a hypothetical desalination supply option, allowing evaluation of this option as part of an optimized water supply portfolio.

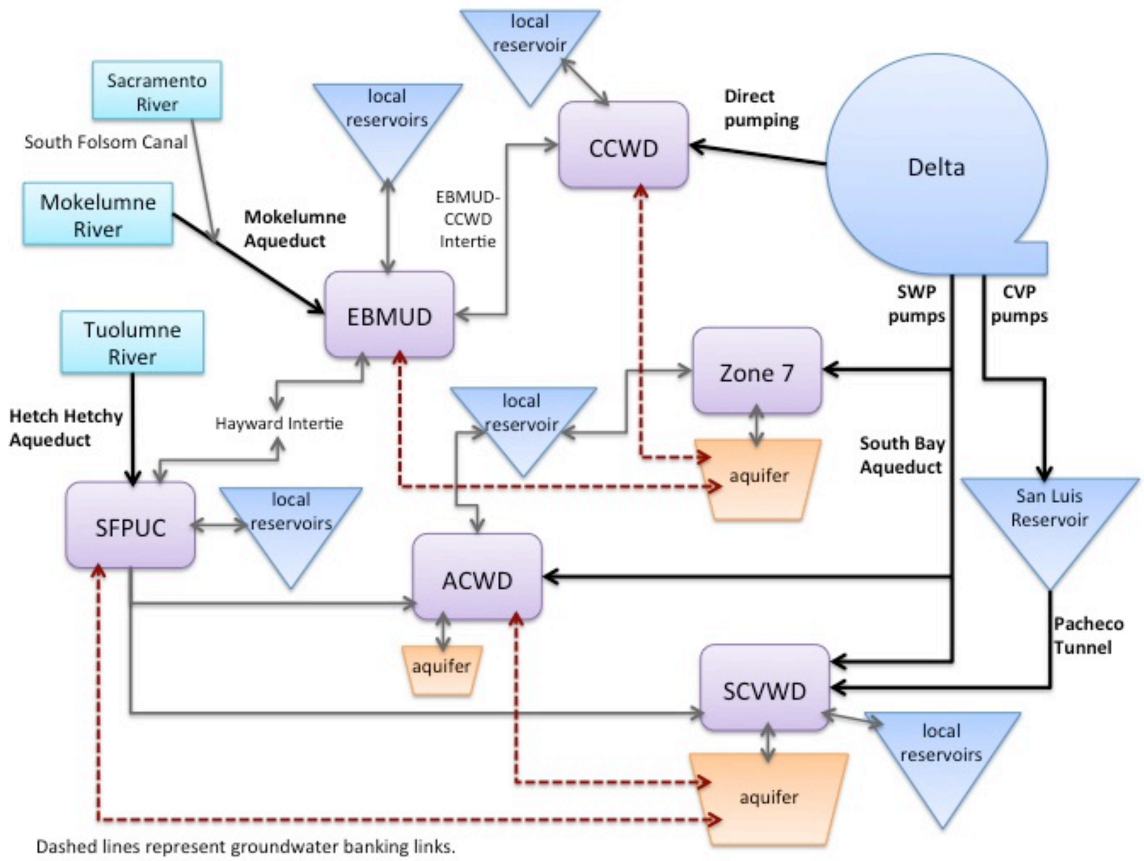


Figure 2-6. Intertied portion of San Francisco Bay Area's water supply system plus groundwater banking.

Table 2-3. Operating costs for expanded infrastructure.

Action	Cost ($/AF)	Source for cost estimate
Contribution to GW bank	$100	Semitropic GW bank fees
Extraction from GW bank + treatment	$325	Semitropic GW bank fees; local treatment costs
Aquifer recharge with recycled water	$1,600	Zone 7 2011 WSE

3 SYSTEM RESULTS

The results presented here give an overview of scenario outcomes on the regional and statewide scale for each case and provide an analysis how the expanded infrastructure was used by the model and the impact on the local aquifers. The system results conclude with an assessment of the expanded infrastructure's effect on regional supply reliability.

These results should be considered with caution as CALVIN assumes perfect institutional flexibility for water transfers and does not model agencies' internal distribution networks. While there would be institutional obstacles to overcome to set up groundwater banking, a number of Bay Area water agencies already have transfer or wheeling agreements in place (BAIRWMP 2006), suggesting that this would be possible. Internal distribution network constraints could potentially limit transfers between agencies. With this in mind, the modeled conveyance capacity for groundwater banking was set to 20 MGD, smaller than the SFPUC-SCVWD and SFPUC-EBMUD emergency interties (but larger than the EBMUD-CCWD emergency intertie**)**. However, for on-going, non-emergency operations, it is likely that additional investment in conveyance would be needed to support groundwater banking.

3.1 Statewide and Regional Water Scarcity

Table 3-1 shows the average annual water scarcity across the model runs for the Bay Area and statewide, along with the forecasted annual demand for year 2050. The first set of runs used the actual import capacity for the Bay Area and represented historical water availability. The second set of runs constrained the Bay Area's import capacity according to water year type and represented water scarce conditions. Within each set, one run had current infrastructure modeled (Base case and run CC) and the other had expanded infrastructure (runs HE and CE), representing the addition of groundwater banking and indirect potable reuse.

Table 3-1. Annual demand and average annual scarcity (TAF/year).

	Year 2050	Scarcity under historical water availability			Scarcity under constrained Bay Area imports		
	Demand	**Base**	**HE**	**Reduction**	**CC**	**CE**	**Reduction**
ACWD	90	0	0	-	1.7	1.2	0.5 (29%)
CCWD	190	0	0	-	0	0	-
EBMUD	280	0	0	-	7.5	6.8	0.7 (9%)
SFPUC	240	0	0	-	6.7	5.9	0.8 (12%)
SCVWD	420	0	0	-	4.2	3.2	1.0 (24%)
Zone 7	80	0	0	-	1.3	1.2	0.1 (8%)
Bay Area Urban	1,300	0	0	-	21	18	3 (14%)
Statewide Urban	11,300	207	207	-	229	226	3 (1%)
Statewide Ag.	25,000	1,800	1,758	42 (2%)	1,860	1,851	9 (0.5%)
Statewide Total	36,300	2,007	1,965	42 (2%)	2,089	2,077	12 (0.6%)
Runs: historical (H) and constrained (C) conditions with current (C) and expanded (E) infrastructure							

In the base case, the Bay Area had no water scarcity, i.e., all demands were met. Statewide, less than 2 percent of urban demands were not met on average, mostly in Southern California. On average, 8 percent of agricultural demands in the state were not met (99% of scarcity was south of the Delta). In the HE model run, representing historical water availability with expanded infrastructure, the Bay Area's use of groundwater banking made 42 TAF/year available to agricultural uses.

The constrained Bay Area imports run (CC) induced an average of 21 TAF/year of water scarcity in the Bay Area (2% of total demand). Constraining the Bay Area imports also affected the rest of the state's water availability. The Bay Area shifted to using more water from direct Delta pumping and through-Delta pumping, because of greater available capacity (Table 2.2). In particular, the Bay Area's increased use of through-Delta pumping reduced the availability of water for other South-of-Delta users by 61 TAF/year.

When the Bay Area's infrastructure was expanded under the constrained imports conditions (run CE), average local water scarcity decreased by 3 TAF/year, a 14% reduction in scarcity from run CC. The water scarcity elsewhere decreased by 9 TAF/year on average. Allowing the Bay Area to keep its gains from the expanded infrastructure (instead of being reallocated to optimize statewide costs) may reduce Bay Area scarcity further.

3.2 Statewide and Regional Costs

Table 3-2 shows the average annual scarcity and operation costs for the Bay Area and statewide. The costs are averages of the annual costs across the 72-year model run. Scarcity cost is the penalty for not meeting the target demand of an urban or agricultural water user. Operating costs are the variable costs of pumping, conveying, storing, and treating water.

Table 3-2. Average scarcity and operation costs ($M/year).

	Historical water availability		Constrained Bay Area imports	
Runs:	**Base**	**HE**	**CC**	**CE**
Bay Area Scarcity Costs	$0	$0	$33	$28
Bay Area Operating Costs	$438	$439	$529	$532
Total Bay Area Cost	**$438**	**$439**	**$562**	**$560**
Statewide Scarcity Costs	$429	$424	$469	$464
Statewide Operating Costs	$3,026	$3,021	$3,079	$3,076
Total Statewide Cost	**$3,455**	**$3,445**	**$3,548**	**$3,540**
Runs: historical (H) and constrained (C) conditions with current (C) and expanded (E) infrastructure				

Under historical water availabilty, expanded infrastructure raised Bay Area operating costs by $1 million/year, but reduced average statewide costs by $10 million/year. Introducing groundwater banking[3] allowed the Bay Area to rely less on through-Delta exports, allowing more water to continue on to the Central Valley and Southern California, reducing scarcity and operating costs

[3] Indirect potable reuse was not used by any of the agencies in run HE.

in those regions. These results suggest expanding the Bay Area's water supply infrastructure is potentially valuable to the state as a whole for reducing average statewide water costs. It is not clear if the expanded infrastructure would be used by the Bay Area in the absence of the scarcity in other regions driving its value.

When Bay Area import capacities were constrained, the average operating and scarcity costs for the region increased by $124 million/year from the base case. The operating costs increased because agencies relied more on expensive supplies, e.g., desalination, when imports were constrained. Expanding infrastructure reduced scarcity costs by $5 million/year, but increased operating costs by $3 million/year, for a net local savings of $2 million/year. On a statewide basis, the Bay Area's expanded infrastructure saved $8 million/year. Under water scarce conditions, the expanded infrastructure has value for the Bay Area on average.

Table 3-3 shows the drought-period scarcity and operation costs for the Bay Area and statewide. These costs were calculated by averaging the annual costs during the three major droughts in the hydrologic record driving the model.

Table 3-3. Drought scarcity and operation costs ($M/year).

	Historical water availability		Constrained Bay Area imports	
Runs:	**Base**	**HE**	**CC**	**CE**
Bay Area Scarcity Costs	$0	$0	$133	$124
Bay Area Operating Costs	$428	$435	$675	$683
Total Bay Area Cost	**$428**	**$435**	**$808**	**$807**
Statewide Scarcity Costs	$431	$429	$574	$562
Statewide Operating Costs	$2944	$2946	$3149	$3150
Total Statewide Cost	**$3,375**	**$3,375**	**$3,723**	**$3,712**
Runs: historical (H) and constrained (C) conditions with current (C) and expanded (E) infrastructure				

In droughts, the base case scarcity costs remained zero in the Bay Area while the operating costs dropped by $10 million/year, due to a shift in water sources during droughts. The main driver was the agencies that normally rely on relatively expensive through-Delta supplies switch to cheaper groundwater during droughts. Expanding the infrastructure raised Bay Area operating costs by $7 million per year during droughts. Operating and scarcity costs were reduced by an equivalent amount elsewhere in the state as more water was delivered to the Central Valley and Southern California. While scarcity costs for the state decreased with the expansion of Bay Area infrastructure, operating costs increased by a similar amount, resulting no net gain from the infrastructure during droughts.

When Bay Area imports were constrained, regional costs increased by $370 million/year during droughts. Meanwhile statewide cost only increased by $348 million/year, indicating that there was a savings of $22 million/year elsewhere in the system, making use of the water denied to the Bay Area. The expanded infrastructure reduced Bay Area scarcity costs by $9 million/year, but increased operating costs by $8 million/year, resulting in a net gain of $1 million/year in droughts. Statewide, expanding Bay Area's infrastructure resulted in a gain of $11 million per year, mostly from reduced scarcity costs. Under water scarce conditions, the expanded infrastructure has some value for the Bay Area in droughts, but has more value for the rest of the statewide system.

Table 3-4 summarizes changes in total costs when the Bay Area's infrastructure is expanded to include groundwater banking and indirect potable reuse. Under historical water availability conditions, this model showed that expanding infrastructure is not economically sensible for the Bay Area (current water supply options are cheaper and available enough). The rest of the state could benefit from the Bay Area having a local groundwater banking program because more water would be available to other South-of-Delta exporters. Under water scarce conditions, groundwater banking and indirect potable reuse were economically attractive for the Bay Area with an average savings of $2 million per year. Again, the rest of the state saw an even greater cost reduction than the Bay Area, suggesting that some of the cost savings were reallocated elsewhere to optimize the entire system.

Table 3-4. Effect of expanding Bay Area's infrastructure on total costs ($M/year).

	Historical water availability		Constrained Bay Area imports	
	Average	Drought	Average	Drought
Change in Bay Area Costs	+$1	+$7	-$2	-$1
Change in Statewide Costs	-$10	-	-$8	-$11

3.3 Operations

3.3.1 Import operations

Figure 3-1 shows the effect of the water availability constraints and the expanded infrastructure on the Bay Area import sources and quantities. With expanded infrastructure, the imports from the Sierras increased while the South-of-Delta imports decreased relative to the base case. This shift in source increased Bay Area's operating costs[4] but reduced scarcity and operating costs in the rest of the state. Under the constrained conditions, the imports from the Sierras decreased significantly because their conveyances (Mokelumne and Hetch Hetchy aqueducts) had the least excess capacity. Direct Delta and South-of-Delta pumping increased to compensate for the loss of Sierra supplies, resulting in the additional scarcity seen in the rest of the state. With expanded infrastructure, Mokelumne imports increased about 10 TAF/year and South Bay Aqueduct imports decreased by a similar amount. The reduced take of South-of-Delta resulted in slightly less scarcity in the rest of the state.

[4] While the imports from the Sierras were initially cheaper, routing them through a groundwater bank renders them more expensive than direct use of South-of-Delta imports.

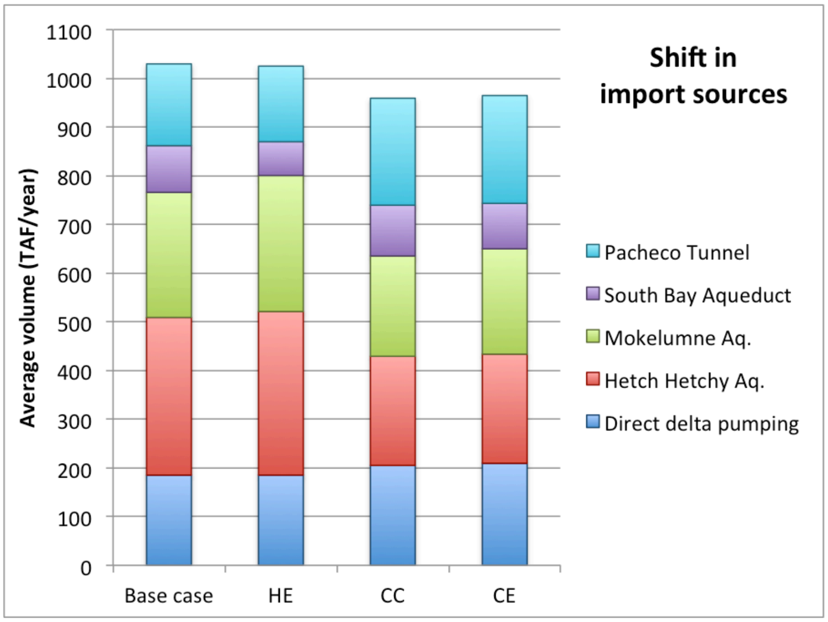


Figure 3-1. Bay Area average imports (TAF/year) across model runs.

Figure 3-2 shows the effect of expanding infrastructure on total Bay Area imports by import constraint level (based on water year type). A value to the right of zero indicates increased imports with expanded infrastructure, and to the left of zero indicates decreased imports. Expanding the infrastructure shifted the timing of Bay Area imports. In the driest 25% of years, the Bay Area slightly reduced its imports. The changes in imports in the dry years (below 50%, but above 25%) balanced out to around zero. But in the wet years (above 50%), the Bay Area tended to increase its imports, with an average increase of 10 TAF/year. The shift in import timing suggests a more conjunctive-use style of operation would be available to the Bay Area if regional groundwater banking were implemented. On top of increasing local reserves in the event of an emergency, this style of operation helps reduce statewide scarcity because more water is available to others.

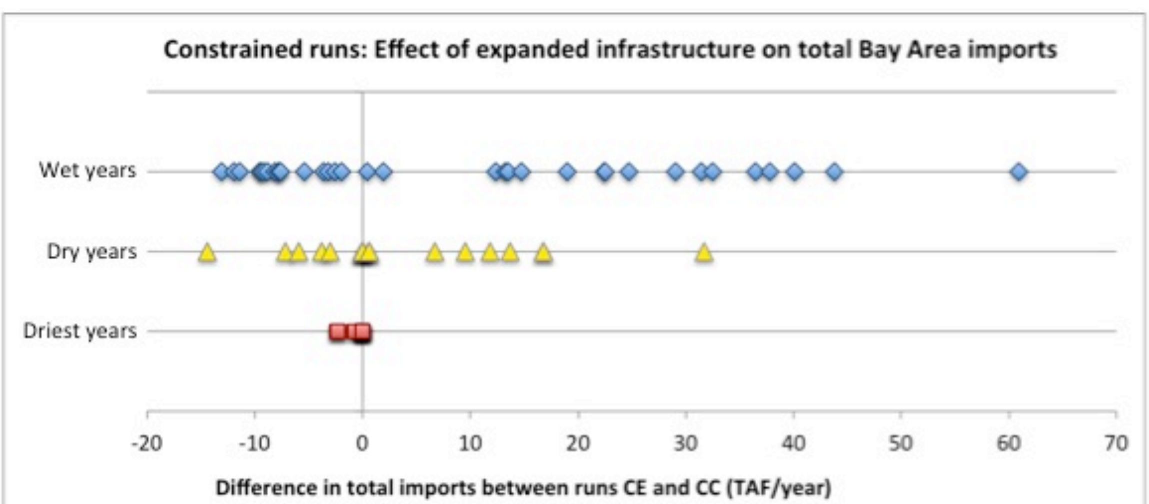


Figure 3-2. Change in total Bay Area imports by constraint level.

3.3.2 Operation of Expanded Infrastructure

Table 3-5 and Figures 3-3 to 3-5 show the use of different components of the expanded infrastructure for historical water availability (run HE) and constrained water availability (run CE). The annual usage levels were plotted over time to show operations of groundwater banks. Recharge with recycled water was plotted at a monthly scale to show capacity effects. No indirect potable reuse occurred in run HE, so the results were not plotted.

Table 3-5. Use of expanded infrastructure (percent of months).

Infrastructure	HE	CE
Groundwater Banking		
CCWD contribution to Zone 7	0%	11%
CCWD extraction from Zone 7	0%	3%
EBMUD contribution to Zone 7	100%	63%
EBMUD extraction from Zone 7	0%	21%
SFPUC contribution to SCVWD	76%	3%
SFPUC extraction from SCVWD	0%	8%
ACWD extraction from SCVWD*	30%	44%
Indirect Potable Reuse		
Zone 7 artificial recharge with R.W.	0%	17%
SCVWD artificial recharge with R.W.	0%	6%
ACWD artificial recharge with R.W.	0%	13%
Runs: historical (H) and constrained (C) conditions with expanded (E) infrastructure		

*No distinct contribution because ACWD and SCVWD both receive water from South Bay Aqueduct.

Table 3-5 provides an indication of which components of the expanded infrastructure were useful. The model did not show the groundwater banking infrastructure between CCWD and Zone 7 to be particularly useful, but this is likely the result of the modeled scenario not properly inducing scarcity for CCWD (discussed further in the Local Agency Analysis section). Meanwhile, the results suggested that the groundwater banking infrastructure between EBMUD and Zone 7 could be very useful. The results were mixed for whether SCVWD benefited from being a groundwater bank. SFPUC did not have much to contribute to SCVWD's aquifer under constrained water conditions, and it did not extract much either. ACWD did use SCVWD's aquifer, frequently as an alternative to its own more expensive groundwater, but also as a supplemental source in times of need. The indirect potable reuse infrastructure was not used at all under historical water availability, but the infrastructure proved useful under water-scarce conditions.

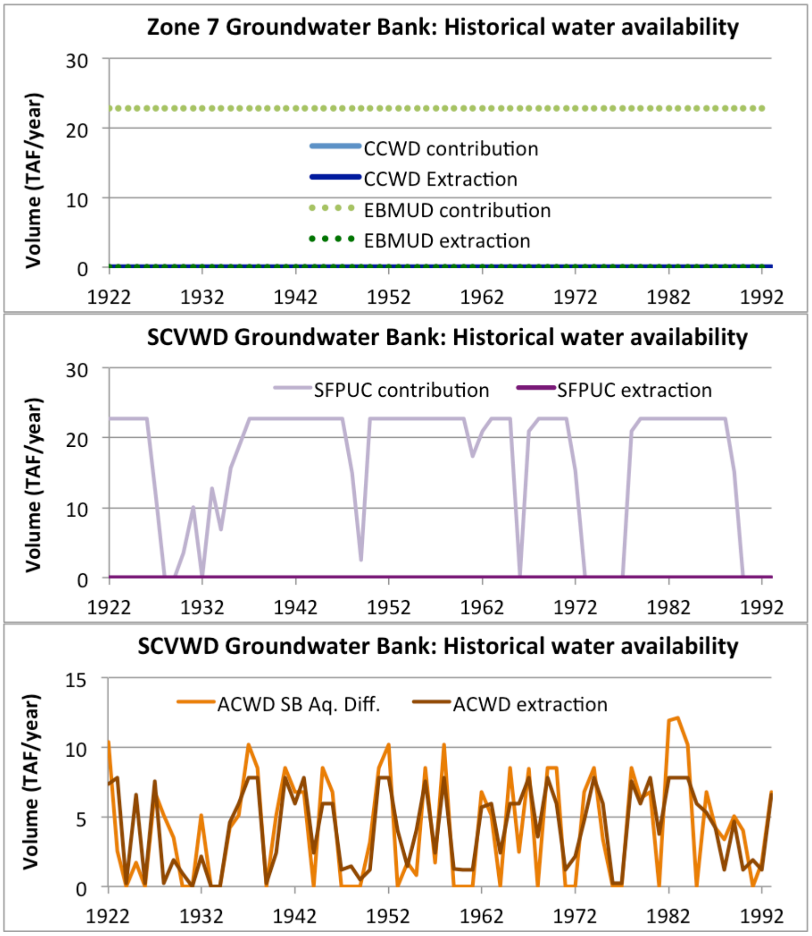


Figure 3-3. Groundwater banking contributions and extractions under historic water availability.

With historical water availability, the groundwater banks mainly served to route imported Sierra water supplies to the host agencies, Zone 7 and SCVWD. The access to imported Sierra water allowed Zone 7 and SCVWD to reduce their take of South-of-Delta supplies, which are in more demand by the rest of the state. Between the base case and run HE, the total Sierra imports to the Bay Area increased by 35 TAF/year while total South-of-Delta imports decreased by 39 TAF/year. The top graph in Figure 3-3 shows EBMUD providing a constant supply of imported Mokelumne River water to Zone 7 aquifer at maximum capacity and not withdrawing anything in return. In essence, EBMUD is selling or wheeling excess water to Zone 7. Likewise, the middle graph in Figure 3-3 shows SFPUC providing imported Tuolumne River water to SCVWD aquifer about three-quarters of the time (also at maximum capacity), and not withdrawing anything in return. Additionally, ACWD used the SCVWD groundwater bank as an occasional supplemental source (it partially replaces its own groundwater pumping, which is more expensive due to demineralization costs). The bottom graph in Figure 3-3 shows ACWD extracting water from SCVWD's aquifer about a third of the time but rarely at full capacity. There was no explicit representation of ACWD's contributions to the aquifer because ACWD was served upstream of SCVWD along the South Bay Aqueduct. However, ACWD could contribute to SCVWD's aquifer by taking less water from the aqueduct, so the difference between ACWD's take from the South Bay aqueduct in the base case and run HE was plotted.

Figure 3-3 shows that ACWD reduces its import of South-of-Delta supplies by an amount similar to its extractions of SCVWD groundwater.

Under constrained water availability, CCWD, EBMUD, SFPUC, and ACWD all contributed to and extracted from their groundwater bank to varying extents (Figure 3-4). The top graph in Figure 3-4 shows how the import constraints varied over the simulation, indicating the availability of water supplies. Two long droughts occurred in WY 1929-1934 and WY 1987-1992, and one short, but extreme, drought in WY 1976-1977. The import constraint time series shows there were other periods of water scarcity as well, including the late 1940s and the late 1950s to early 1960s.

CCWD contributed occasionally during or leading up to long droughts and limited its extractions to short periods of scarcity. CCWD's main supply, pumping from the Delta, was relatively expensive compared to EBMUD's mostly gravity-driven Sierra imports, so it was a less appealing source of recharge for the Zone 7 aquifer. CCWD only rarely extracted from the bank because its supply was far less constrained than other agencies (because its pumping capacity so greatly exceeds its demands).

EBMUD was the only consistent conjunctive use type groundwater bank user, frequently contributing water in wetter periods and withdrawing water in water-scarce periods. EBMUD provided a relatively cheap source of water for aquifer recharge in plentiful times, but then faced unmet demands or costly supply alternatives in scarce times. These attributes made EBMUD an ideal agency for participating in groundwater banking.

SFPUC infrequently participated in the groundwater bank. It contributed right at beginning of lengthy wet periods and extracted during short or moderate droughts, but not long droughts. While SFPUC could theoretically provide a cheap water source for recharging SCVWD's aquifer, SFPUC already serves as a regional wholesaler, and its supplies are in high demand for immediate use. As a result, there was little remaining supply to store for future need. SFPUC only extracted water when there was less competition for it because its capacity exceeded its modeled demands by 40%, and so it was less affected by the import constraints (compared to EBMUD whose capacity exceeded its demands by only 30%).

ACWD mainly treated SCVWD's aquifer as an alternative to its own more expensive groundwater, as opposed to a supplemental source in times of need. It frequently extracted water from SCVWD's aquifer, but refrained from extractions during long droughts when there was more competition for the banked water. ACWD reduced its take from South Bay Aqueduct (allowing more water to continue on to SCVWD), to correspond with extracting cheaper groundwater from SCVWD. On average, ACWD reduced its take from South Bay Aqueduct by 5 TAF/year while extracting 7 TAF/year.

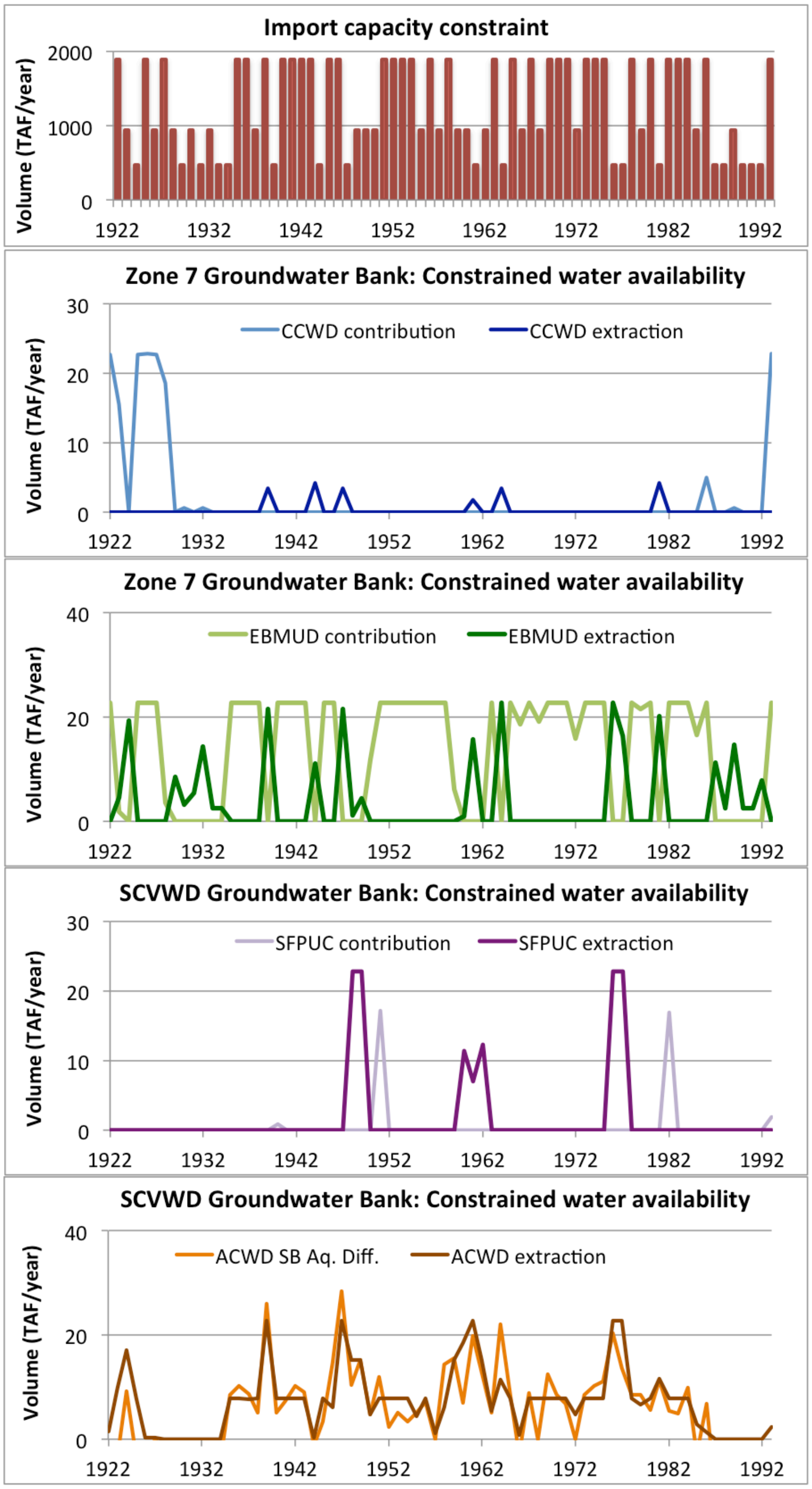


Figure 3-4. Groundwater banking contributions and extractions under constrained water availability.

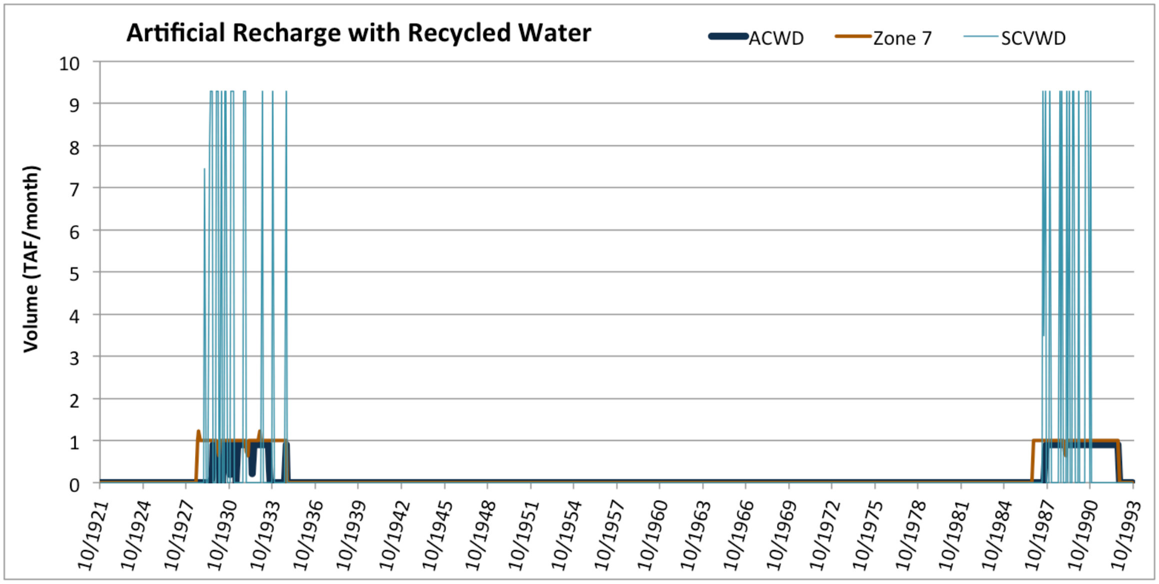


Figure 3-5. Recharge for indirect potable reuse under constrained water availability.

Under constrained water availability, all agencies with access to indirect potable reuse employed it as a source during long droughts. Figure 3-5 shows ACWD, Zone 7, and SCVWD recharging their aquifers with recycled water during the droughts of WY 1929-1934 and WY 1987-1992. SCVWD had a large maximum recycled water recharge capacity (100 MGD), so the supply was switched on and off to meet short-term demands. ACWD and Zone 7 had smaller maximum recycled water recharge capacities, and so they tended to use this supply in a steadier, longer-term fashion.

The intermittent or short-term use of a capital-intensive supply like recycled water or desalination is a consequence of CALVIN only modeling variable costs. A two-stage model allowing decisions on investing in infrastructure would be required to more accurately optimize the use of these types of supplies (but at CALVIN's scale, the computational challenges of a two-stage model would be immense). However, while the model does not mimic realistic operations of capital-intensive supplies, it does show when and how often these types of supplies might be valuable.

3.3.3 Operation of Aquifers

Table 3-6 and Figures 3-6 to 3-7 show how acting as a groundwater bank affected Zone 7's operation of Livermore Valley Aquifer. Zone 7's average groundwater pumping rate approximately doubled due to banking operations, under both historical and constrained water availability conditions.

Table 3-6. Zone 7's Livermore Valley Aquifer operations: Average volumes (TAF/year).

	Historical water availability		Constrained Bay Area imports	
Runs:	Base	HE	CC	CE
Baseline groundwater inflows	15.6	15.6	15.6	15.6
Recharge by host	0	0	0.6	2.0
Recharge by others	-	22.8	-	15.8
Total Recharge	**15.6**	**38.4**	**16.2**	**33.4**
Pumping by host	15.6	38.4	16.1	29.4
Pumping by others	-	0	-	3.9
Total Pumping	**15.6**	**38.4**	**16.1**	**33.3**
Runs: historical (H) and constrained (C) conditions with current (C) and expanded (E) infrastructure				

Minor discrepancies in totals due to rounding.

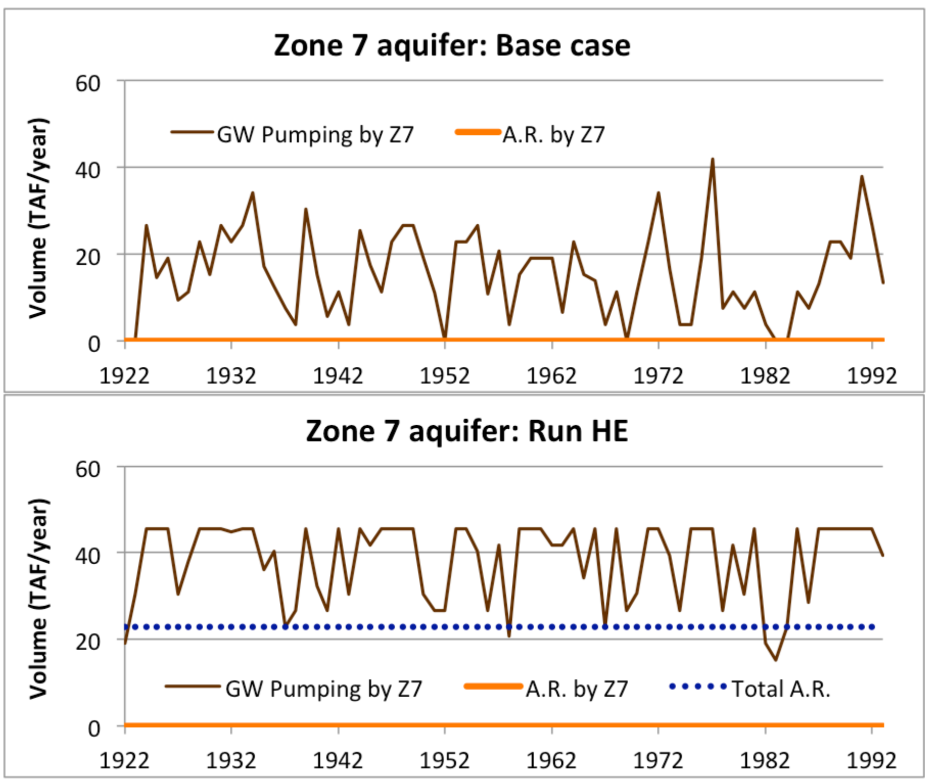


Figure 3-6. Zone 7 groundwater pumping and recharge under historical water availability.

In the base case, Zone 7 limited its groundwater pumping to natural recharge levels, and did not perform any artificial recharge. When groundwater banking was allowed under historical water availability, the aquifer received a steady contribution of less expensive surface water from EBMUD. The recharge influx allowed Zone 7 to increase its groundwater pumping by nearly 250% on average. Zone 7's groundwater pumping operations did not change much beyond having the baseline shift up about 20 TAF/year, although that did result in hitting maximum pumping capacity regularly (which never occurred in the base case).

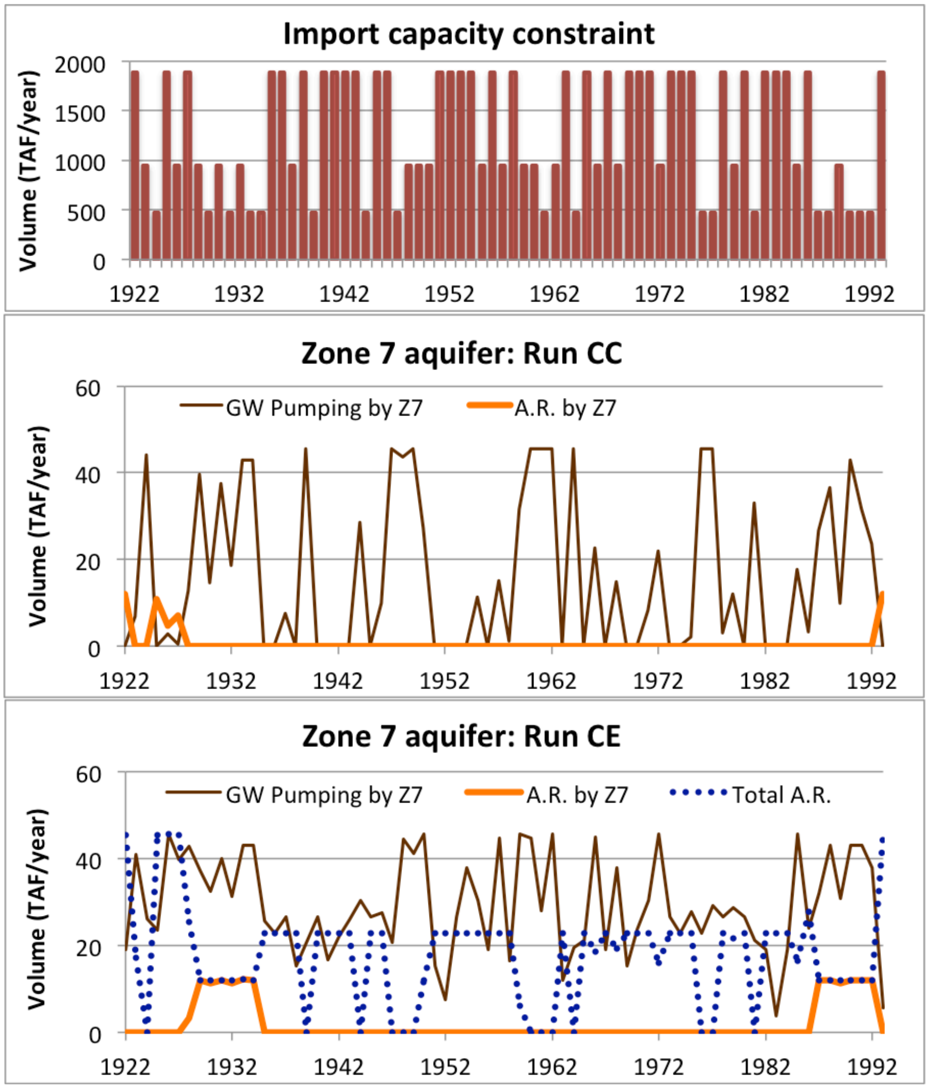


Figure 3-7. Zone 7 groundwater pumping and recharge under constrained water availability.

Under constrained water availability conditions, Zone 7 treated groundwater as an emergency supply. The agency increased groundwater pumping during scarce water periods, and shifted to other supplies when water was more plentiful. Zone 7 employed a small amount of artificial recharge, but mainly relied on natural recharge to replenish the aquifer. Expanding infrastructure to allow banking and recharge with recycled water led to increases in Zone 7's pumping even though other agencies were now competing for scarcer supplies. Between the contributions from other agencies when import supplies were plentiful and indirect potable reuse during long droughts, Zone 7 did not have to curtail pumping as much between water-scarce periods. However, Zone 7 also no longer pumped as heavily during some dry periods, due to the competing needs of other agencies.

Table 3-7 and Figures 3-8 to 3-9 show how serving as a groundwater bank affected SCVWD's operation of Santa Clara Valley Aquifer. SCVWD's average groundwater pumping increased

15% when infrastructure was expanded with historical water availability. When water supplies were constrained, the expanded infrastructure led to slightly less groundwater pumping by SCVWD.

Table 3-7. SCVWD's Santa Clara Valley Aquifer operations: Average volumes (TAF/year).

	Historic water availability		Constrained Bay Area imports	
Runs:	**Base**	**HE**	**CC**	**CE**
Baseline groundwater inflows	83	83	83	83
Recharge by host	0	0	13	20
Recharge by others	-	17	-	0.5
Total Recharge	**83**	**100**	**96**	**103**
Pumping by host	83	96	96	94
Pumping by others*	-	4	-	9
Total Pumping	**83**	**100**	**96**	**103**

Runs: historical (H) and constrained (C) conditions with current (C) and expanded (E) infrastructure

Minor discrepancies in totals due to rounding.

*In exchange for extractions, ACWD contributes to SCVWD by reducing its take from South Bay Aqueduct: 4 TAF/year in Run HE and 5 TAF/year in Run CE.

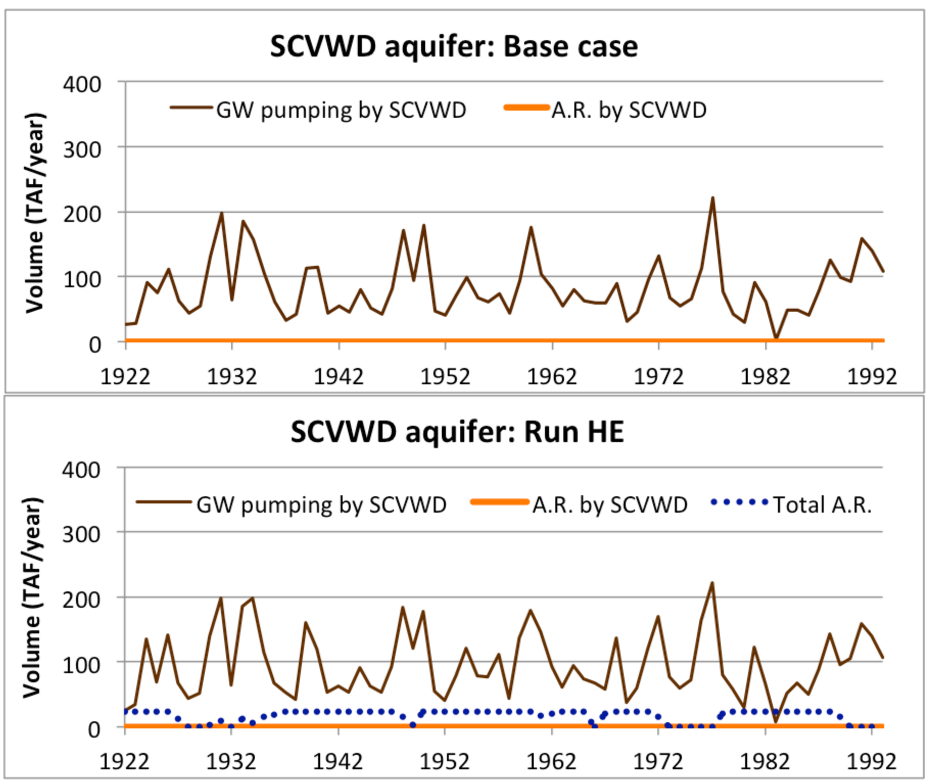


Figure 3-8. SCVWD groundwater pumping and recharge under historical water availability.

In the base case, SCVWD limited its groundwater pumping to natural recharge levels, and did not employ artificial recharge. When groundwater banking was allowed under historical water availability, the aquifer received intermittent contributions of less expensive surface water from SFPUC. The recharge influx allowed SCVWD to increase its groundwater pumping by 15% on average. SCVWD's groundwater pumping operations did not change much beyond occasionally increasing its dry-period pumping relative to the base case. SCVWD's groundwater pumping was probably modulated by competition from ACWD; if ACWD did not have access to the aquifer, SCVWD's pumping would likely have increased even more.

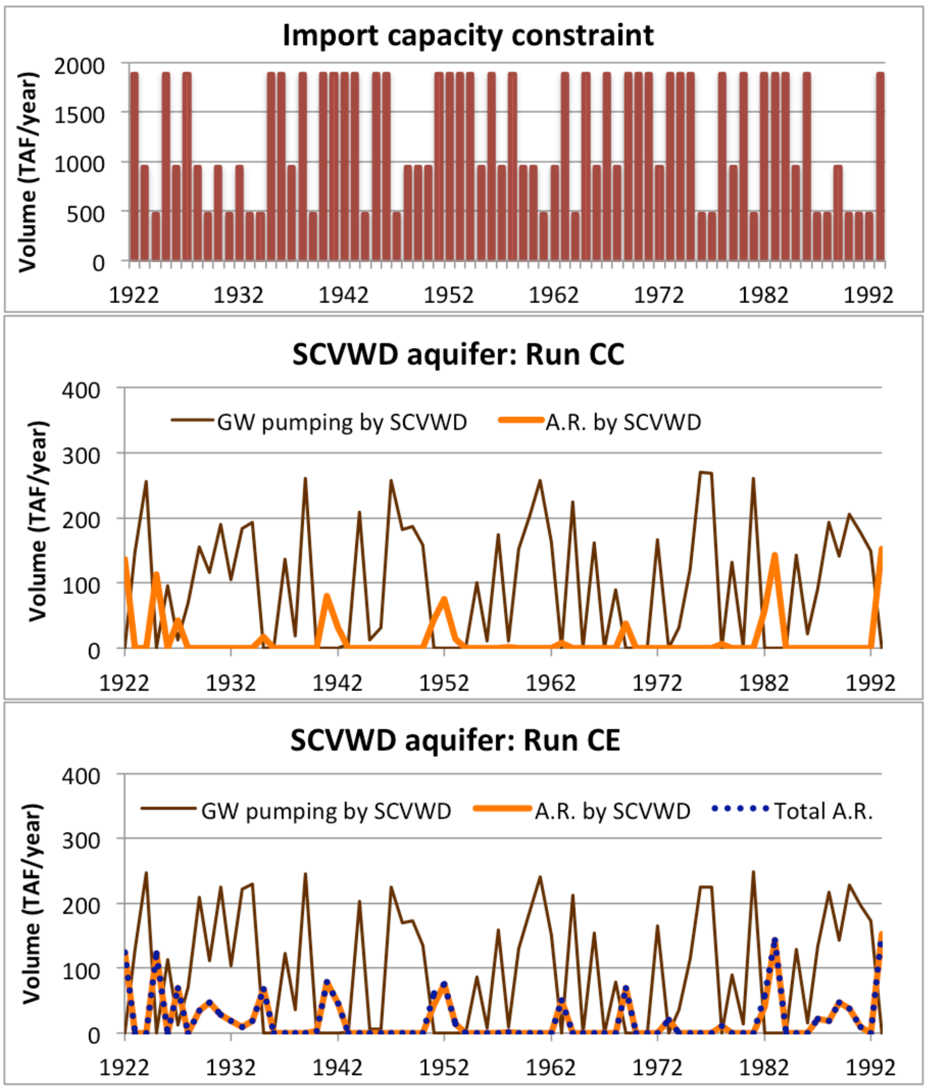


Figure 3-9. SCVWD groundwater pumping and recharge under constrained water availability.

With constrained water availability, SCVWD treated groundwater as an emergency supply, as had Zone 7. SCVWD increased groundwater pumping during scarce water periods, and shifted to other supplies when water was more plentiful. The agency performed some recharge, but largely relied on natural recharge to build stores back up. When infrastructure was expanded to allow banking and recharge with recycled water, SCVWD shifted to being slightly more of a supplier, with other agencies pumping more than they contributed. SCVWD's recharge rate increased, mainly due to activating indirect potable reuse during long droughts, and its pumping decreased slightly as other agencies were now competing for scarcer supplies. Overall, SCVWD's operations did not change much with the additional infrastructure (perhaps in part because the scale of its operations eclipse the groundwater banking infrastructure capacity). Pumping increased slightly during long droughts because of the new supply provided by indirect potable reuse. Pumping decreased slightly during shorter periods of scarcity due to the competing needs of other agencies.

3.4 Regional Supply Reliability

Figure 3-10 shows the effect of the expanded infrastructure (plus the broader system re-operation) on the Bay Area's water supply.

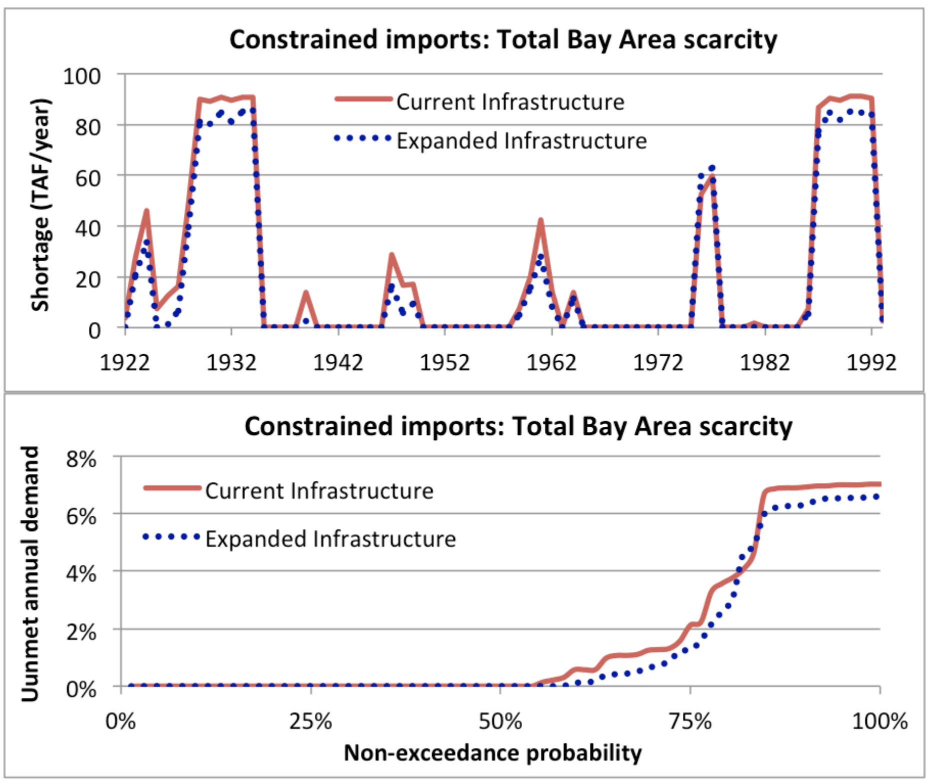


Figure 3-10. Effect of expanded infrastructure on Bay Area water supply.

Groundwater banking and indirect potable reuse were useful for different aspects of scarcity reduction. Indirect potable reuse was only employed during long droughts (Figure 3-5), and served to reduce extreme scarcity. Meanwhile, the groundwater banking reduced short-term moderate scarcity. In combination, regional groundwater banking and indirect potable reuse reduced water scarcity in the Bay Area by 14% on average and by 6% during droughts.

4 LOCAL AGENCY RESULTS

This section presents how the constrained imports and expanded infrastructure affect each agency. Optimized portfolios and their costs under average conditions are shown for the set of scenarios. Drought-period portfolios and costs are briefly discussed (associated figures and tables are in the Appendix). Impacts to supply reliability and willingness to pay for supply and additional infrastructure are also evaluated for each agency. The marginal willingness-to-pay (mWTP), or marginal value (MV), is the value of increasing supply or capacity by one unit, i.e., 1 TAF/month. The annual maximum mWTPs, or MVs, were calculated using the greatest monthly value that occurred in a year, resulting in a time series that reflects the greatest need (either due to scarcity or cost of other supply options) in a given year.

A caveat on interpretation of results is necessary given CAVLIN's limitations. In some cases these modeling results are likely to be optimistic, as internal distribution constraints and institutional constraints may further limit operational flexibility. Additionally, the model is not able to constrain withdrawals to be equal or less than water deposits, as an actual groundwater bank might operate. However, the results still can indicate the potential value of the proposed infrastructure, as well as the benefit of pooling resources in this manner, even if more realistic operations cannot be modeled. Perhaps more importantly, the model results can indicate if there is no value in the proposed infrastructure, due to excess existing capacity, limited supplies, or lack of storage.

4.1 Summary

Table 4.1 presents a results summary for the local agencies across the model runs. Total cost, shortage vulnerability, supply reliability, marginal willingness-to-pay for supply, and marginal value of expanded infrastructure are shown for each agency. The total cost was calculated as the average annual operation and scarcity costs across the 72 years. It should be noted that the operation cost did not represent the full operating costs of an agency; rather, the operation cost only accounted for variable costs, and only for operations represented in the model. The vulnerability performance metric was defined as annual average shortage divided by annual water demand (Loucks and van Beek 2005). The reliability performance metric was defined as the percent of time water demand was fully supplied (McMahon et al. 2006). The marginal value of expanded infrastructure was the value of increasing capacity by one unit.

Table 4-1. Local agencies results summary.

Agency	Result	Base	HE	CC	CE
ACWD*	Total cost ($M/yr)	$60	$53	$70	$61
	Vulnerability (percent of demand unmet)	0%	0%	1.9%	1.4%
	Reliability (percent of months demand met)	100%	100%	64%	74%
	Max. MV of groundwater bank extraction ($/AF)	$116	$1	$838	$637
	Max. MV of recharge with recycled water ($/AF)	$0	$0	$122	$15
CCWD	Total cost ($M/yr)	$88	$88	$97	$99
	Vulnerability (percent of demand unmet)	0%	0%	0%	0%
	Reliability (percent of months demand met)	100%	100%	100%	100%
	Max. MV of groundwater bank extraction ($/AF)	$0	$0	$574	$1
	Max. MV of groundwater bank contribution ($/AF)	$112	$0	$1,252	$758
EBMUD	Total cost ($M/yr)	$66	$72	$92	$91
	Vulnerability (percent of demand unmet)	0%	0%	2.7%	2.4%
	Reliability (percent of months demand met)	100%	100%	69%	72%
	Max. MV of groundwater bank extraction ($/AF)	$0	$0	$557	$383
	Max. MV of groundwater bank contribution ($/AF)	$401	$71	$1,138	$363
SFPUC	Total cost ($M/yr)	$44	$46	$79	$72
	Vulnerability (percent of demand unmet)	0%	0%	2.8%	2.5%
	Reliability (percent of months demand met)	100%	100%	61%	65%
	Max. MV of groundwater bank extraction ($/AF)	$0	$0	$653	$460
	Max. MV of groundwater bank contribution ($/AF)	$438	$339	$436	$19
SCVWD**	Total cost ($M/yr)	$137	$133	$180	$184
	Vulnerability (percent of demand unmet)	0%	0%	1.0%	0.8%
	Reliability (percent of months demand met)	100%	100%	82%	83%
	Max. MV of groundwater pumping ($/AF)	$19	$21	$200	$744
	Max. MV of artificial recharge ($/AF)	$0	$0	$17	$19
Zone 7**	Total cost ($M/yr)	$42	$47	$45	$53
	Vulnerability (percent of demand unmet)	0%	0%	1.6%	1.5%
	Reliability (percent of months demand met)	100%	100%	76%	79%
	Max. MV of groundwater pumping ($/AF)	$24	$42	$1,114	$1,180
	Max. MV of artificial recharge ($/AF)	$0	$90	$140	$90
Runs: historical (H) and constrained (C) conditions with current (C) and expanded (E) infrastructure; MV – marginal value					

*No explicit representation of ACWD groundwater bank contribution because ACWD was served upstream of SCVWD along the same aqueduct. ACWD contributed to SCVWD's aquifer by taking less water from the aqueduct.
**Maximum marginal values of expanding recharge with recycled water were omitted for SCVWD and Zone 7 because the values were all zero due to oversized capacity in model.

The expanded infrastructure had varying effects on agencies' total costs (Table 4.1). The magnitude and direction of cost shifts resulted from the interplay of existing sources, new sources, and additional potential demands on supply (from newly intertied agencies). Several agencies experienced consistent shifts due to expanded infrastructure. ACWD's access to cheaper water reduced overall costs while Zone 7 saw their costs increase due to greater demand for their water. The rest of the agencies had more complicated cost shifts that depended on whether or not imports were constrained. The inequality in distribution of costs and benefits amongst the agencies largely resulted from using an optimization model with the objective of minimizing total system-wide costs and that lacks operational policy rules. Under standard groundwater banking operations, withdrawals would be limited to deposits (minus losses), and no agency could claim the contributions of other agencies to their detriment (although they might buy and sell stored water).

None of the agencies were vulnerable to shortages under historical water availability (Table 4.1). Constrained imports induced scarcity in all water agencies (except CCWD, which was buffered by its excess intake capacity). Groundwater banking and indirect potable reuse reduced vulnerability for all agencies facing scarcity. Some benefited more than others because of the lack of operational policy constraints on groundwater banking and because of system re-operation to reduce worst scarcity.

All agencies experienced 100% supply reliability under historical water availability (Table 4.1), meaning all of their water demands were met through some economically efficient combination of sources. Constrained imports reduced supply reliability for all agencies except CCWD. Groundwater banking improved supply reliability, mainly during short periods of moderate scarcity. Meanwhile, indirect potable reuse served to reduce severity of shortages but did not improve supply reliability by this performance metric. Indirect potable reuse was too expensive to fully displace scarcity in an economically efficient manner.

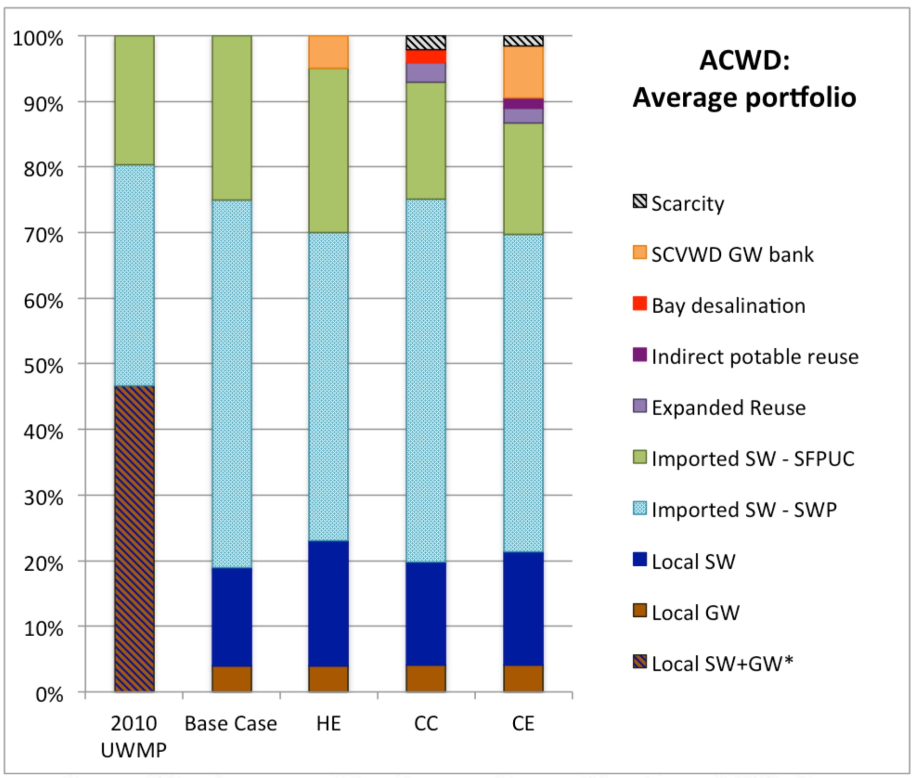
The maximum marginal value of expanding access to groundwater (both for extraction and contribution/recharge) ranged from zero to several hundred dollars per acre-foot under historical water availability. The expanded infrastructure was generally not valuable to the Bay Area under these conditions, although it was valuable for decreasing the Bay Area's take of South-of-Delta imports to reduce statewide scarcity. When imports were constrained, the maximum marginal value of expanding access to groundwater generally ranged from several hundred dollars per acre-foot to over a thousand dollars per acre-foot. The results suggest the groundwater banking infrastructure is valuable to the Bay Area water agencies under scarce conditions.

Maximum marginal value of expanding capacity to recharge aquifer with recycled water: Indirect potable reuse was not used by any agency under historical water availability conditions, so the marginal value of expanding capacity to recharge aquifer with recycled water was zero. When imports were constrained, all agencies with indirect potable reuse employed it. However, the modeled capacity was oversized for SCVWD and Zone 7 (100 and 30 MGD respectively), so there was no value in expanding it. Interestingly, the marginal value of introducing indirect potable reuse (i.e., expanding from 0 TAF/month to 1 TAF/month) was zero for SCVWD and Zone 7 under constrained imports. This suggests that SCVWD and Zone 7 would not have employed indirect potable reuse without the additional demands on their aquifer that came with hosting groundwater banks.

4.2 Alameda County Water District (ACWD)

Supply Portfolio

Figure 4-1 shows ACWD's actual supply portfolio and the average optimized portfolios for the modeled scenarios. ACWD's recent average supply portfolio was obtained from the agency's 2010 Urban Water Management Plan (UWMP). ACWD meets nearly half its water supply needs with local supplies. The rest of it supply comes from State Water Project (SWP) imports through the Delta and Sierra imports provided by SFPUC. Local surface water (SW) and groundwater (GW) are shown as combined in this portfolio because of how ACWD reports its water use. The agency uses local runoff from Alameda Creek watershed to replenish its aquifer, and counts the subsequent supply as groundwater use. Unfortunately, due to lack of available data, this local surface water and groundwater are not represented in the model, leading to an underestimate of ACWD's local supplies. In the model, the aquifer is treated as storage, not as a supply (except for incidental recharge from exterior urban water use). Another source of local surface water, Lake del Valle, is, however, represented.



Runs: historical (H) and constrained (C) conditions with current (C) and expanded (E) infrastructure

Figure 4-1. ACWD average supply portfolio.

In the base case, ACWD relied mainly on SWP imports, supplementing with local surface water and deliveries from SFPUC (Figure 4-1). When infrastructure was expanded under historical water availability conditions, ACWD reduced its own banking of SWP water and shifted to extracting from SCVWD's aquifer, to save on operating costs (Table 4-1). ACWD's groundwater treatment was more expensive than SCVWD's because of past saltwater intrusion resulting in additional demineralization costs (ACWD 2010 UWMP). When SWP imports were reduced, local surface water became a larger fraction of the water delivered by South Bay Aqueduct, also lowering operational costs.

Table 4-2. ACWD average costs ($M/year).

	Historic water availability		Constrained Bay Area imports	
Runs:	**Base**	**HE**	**CC**	**CE**
ACWD Scarcity Costs	$0	$0	$2.5	$1.8
ACWD Operating Costs	$60	$53	$67	$59
Total Cost	**$60**	**$53**	**$70**	**$61**
Runs: historical (H) and constrained (C) conditions with current (C) and expanded (E) infrastructure				

When imports were constrained, the main impact on ACWD's supply was a reduction in SFPUC deliveries (Figure 4-1). This loss resulted in the use of more expensive supplies, as well as some scarcity, driving up both scarcity and operating costs (Table 4-1). Expanding the infrastructure improved ACWD's supply options. The agency used both groundwater from SCVWD's aquifer and its own groundwater from recharge with recycled water, allowing it to drop the extremely expensive desalination and reduce scarcity (Table 4-1).

During droughts under constrained import conditions, ACWD's supplies from SWP and SFPUC were more limited, leading to significant use of expensive supplies (non-potable reuse and desalination), as well as greater scarcity, driving up the total cost (Figure 7-1 and Table 7-1 in Appendix). Expanding infrastructure allowed replacement of desalination, the most expensive supply option, with indirect potable reuse and groundwater extractions from SCVWD. However, those operational cost savings were more than offset by reduced SFPUC supplies, replaced by more expensive SWP supplies. Scarcity cost decreased slightly, but the total cost increased due to operational costs.

Supply Reliability and Willingness-To-Pay

Figure 4-2 shows ACWD's shortage levels under constrained import conditions with and without groundwater banking and indirect potable reuse. The expanded infrastructure reduced shortages during all water-scarce periods except the short, but extreme, drought (WYs 1976-1977). During the short drought, the pumping capacity limited how much groundwater the agencies (SCVWD, ACWD, and SFPUC) could extract from SCVWD's aquifer. Otherwise, groundwater banking reduced short-term moderate shortages, while indirect potable reuse reduced shortages during the long droughts. The non-exeedance plot shows the same trend, a general reduction in shortage level except for the moderate shortage that occurred from the WYs 1976-1977 drought.

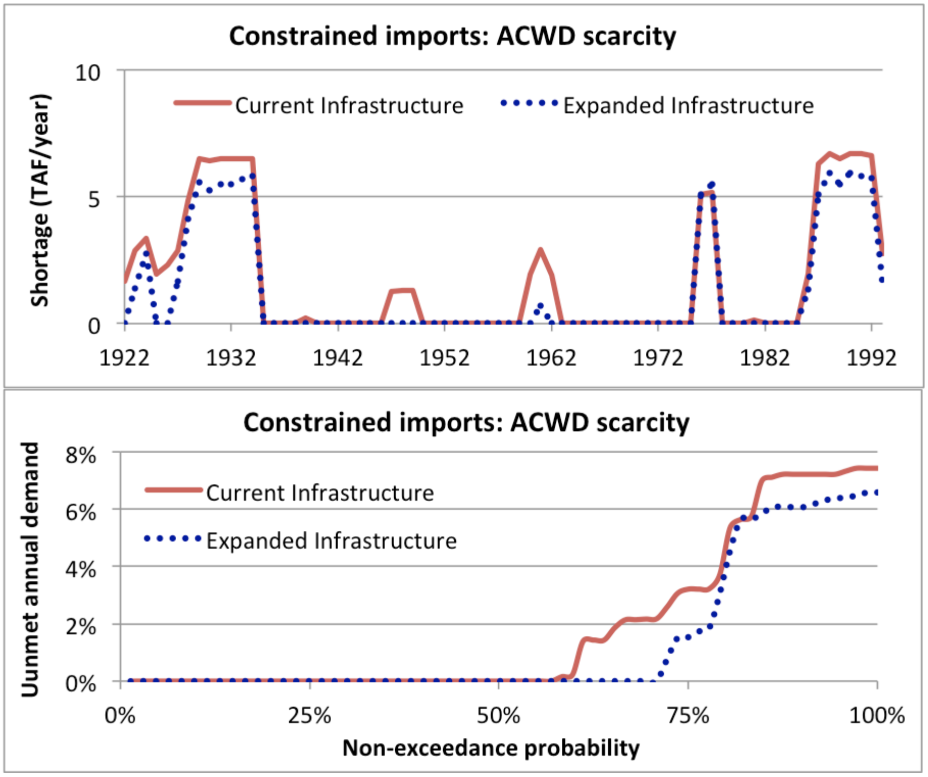
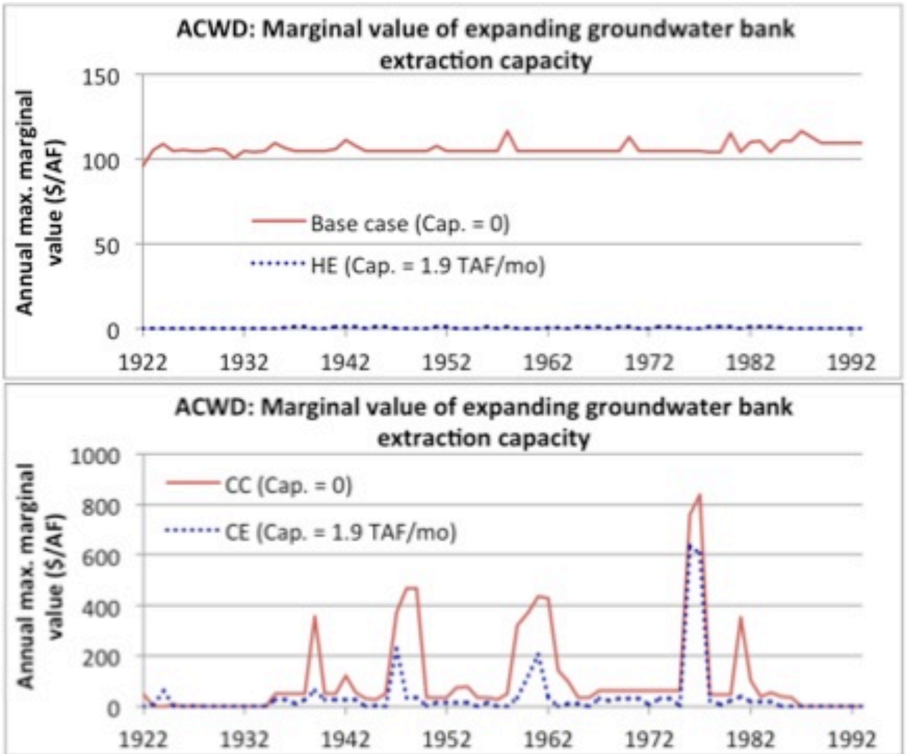


Figure 4-2. ACWD unmet demands.

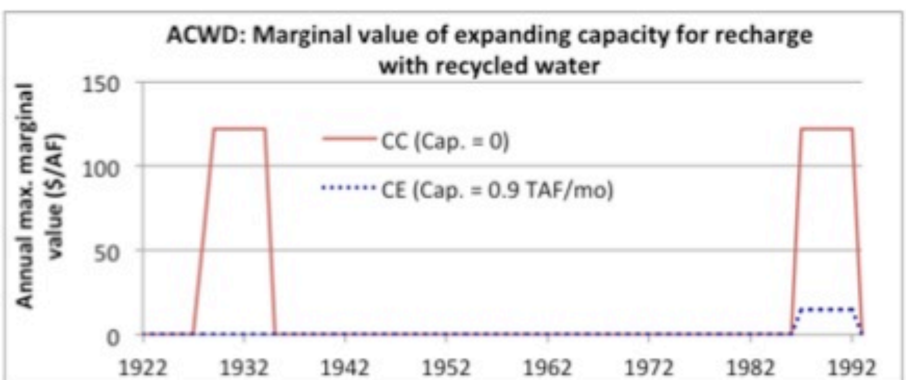
Figure 4-3 shows ACWD's annual maximum willingness-to-pay to expand access to the groundwater bank. In the base case, expanding the access to SCVWD's aquifer from no access to 1 TAF/month was consistently worth around $100/AF. When ACWD has 1.9 TAF/month extraction capacity in run HE, the marginal value of expanding the capacity was around $1/AF, so there was almost no value in expanding capacity further. This was consistent with ACWD operations in the HE run; it used SCVWD's aquifer regularly as a small replacement supply for its SWP imports. With constrained imports, the marginal value of groundwater bank access increased greatly during periods of shortage. In both runs, the marginal value of expanding bank access drops between periods of scarcity, because the water was more valuable being stored for future, more pressing needs, than being used immediately by ACWD.

Figure 4-4 shows the annual maximum marginal value of expanding ACWD's capacity for recharge with recycled water. The marginal value of expanding indirect potable reuse (IPR) under historical water availability was consistently zero, so it was not plotted. In run CC, expanding IPR has value only during the two long droughts. Increasing the recycled water recharge capacity from zero to 1 TAF/month was worth $122/AF during these droughts. In run CE, the IPR capacity is 0.9 TAF/month, and the marginal value to expand capacity was only $15/AF during the second drought, and zero the rest of the time. Basically, there was no value in further expanding IPR past 0.9 TAF/month (10 MGD).



Runs: historical (H) and constrained (C) conditions with current (C) and expanded (E) infrastructure

Figure 4-3. Marginal value of expanding ACWD's groundwater bank extraction capacity.



Runs: constrained (C) conditions with current (C) and expanded (E) infrastructure

Figure 4-4. Marginal value of expanding ACWD's indirect potable reuse capacity.

Conclusion

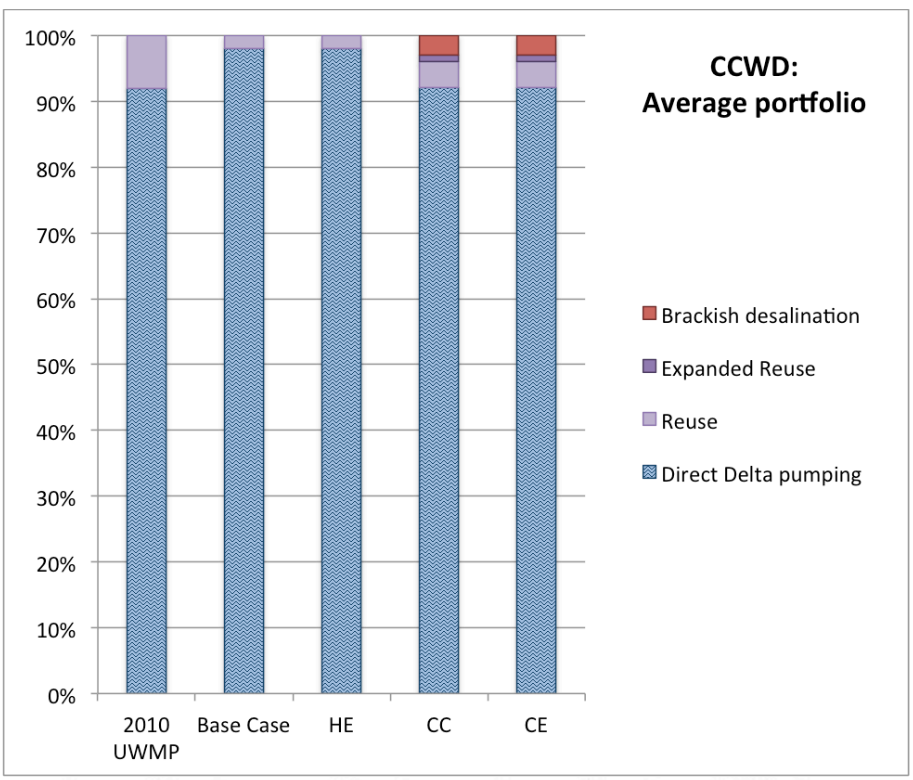
The model results indicated that expanding the infrastructure improved ACWD's supply options and reduced vulnerability to scarcity. Groundwater banking with SCVWD improved supply reliability for moderate scarcity conditions, while indirect potable reuse improved supply reliability for more intense scarcity conditions.

While the model overestimated ACWD's reliance on SWP water as providing just over half its supply, the agency does rely on through-Delta imports for a third of its supply. This reliance leaves the agency vulnerable to Delta pumping restrictions and salinity problems from sudden catastrophic levee failure or long-term sea level rise. In a short-term emergency, ACWD could potentially rely on its local storage (but it is relatively small) and be supplied additional water by SFPUC. But under long-term reductions in SWP imports (or SFPUC deliveries), increased water recycling, including indirect potable reuse, and participating in groundwater banking with a neighboring agency could be an economically sensible way to reduce scarcity.

4.3 Contra Costa Water District (CCWD)

Supply Portfolio

Figure 4-5 shows CCWD's actual supply portfolio (CCWD 2010 UWMP) and the average optimized portfolios for the modeled scenarios. CCWD obtains over 90% of its supply directly from the Delta, using intakes in four locations. The intakes are operated based on relative costs and local salinity conditions, as well as regulatory prescriptions. The remaining supply comes from water reuse, mainly at industrial sites, and a minor amount of local well water. Additionally, an intertie between CCWD and EBMUD can be used for water transfers. The model underestimates the recycled water use because of its expense relative to Delta pumping; however, it does include some water reuse as part of the baseline optimized portfolio.



Runs: historical (H) and constrained (C) conditions with current (C) and expanded (E) infrastructure

Figure 4-5. CCWD average supply portfolio.

Table 4-3. CCWD average costs ($M/year).

	Historic water availability		Constrained Bay Area imports	
Runs:	Baseline	HE	CC	CE
CCWD Scarcity Costs	$0	$0	$0	$0
CCWD Operating Costs	$88	$88	$97	$99
Total Cost	**$88**	**$88**	**$97**	**$99**
Runs: historical (H) and constrained (C) conditions with current (C) and expanded (E) infrastructure				

In the base case, CCWD relied on direct Delta pumping for 98% of its supply on average, with the remainder provided by reclaimed water. Expanding infrastructure to include groundwater banking with Zone 7 water agency did not change CCWD's optimal portfolio or costs (Table 4-2). The groundwater bank was not used because direct pumping from the Delta was cheaper and did not hit capacity constraints under historical water availability conditions.

When direct Delta pumping was constrained, CCWD increased its use of recycled water and introduced brackish desalination as a supplemental supply. However, given CCWD's large excess pumping capacity[5], the modeled constraints were not as binding as they were for other agencies. As a result, CCWD still relied heavily on Delta pumping, it did not incur any scarcity, and its average costs did not increase as much as other agencies under the constrained water availability scenario. Expanding the infrastructure did not change CCWD's optimal supply portfolio, but did increase its operation costs. Access to a groundwater bank resulted in CCWD contributing a small amount of water and withdrawing an even smaller amount. Because CCWD's supply needs were less pressing than the other agencies participating in the Zone 7 groundwater bank, it mainly supplemented with more expensive brackish desalination after it had hit its water recycling capacity.

During droughts, CCWD expanded its use of the more expensive options as Delta pumping was reduced to 80% of its supply (Figure 7-2 in Appendix). In particular, its use of brackish desalination for 12% of its supply drove up operation costs (Table 7-2 in Appendix). However, despite being driven to more expensive supply options, it still incurred no scarcity.

Supply Reliability and Willingness-To-Pay

The supply was 100% reliable in these scenarios because the modeled constraints had limited impact on CCWD due the agency's excess pumping capacity. Given CCWD's dependence on the Delta, a better way to test their supply reliability under water scarce conditions would be to model salinity-induced pumping limitations (e.g., cease Delta pumping during low-flow periods in dry years).

[5] It is worth noting that one of the reasons CCWD has such excessive capacity is that operations in the Delta are already constrained by water quality and regulations that effectively reduce the time and quantity available far below intake capacity.

Figure 4-6 shows CCWD's annual maximum willingness-to-pay to expand access to the groundwater bank under constrained water conditions. (No plot is shown for historical water availability because there was no value in expanding access.) In run CC, the maximum WTP to expand access to Zone 7's aquifer from no access to 1 TAF/month was zero most of the time, but, during several periods of short-term scarcity, the marginal value increased to approximately $500/AF. During short periods of scarcity, other agencies had less need for groundwater from Zone 7, and so it was a viable source for CCWD. When CCWD had 1.9 TAF/month extracting capacity in run CE, the marginal value of expanding the capacity was zero, so there was no value in expanding capacity further.

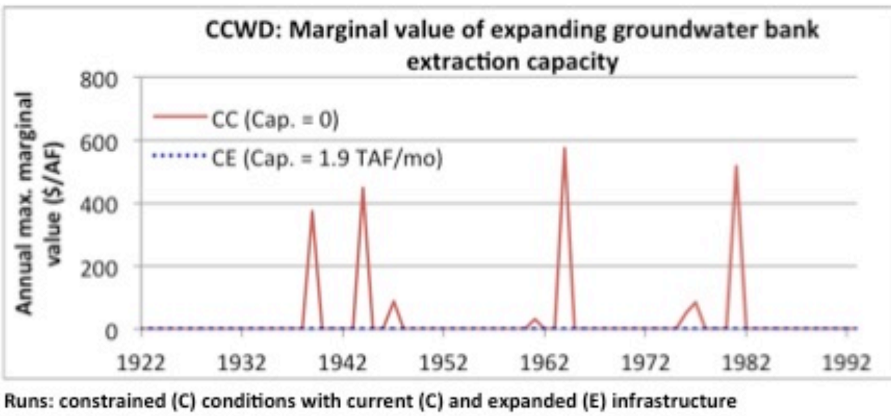


Figure 4-6. Marginal value of expanding CCWD's groundwater bank extraction capacity.

Figure 4-7 shows the annual maximum marginal value of expanding CCWD's capacity for contributing to Zone 7's aquifer. In the base case, expanding the contribution capacity from zero to 1 TAF/month was consistently worth around $90/AF; Zone 7 would have benefited from the additional supplies. When CCWD had 1.9 TAF/month contributing capacity in run HE, the marginal value of expanding the capacity was zero. In run HE, no groundwater bank contributions were made by CCWD, because Zone 7 had access to less expensive water from EBMUD. With constrained imports, the marginal value of CCWD's groundwater bank contributions increased greatly during periods of shortage. In run CC, the maximum WTP to expand contributions to the aquifer from zero to 1 TAF/month was over $1,000/AF. CCWD's contributions leading up to and during long droughts would have been valuable to Zone 7. In run CE, the maximum WTP to expand contribution capacity to Zone 7's aquifer from 1.9 TAF/month to 2.9 TAF/month was around $750/AF, but was zero most of the time, reflecting Zone 7's gain of EBMUD as a source.

The U.S. Bureau of Reclamation is considering further expansion[6] of CCWD's Los Vaqueros Reservoir as a way to reduce Bay Area water supply vulnerability (Los Vaqueros Reservoir Expansion Project EIS/EIR 2010). An option under evaluation is an expansion to 275 TAF coupled with building a connection to South Bay reservoirs. The marginal value of expanding

[6] CCWD expanded Los Vaqueros Reservoir from 100 TAF to 160 TAF in 2012 to improve the district's supply reliability. Further expansion is being considered to improve regional supply reliability and increase Delta operational flexibility (http://www.water.ca.gov/storage/losvaq/).

Los Vaqueros Reservoir was evaluated to see if the groundwater banking affected the value of reservoir expansion. Figure 4-8 shows marginal value of expanding Los Vaqueros Reservoir under constrained water availability. The marginal value of reservoir expansion was zero with historical water availability (not shown).

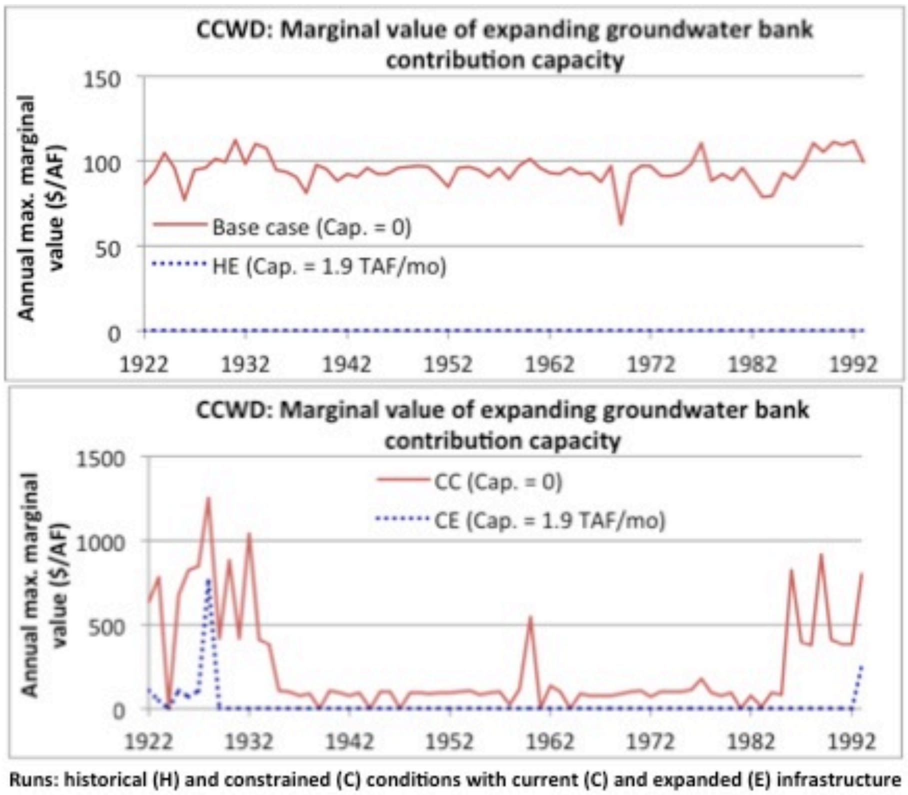


Figure 4-7. Marginal value of expanding CCWD's groundwater bank contribution capacity.

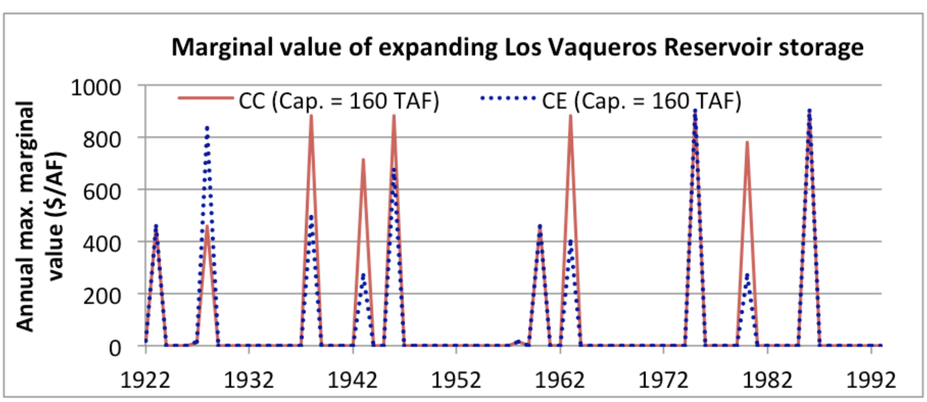


Figure 4-8. Marginal value of expanding CCWD's reservoir capacity.

Figure 4-8 shows that in ten out of 72 years expanding the reservoir (from the present size of 160 TAF) had significant value. Groundwater banking lowered the marginal value in five of those years, when CCWD was able to extract from Zone 7's aquifer (i.e., during short periods of moderate scarcity). The banking had no impact on the marginal value of reservoir expansion in four years, corresponding to periods of limited water availability when CCWD was unable to extract from Zone 7's aquifer (because other agencies' needs were greater). In one year, WY 1928, the marginal value of reservoir storage actually increased with groundwater banking, because the Bay Area was heading into a long drought and the additional reservoir storage became even more valuable when other agencies had access to it via groundwater banking contributions.

Conclusion

The modeled constrained water availability case did not induce water scarcity in CCWD, and so the results do not show if local groundwater banking would be valuable to the agency under water scarce conditions. Despite the lack of scarcity, CCWD's marginal willingness-to-pay for access to Zone 7's aquifer was $400 - $600/AF during some periods of constrained imports. Additionally, the results suggest that the proposed groundwater banking and the potential reservoir expansion do not result in a zero-sum game. They rarely compete for the same supply and the extra storage from reservoir expansion would be useful during droughts (the additional space provided by access to 'under-utilized' aquifers is simply not enough for long droughts).

Given CCWD's dependence on the Delta and limited other sources, it is highly vulnerable to Delta pumping restrictions and salinity problems from sudden catastrophic levee failure or long-term sea level rise. In a short-term emergency, CCWD could rely on its local storage (assuming it is not in a depleted state) and be supplied additional water by EBMUD. But, under long-term seasonal reductions in Delta pumping, in addition filling its own local storage, participating in groundwater banking with a neighboring agency could be an option for increasing supply reliability. Because of its different supply source/intake from the other agencies, CCWD could be complementary partner for banking or other transfers.

4.4 East Bay Municipal Utility District (EBMUD)

Supply Portfolio

Figure 4-8 shows EBMUD's actual supply portfolio (EBMUD 2010 UWMP) and the average optimized portfolios for the modeled scenarios. The vast majority of EBMUD's water supply comes from Mokelumne River watershed in the Sierras, supplemented by small amounts of local runoff. Additionally, reuse projects meet approximately 5% of service area use. In drought periods, EBMUD has a contract for supplemental water from the Sacramento River via the Freeport Regional Water Facility. The model overestimates the use of the Freeport project and underestimates the use of recycled water because the imported surface water is cheaper and the model optimizes based on variable cost economics, not policy such as drought-only restrictions.

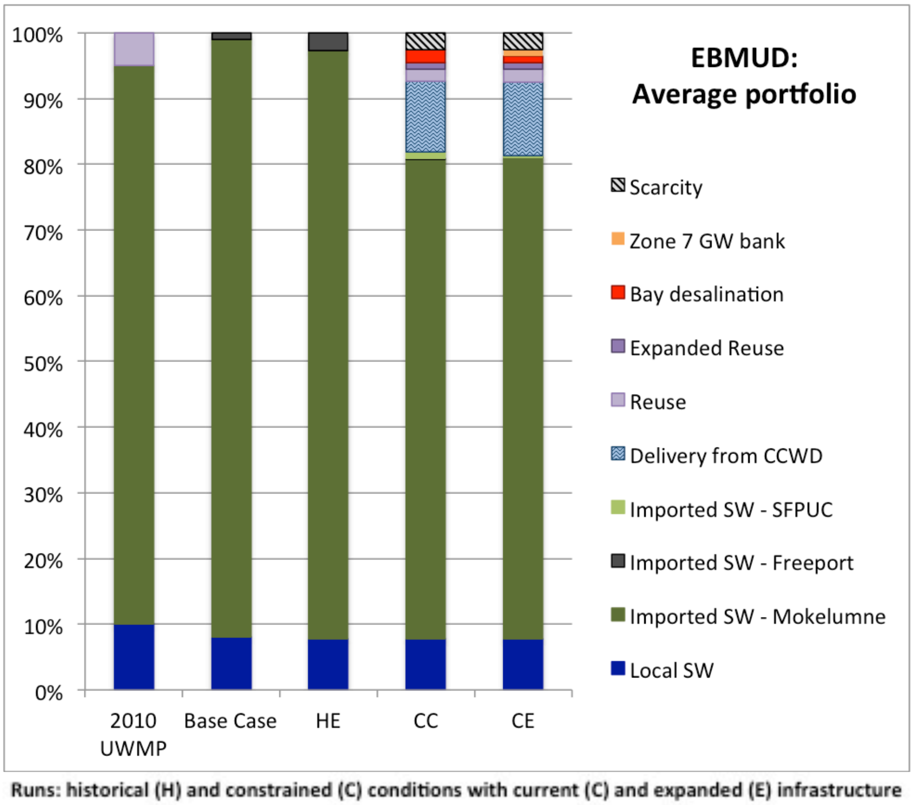


Figure 4-9. EBMUD average supply portfolio.

Table 4-4. EBMUD average costs ($M/year).

	Historic water availability		Constrained Bay Area imports	
Runs:	Baseline	HE	CC	CE
EBMUD Scarcity Costs	$0	$0	$12	$10
EBMUD Operating Costs	$66	$72	$80	$81
Total Cost	**$66**	**$72**	**$92**	**$91**
Runs: historical (H) and constrained (C) conditions with current (C) and expanded (E) infrastructure				

In the base case, EBMUD relied heavily on Mokelumne River imports, supplementing with local surface water and Sacramento River water via the Freeport facility. When infrastructure was expanded under historical water availability conditions, EBMUD increased its overall imports to contribute to Zone 7's supply. This resulted in greater use of the Freeport intake to supplement Mokelumne River supplies, raising operating costs (Table 4-3).

When imports were constrained, imports from Mokelumne River were reduced from being 90% of EBMUD's supply to being just under three-quarters of its supply on average. A sizable fraction of this loss of supply was made up by deliveries from CCWD via the EBMUD-CCWD intertie. The supply was also supplemented with small amounts of reuse, desalination, and deliveries from SFPUC. However, some scarcity was present as well; it was more economical to have scarcity than meet the remaining demand with an expensive supply like desalination. When the infrastructure was expanded, EBMUD's scarcity and operation costs were reduced as

EBMUD used groundwater banking supplies to replace some desalination (but it also lost some of SFPUC's deliveries, which were rerouted to more pressing needs).

During droughts, EBMUD's Mokelumne River imports were reduced by almost half under the constrained conditions (Figure 7-3 in Appendix). EBMUD relied heavily on deliveries from CCWD to make up a significant portion of the lost supply, but also supplemented with water recycling and desalination, and still incurred scarcity. Expanding infrastructure allowed groundwater extractions from Zone 7 to partially replace desalination and reduce scarcity slightly, lowering overall costs (Table 7-3 in Appendix).

Supply Reliability and Willingness-To-Pay

Figure 4-9 shows EBMUD's shortage levels under constrained import conditions with and without groundwater banking. The expanded infrastructure reduced shortages during short water-scarce periods, but not during longer, more intense periods of scarcity. During the drought periods, the expanded infrastructure allowed EBMUD to reduce the amount of desalination it used. Under standard groundwater bank operations, EBMUD would have benefited much more given that in the model the agency, on average, contributing 10 TAF/year more than it was extracting.

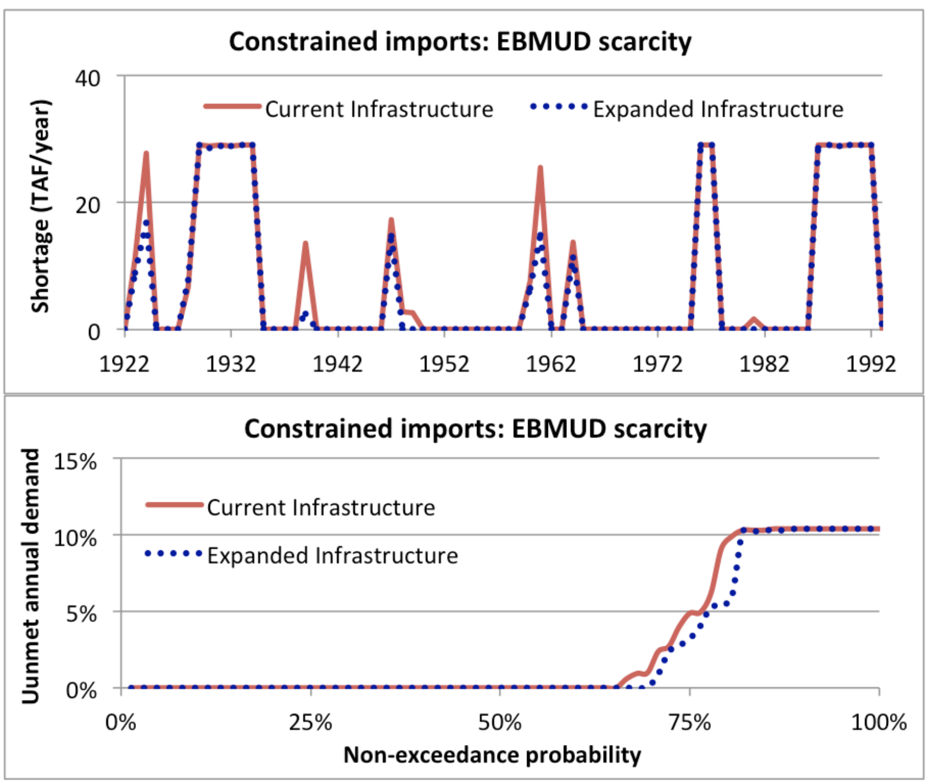


Figure 4-10. EBMUD unmet demands.

Figure 4-10 shows EBMUD's annual maximum willingness-to-pay to expand access to the groundwater bank under constrained water conditions. (No plot is shown for historical water availability because there was no value in expanding access.) For both runs, during short periods of scarcity, there was value in expanding EBMUD's groundwater bank extraction capacity. During the two longer droughts, WYs 1929-1934 and WYs 1987-1992, there was little-to-no value in expanding extraction capacity because little bank water was available to EBMUD. The rest of the time, with supplies more plentiful, there was no value in expanding capacity for a more expensive source of water.

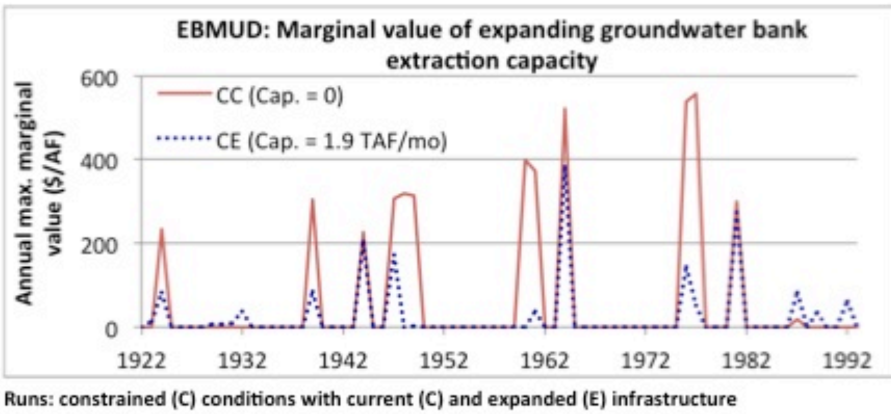


Figure 4-11. Marginal value of expanding EBMUD's groundwater bank extraction capacity.

Figure 4-11 shows the annual maximum marginal value of expanding EBMUD's capacity for contributing to Zone 7's aquifer. In the base case, expanding the contribution capacity from zero to 1 TAF/month was consistently worth around $350/AF; Zone 7 would have benefited from the additional supplies. When EBMUD had 1.9 TAF/month contribution capacity in run HE, the marginal value of expanding the capacity was around $75/AF, except during periods of scarcity, when it dropped to $50/AF.

With constrained imports, the marginal value of EBMUD's groundwater bank contributions increased greatly immediately preceding periods of shortage and dropped to zero during shortages. In run CC, the maximum WTP to expand contributions to the aquifer from zero to 1 TAF/month was over $1,000/AF just before the two long droughts. The contributions from EBMUD to Zone 7's aquifer would have been very valuable for reducing Zone 7's scarcity. In run CE, the maximum WTP to expand contribution capacity to Zone 7's aquifer from 1.9 TAF/month to 2.9 TAF/month was around $100/AF when water was not scarce, so there was some value in expanding capacity further.

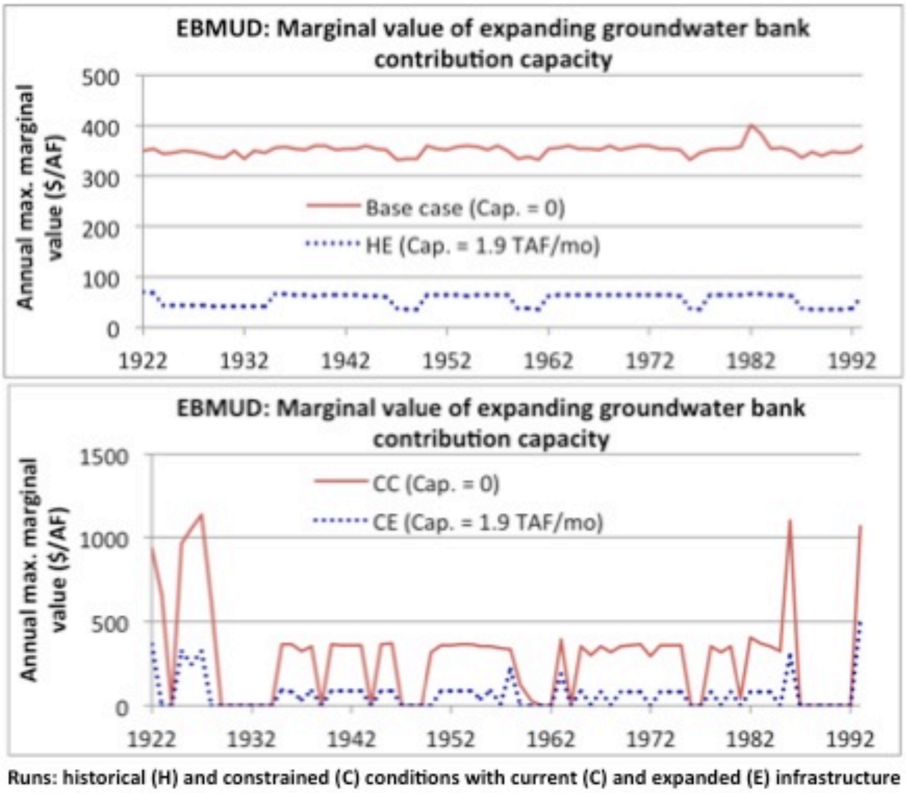


Figure 4-12. Marginal value of expanding EBMUD's groundwater bank contribution capacity.

Conclusion

The model results indicated that expanding the infrastructure improved EBMUD's supply options and reduced some vulnerability to scarcity. Because the modeled constraints induced such intense scarcity for EBMUD (due to limited excess capacity on Mokelumne Aqueduct), the agency employed significant desalination during droughts and the limited groundwater it could access from Zone 7 could only partly replace this desalination. As a result, EBMUD's drought shortages did not decrease with groundwater banking, but its operational costs decreased.

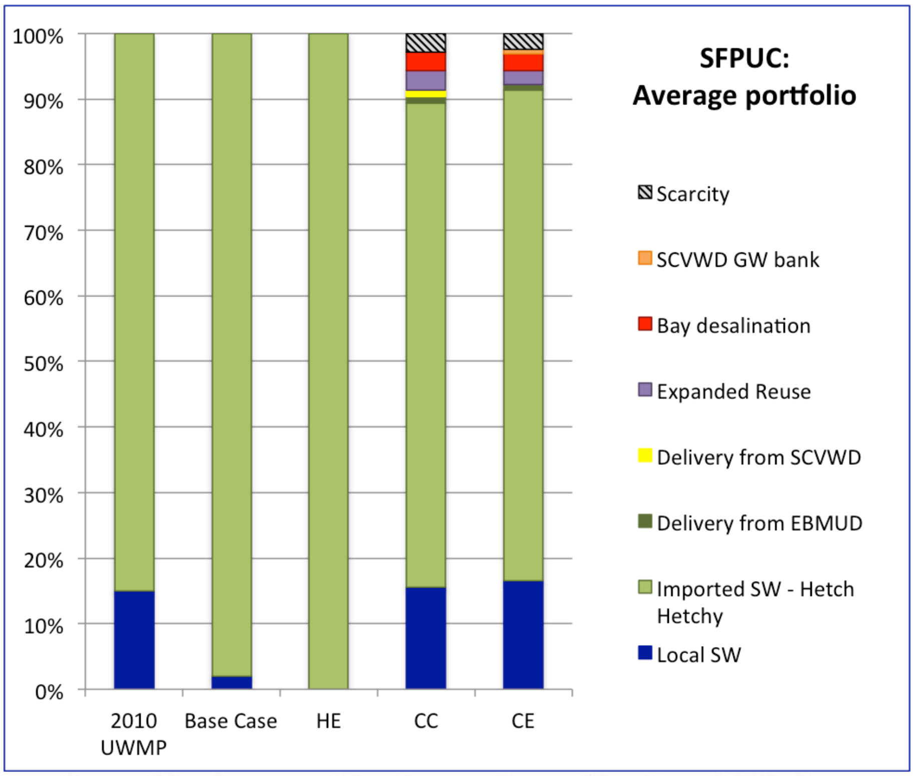
EBMUD appears to be a good candidate for participating in groundwater banking. It can potentially provide a relatively inexpensive source of water for aquifer recharge in plentiful times (although this depends on water rights and more senior rights' holders demands, as well as environmental regulations on the Mokelumne River). On the flip side, it has limited local storage and faces unmet demands or costly supply alternatives in scarce times.

EBMUD has recently initiated its own groundwater project. It developed a small groundwater facility that artificially recharges in wet years and can pump 1 MGD in dry years. This facility may be expanded up to 10 MGD, depending on the success of the pilot project. However, it is not clear how suitable the broader South East Bay Plain aquifer is as a drinking water source; concerns include historical industrial contamination and salinity intrusion (EBMUD 2013 GMP).

4.5 San Francisco Public Utility Commission (SFPUC)

Supply Portfolio

Figure 4-12 shows SFPUC's actual supply portfolio (from SFPUC's 2010 UWMP) and the average optimized portfolios for the modeled scenarios. About 85% of SFPUC's water supply is imported from Upper Tuolumne River Watershed in the Sierras via the gravity-driven Hetch Hetchy aqueduct. The remainder is from local surface waters in the Alameda and Peninsula watersheds, where SFPUC operates additional reservoirs. The model preferentially uses the Tuolumne River imports because the water, which has filtration avoidance status, cost less to treat than local runoff.



Runs: historical (H) and constrained (C) conditions with current (C) and expanded (E) infrastructure

Figure 4-13. SFPUC average supply portfolio.

Table 4-5. SFPUC average costs ($M/year).

	Historic water availability		Constrained Bay Area imports	
Runs:	**Baseline**	**HE**	**CC**	**CE**
SFPUC Scarcity Costs	$0	$0	$9.8	$8.8
SFPUC Operating Costs	$44	$46	$69	$63
Total Cost	**$44**	**$46**	**$79**	**$72**
Runs: historical (H) and constrained (C) conditions with current (C) and expanded (E) infrastructure				

In the base case, SFPUC used imported Tuolumne River water for 98% of its supply and local runoff for the rest. With expanded infrastructure, SFPUC imported additional water for contributing to SCVWD's aquifer, increasing operation costs (Table 4-4). The expanded infrastructure also allowed SFPUC to avoid using any local runoff.

When imports were constrained, scarcity was induced for SFPUC. Tuolumne River water dropped to three-quarters of SFPUC's supply and local runoff increased to 15% of the supply. SFPUC's supply was partially supplemented with small amounts of reuse, desalination, and transfers from other water agencies. The use of more expensive supplies plus scarcity costs increased SFPUC's costs significantly from the base case (Table 4-4). Expanding the infrastructure reduced scarcity a little and operational costs by more, in part because it reduced scarcity at other agencies, allowing SFPUC to keep more of its imported supplies.

During droughts, SFPUC's main source was reduced to 55% of its supply (Figure 7-4 in Appendix). In addition to incurring scarcity, it used desalination for about 15% of its supply, and supplemented with recycled water and a small amount of water delivered by SCVWD. Expanding infrastructure allowed SFPUC to use the groundwater bank, reducing reliance on the more expensive SCVWD transfer and the very expensive desalination enough to lower drought operating costs by $18M/year (Table 7-4 in Appendix).

Supply Reliability and Willingness-To-Pay

Figure 4-13 shows SFPUC's shortage levels under constrained import conditions with and without groundwater banking. The expanded infrastructure reduced shortages during short water-scarce periods, but not during longer, more intense periods of scarcity. In the long droughts, despite SFPUC's greater relative unmet demands, the banked water was allocated to SCVWD to optimize total scarcity and operational costs. While SFPUC did not extract any groundwater from the bank during the long droughts, the expanded infrastructure resulted in other agencies' needs being less pressing, allowing SFPUC to keep more of its own supplies and reduce its use of desalination during these long water scarce periods.

Figure 4-14 shows SFPUC's annual maximum willingness-to-pay to expand access to the groundwater bank under constrained water conditions. (No plot is shown for historical water availability because there was no value in expanding access.) For both runs, during short periods of scarcity, there was value in expanding SFPUC's groundwater bank extraction capacity. During the two longer droughts, WYs 1929-1934 and WYs 1987-1992, there was little-to-no value in expanding extraction capacity because the groundwater was more valuable to SCVWD. The rest of the time, with supplies more plentiful, there was no value in expanding capacity for a more expensive source of water.

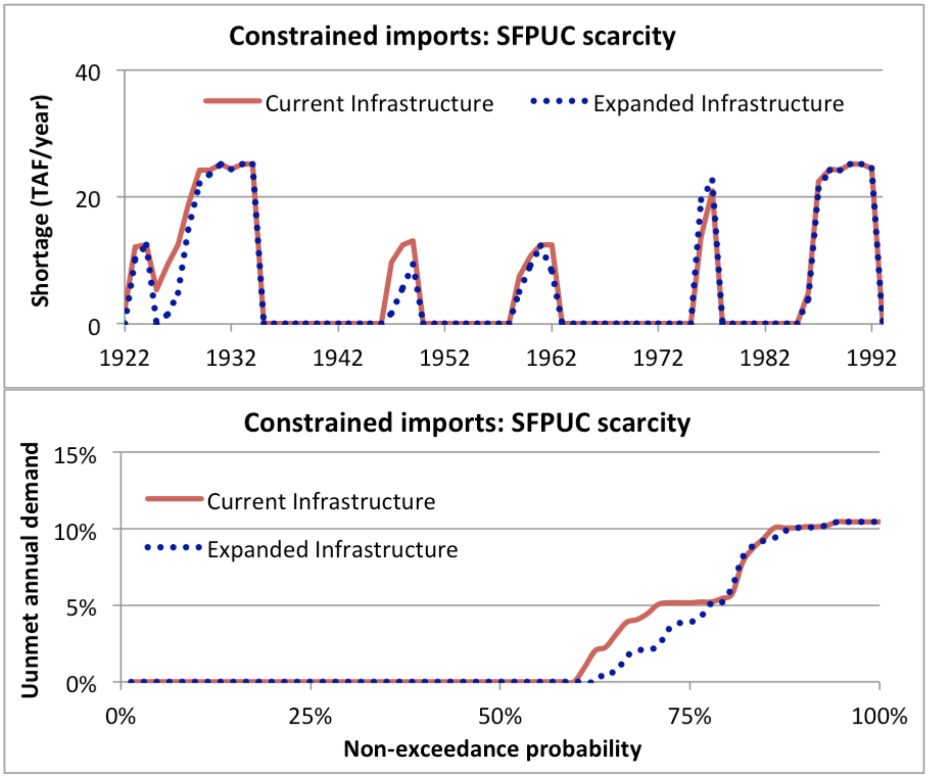


Figure 4-14. SFPUC unmet demand.

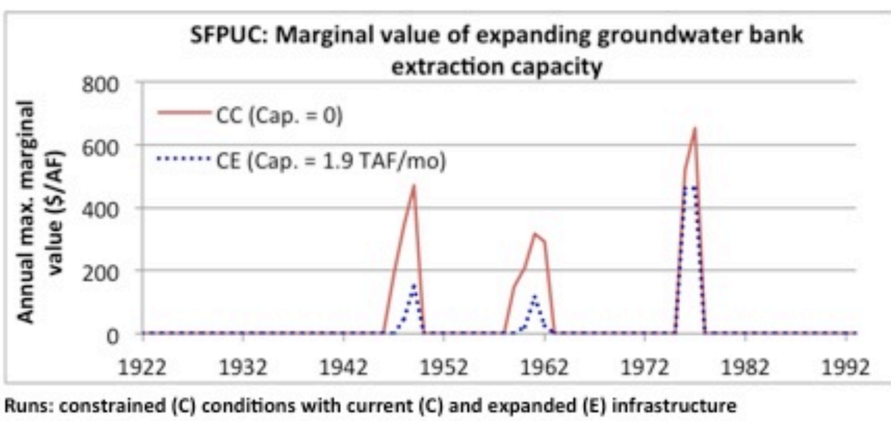


Figure 4-15. Marginal value of expanding SFPUC's groundwater bank extraction capacity.

Figure 4-15 shows the annual maximum marginal value of expanding SFPUC's capacity for contributing to SCVWD's aquifer. In the base case, expanding the contribution capacity from zero to 1 TAF/month was consistently worth around $400/AF; SCVWD would have benefited from the additional supplies. When SFPUC had 1.9 TAF/month contributing capacity in run HE, expanding capacity to 2.9 TAF/month had value at the beginning of wet periods and tapered off as scarce periods approached.

With constrained imports, the marginal value of expanding SFPUC's groundwater bank contributions was zero most of the time (the main exception was WYs 1982-1983, one of the wettest periods on record). Under the constrained imports, SPFUC's more limited supplies were in constant demand for immediate use. This corresponds with SFPUC's groundwater banking operations; under constrained imports, the agency rarely had extra water to contribute.

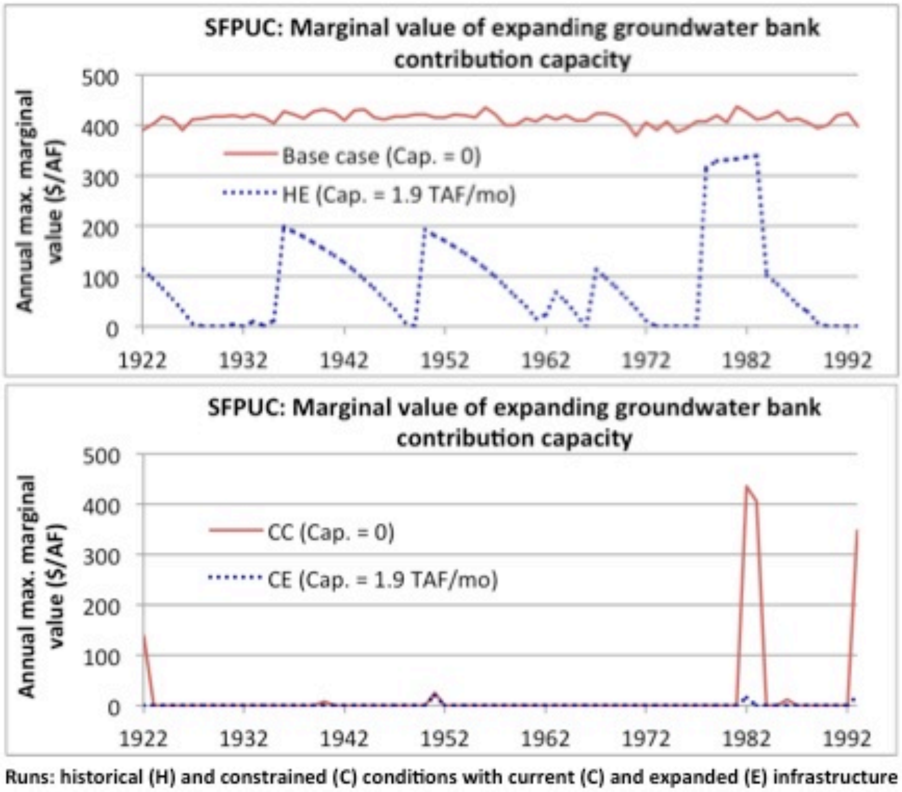


Figure 4-16. Marginal value of expanding SFPUC's groundwater bank contribution capacity.

Conclusion

The model results indicated that expanding the infrastructure improved SFPUC's supply options and slightly reduced vulnerability to scarcity. Because the modeled constraints induced such intense scarcity for SFPUC due to limited excess capacity on Hetch Hetchy Aqueduct, the agency employed significant desalination during droughts. SFPUC obtained very little groundwater from SCVWD (none during the long droughts), only replacing a small part of the supply from desalination. As a result, SFPUC's drought shortages did not decrease with groundwater banking, but its operational costs decreased.

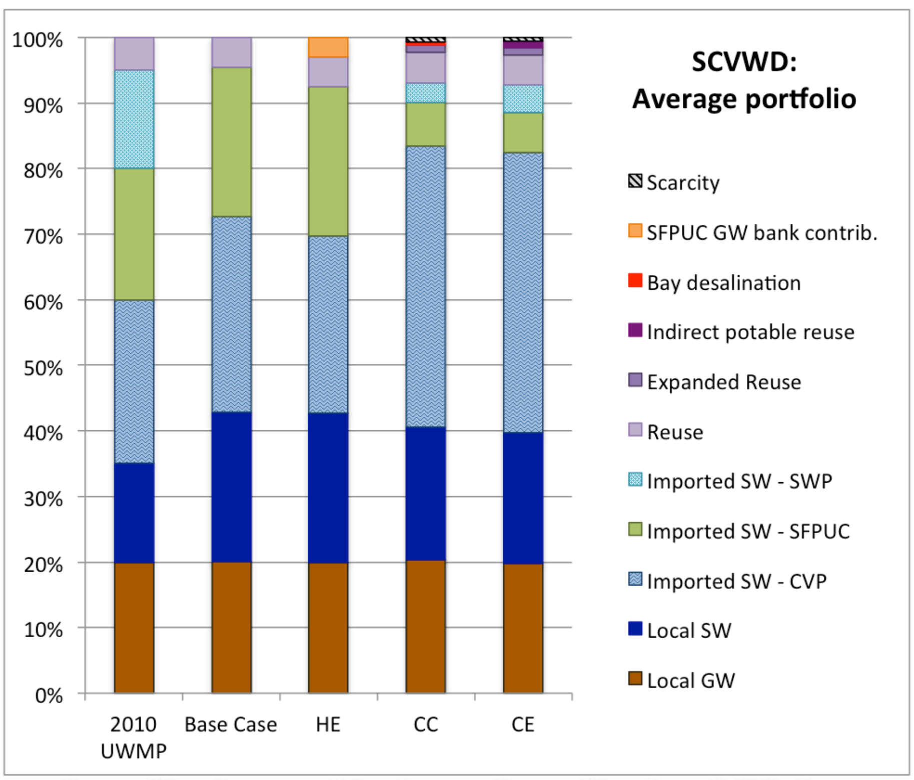
At first glance, SFPUC might not seem like a good candidate for groundwater banking, between the demands on its supply and its substantial local storage. However, though SFPUC is a regional water supplier with extensive demands for their supplies, in above normal to wet years, demands tend to drop and the agency may have surplus supply that could be routed to a groundwater bank. Additionally, while SFPUC has nearly 200 TAF of operational storage in local reservoirs, many of these reservoirs are near major faults (or right on a major fault, in the case of Crystal Springs Reservoir). Groundwater banking could provide a less seismically vulnerable local supply.

SFPUC is presently developing several groundwater projects to decrease water supply vulnerability. Within its retail area, it is planning to install four new wells with an estimated total capacity of 2.8 MGD, and to convert two existing irrigation wells (1.2 MGD capacity) to drinking water facilities (SFPUC 2012). Within its wholesale area, SFPUC has partnered with several San Mateo County agencies on the Regional Groundwater Storage and Recovery project. SFPUC provides additional surface water in normal to wet years to the partner agencies to reduce the amount of groundwater pumped from the South Westside Groundwater Basin (SFPUC 2012). In drought years, the stored groundwater could provide up to 7.2 MGD, reducing demands on SFPUC.

4.6 Santa Clara Valley Water District (SCVWD)

Supply Portfolio

Figure 4-16 shows SCVWD's actual supply portfolio (from SCVWD's 2010 UWMP) and the average optimized portfolios for the modeled scenarios. SCVWD has one of the most diverse portfolios in Bay Area. About 60% of the supply is imported, with 40% pumped through the Delta (25% Central Valley Project (CVP) and 15% State Water Project (SWP)) and with 20% from SFPUC's Hetch Hetchy system. The rest comes from local groundwater (20%), local runoff (15%) and reuse (5%). The model preferentially uses CVP supplies over SWP supplies because of cost.



Runs: historical (H) and constrained (C) conditions with current (C) and expanded (E) infrastructure

Figure 4-17. SCVWD average supply portfolio.

Table 4-6. SCVWD average costs ($M/year).

	Historic water availability		Constrained Bay Area imports	
Runs:	**Base**	**HE**	**CC**	**CE**
SCVWD Scarcity Costs	$0	$0	$6.7	$5.0
SCVWD Operating Costs	$137	$133	$173	$179
Total Cost	**$137**	**$133**	**$180**	**$184**
Runs: historical (H) and constrained (C) conditions with current (C) and expanded (E) infrastructure				

In the base case, SCVWD relied on local supplies (reuse, local runoff and groundwater) for about half its supply, and imported supplies (30% CVP, 25% SFPUC) for the rest (Figure 4-16). When infrastructure was expanded, SFPUC received additional SFPUC supplies from groundwater bank contributions. These contributions replaced more expensive CVP supplies, reducing operation costs (Table 4-5).

When imports were constrained, a small amount of scarcity was induced and operating costs increased as SCVWD's portfolio shifted to more expensive sources (Table 4-5). Deliveries from SFPUC were reduced and replaced by increased through-Delta imports[7] plus expanded water recycling and a small amount of desalination. Expanded infrastructure lowered scarcity, and replaced desalination with slightly less expensive indirect potable reuse ($2072/AF versus $1841/AF). Operating costs increased overall because more water was produced.

During droughts, deliveries from SFPUC were reduced to a trickle, and SCVWD shifted to a heavy reliance on groundwater (Figure 7-5 in Appendix). SCVWD also supplemented with greatly expanded water recycling and some desalination, and still incurred scarcity. Expanding infrastructure led to a significant use of indirect potable reuse during droughts, replacing desalination and reducing SCVWD's scarcity. While SCVWD's scarcity costs decreased, the operating costs increased because more water was produced and SFPUC redirected supplies to greater needs (Table 7-5 in Appendix).

Supply Reliability and Willingness-To-Pay

Figure 4-17 shows SCVWD's shortage levels under constrained import conditions with and without groundwater banking. SCVWD only incurred scarcity during the long droughts. With expanded infrastructure, SCVWD's shortage level was reduced by about 5 TAF/year. Indirect potable reuse contributed significantly to reducing shortage; in the long droughts, SCVWD recharged its aquifer with 24 TAF/year of recycled water on average. Despite its banking partners, SFPUC and ACWD, abstaining from extracting during the long drought periods, SCVWD's production of potable recycled water did not translate into an equivalent reduction of scarcity because the new source was replacing desalination and some imports. With SCVWD's new source, some of its imports were reallocated to greater needs.

[7] SCVWD's allocation of SWP water increased under expanded infrastructure because of Zone 7's groundwater banking. Because of contributions from EBMUD, Zone 7 decreased its reliance on imports from the South Bay Aqueduct.

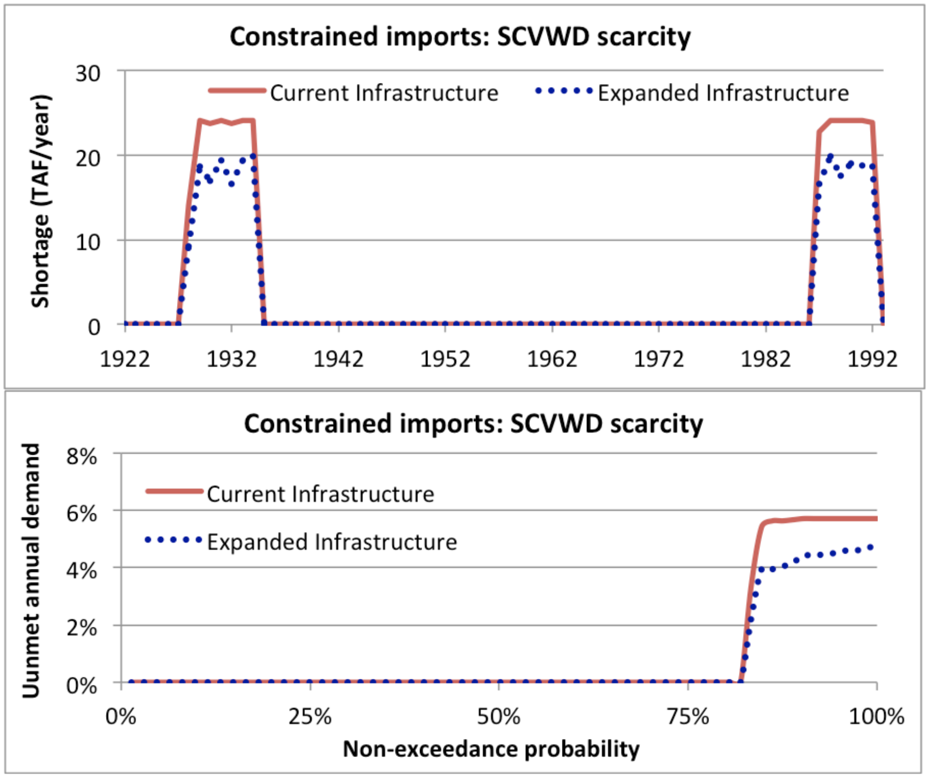


Figure 4-18. SCVWD unmet demand.

Figure 4-18 shows SCVWD's annual maximum willingness-to-pay to expand pumping capacity from 22.5 TAF/month to 23.5 TAF/month. Under historical water availability, there is little value in expanding pumping capacity given other supply options. When imports are constrained, the marginal value of expanding pumping capacity increases during periods of scarcity. In particular, with expanded infrastructure, the value of expanding pumping during the short critical drought (WYs 1976-1977) shot up, because of combined needs of SCVWD, ACWD, and SFPUC.

Figure 4-19 shows SCVWD's annual maximum willingness-to-pay to expand aquifer recharge capacity from 17 TAF/month to 18 TAF/month. There was no value in increasing recharge in dry years and a small amount of value to expand recharge capacity during wetter years. The marginal value increased slightly with expanded infrastructure because of access to additional supplies.

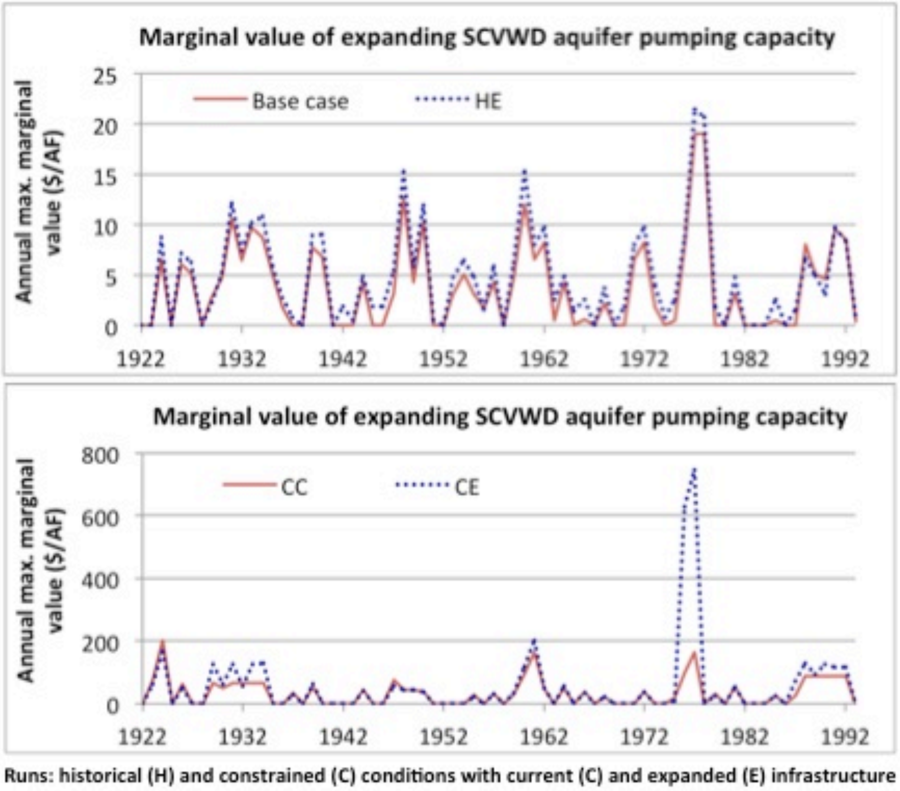


Figure 4-19. Marginal value of expanding SCVWD's aquifer pumping capacity.

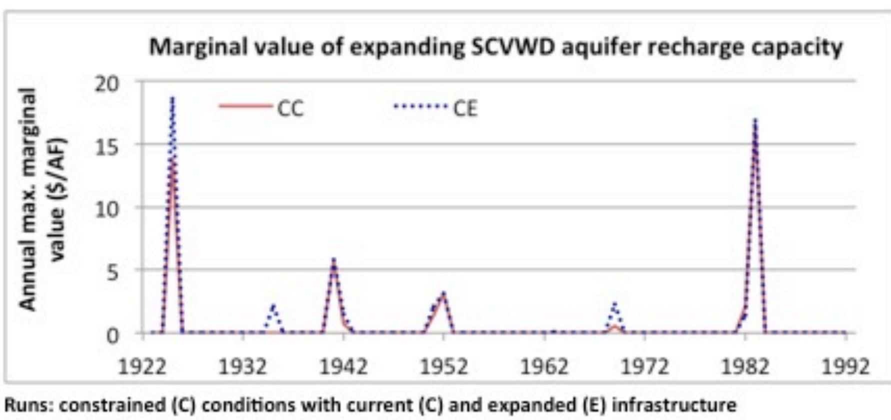


Figure 4-20. Marginal value of expanding SCVWD's aquifer recharge capacity.

The maximum willingness-to-pay to expand SCVWD's capacity for artificial recharge with recycled water was all zeros, so it was not plotted. In run CE, SCVWD's indirect potable reuse capacity was 9.3 TAF/month (100 MGD). The agency used the infrastructure at its maximum rate intermittently during long droughts, but there was no value in further expanding it under the water scarce conditions modeled. Interestingly, in run CC, the marginal value of introducing indirect potable reuse was zero, despite the scarce conditions. This suggests that SCVWD would not have employed indirect potable reuse without the shift in supplies and the additional demands on its aquifer that came with becoming a groundwater bank.

Figure 4-20 shows the annual maximum willingness-to-pay to expand Santa Clara Valley Aquifer storage. Occasionally, following wet periods, the aquifer hit its upper limit, and there was value in more storage. But usually the marginal value of expanding storage was zero, reflecting limited supplies for recharging the aquifer. This result indicates that storage is rarely a limiting factor relative to supplies to refill the storage, and that SCVWD would not gain much by expanding its storage, even when receiving groundwater banking contributions and recharging with recycled water.

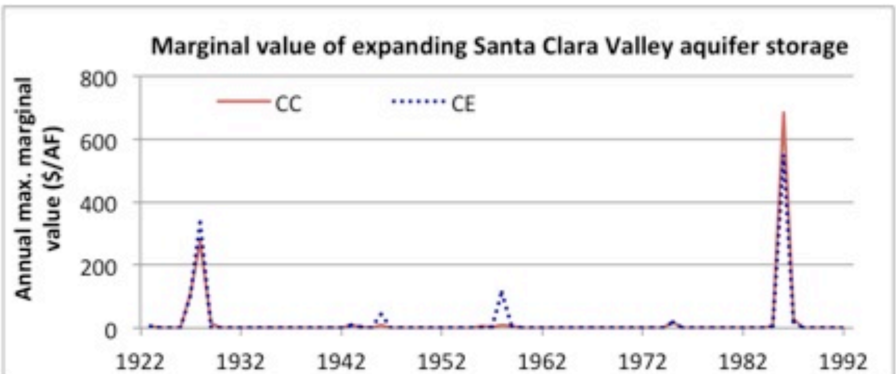


Figure 4-21. Marginal value of expanding SCVWD's aquifer storage capacity.

Overall, the WTP for expanding capacity on groundwater pumping, recharge, and storage did not change much when infrastructure is expanded under constrained conditions. This suggests that SCVWD's existing capacities do not limit groundwater banking (however, ACWD and SFPUC hit their hypothetical infrastructure capacities for groundwater banking with SCVWD).

Conclusion

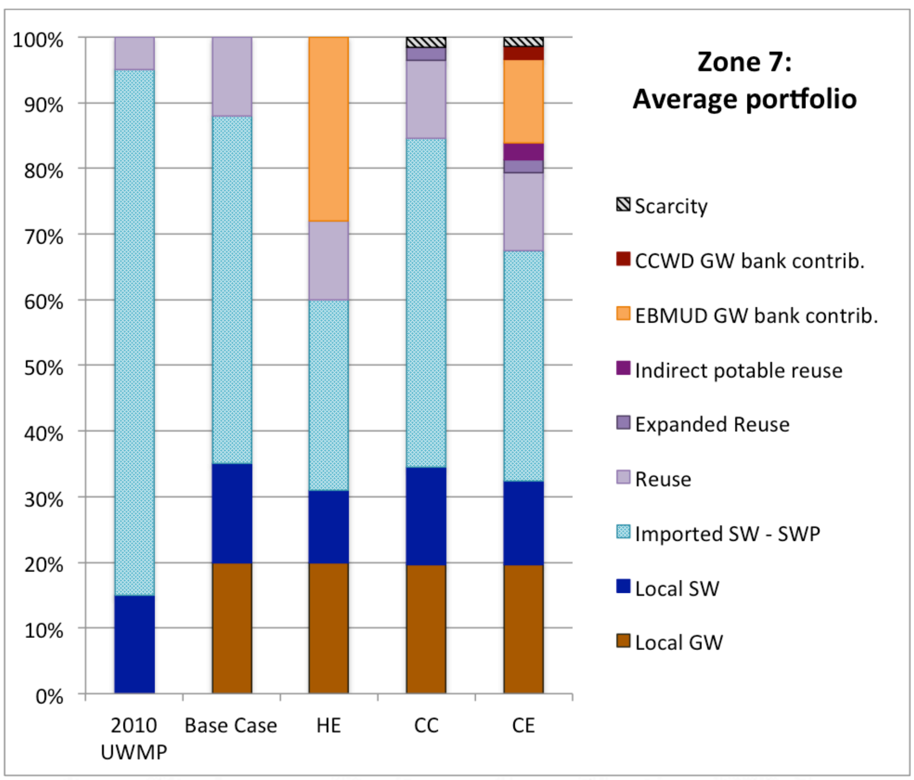
The model results suggest groundwater banking did not have much effect on SCVWD's operations or scarcity, but indirect potable reuse can reduce SCVWD's shortages during long droughts. SCVWD did not have short periods of scarcity like most other agencies. Its large local storage and diversified supply portfolio protected it from incurring shortages during short water-scarce periods. However, during long droughts, the large storage and diversified supply were not enough to prevent shortages, and a new drought-proof supply like indirect potable reuse proved very useful, as well as cheaper than the main alternative, desalination.

It is not clear if being a groundwater bank for SFPUC and ACWD benefits SCVWD. The agency already receives supplies from SFPUC and it receives part of its supply from the same source and conveyance as ACWD. As a result, there is no additional integration of sources to increase reliability. However, if SFPUC or ACWD had access to additional supplies, there could be benefit in SCVWD acting as a groundwater bank. SCVWD does appear likely to benefit greatly from indirect potable reuse (but the results suggest the artificial recharge with recycled water may only be valuable when the rest of the expanded infrastructure is in place). It is a drought-proof new source of water. Between SCVWD's ample input supply (i.e., wastewater effluent) and sizable aquifer, the potential capacity for indirect potable reuse is quite large. However, cost and other considerations, such as public acceptance, may limit this as a source of water.

4.7 Alameda County Flood Control & Water Conservation District Zone 7 (Zone 7)

Supply Portfolio

Figure 4-21 shows Zone 7 water agency's actual supply portfolio (from Zone 7's 2010 UWMP) and the average optimized portfolios for the modeled scenarios. Zone 7 relies on State Water Project (SWP) through-Delta imports for about 80% of its supply. The remainder is supplied by local runoff (15%) and recycled water (5%). Zone 7 manages its local groundwater basin for storage; the basin is artificially recharged in wet years and drawn from in dry years. Zone 7 employs both local runoff and SWP imports to recharge the aquifer. While the aquifer does experience some natural recharge, Zone 7 does not consider it as a supply (and thus it is not explicitly represented in the 2010 supply portfolio). This natural groundwater inflow is represented in CALVIN, and it is treated as a supply option by the model.



Runs: historical (H) and constrained (C) conditions with current (C) and expanded (E) infrastructure

Figure 4-22. Zone 7 average supply portfolio.

Table 4-7. Zone 7 average costs ($M/year).

	Historic water availability		Constrained Bay Area imports	
Runs:	**Baseline**	**HE**	**CC**	**CE**
Zone 7 Scarcity Costs	$0	$0	$2.0	$1.8
Zone 7 Operating Costs	$42	$47	$43	$51
Total Cost	**$42**	**$47**	**$45**	**$53**
Runs: historical (H) and constrained (C) conditions with current (C) and expanded (E) infrastructure				

In the base case, Zone 7 relied heavily on SWP imports and local supplies, supplementing with a fair amount of reuse. With expanded infrastructure, Zone 7 received substantial groundwater banking contributions from EBMUD, reducing its take of SWP water and allowing it to be allocated to agriculture in the rest of the state. While the supply from EMBUD was less expensive than the SWP supplies, the additional cost of groundwater recharge and pumping resulted in the groundwater bank contribution being a more expensive supply, increasing operational costs (Table 4-6).

When imports were constrained, Zone 7 received less SWP water and some scarcity was induced. The reduced SWP supply was partially replaced with expanded water recycling, increasing operational costs slightly (Table 4-6). Expanding the infrastructure resulted in groundwater bank contributions from both EBMUD and CCWD, and indirect potable reuse, decreasing scarcity and increasing operational costs. This supply shift reduced Zone 7's take of SWP water and reallocated it partially to SCVWD and partially to the rest of the state.

During droughts, SWP supplies were reduced and Zone 7 shifted to a heavy reliance on groundwater (Figure 7-6 in Appendix). The agency also supplemented with expanded water recycling, and still incurred scarcity. With expanded infrastructure, Zone 7 added substantial indirect potable reuse. Surprisingly, Zone 7's drought-period scarcity costs increased slightly with the expanded infrastructure (Table 7-6 in Appendix). This occurred because it received even less SWP supply and it supplied EBMUD with groundwater transfers.

Supply Reliability and Willingness-To-Pay

Figure 4-22 shows Zone 7's shortage levels under constrained import conditions with and without groundwater banking and indirect potable reuse. When the infrastructure was expanded, Zone 7 saw a reduction in its SWP supplies of 13 TAF/year, while the net groundwater bank contribution was 12 TAF/year. As a result, Zone 7's scarcity was only reduced a little on average, and actually increased slightly during droughts. During more intense water scarcity, while Zone 7 employed indirect potable reuse to reduce shortages, it did not gain much between the reduced SWP supplies and EBMUD's extractions. Zone 7's shortage was notably worse during the short critical drought (WYs 1976-1977); EBMUD's need was greater and it extracted about 20 TAF/year during that period. While the groundwater bank generally served as it should for EBMUD, Zone 7 benefited less than it could have because the system was re-operated to reduce South-of-Delta imports.

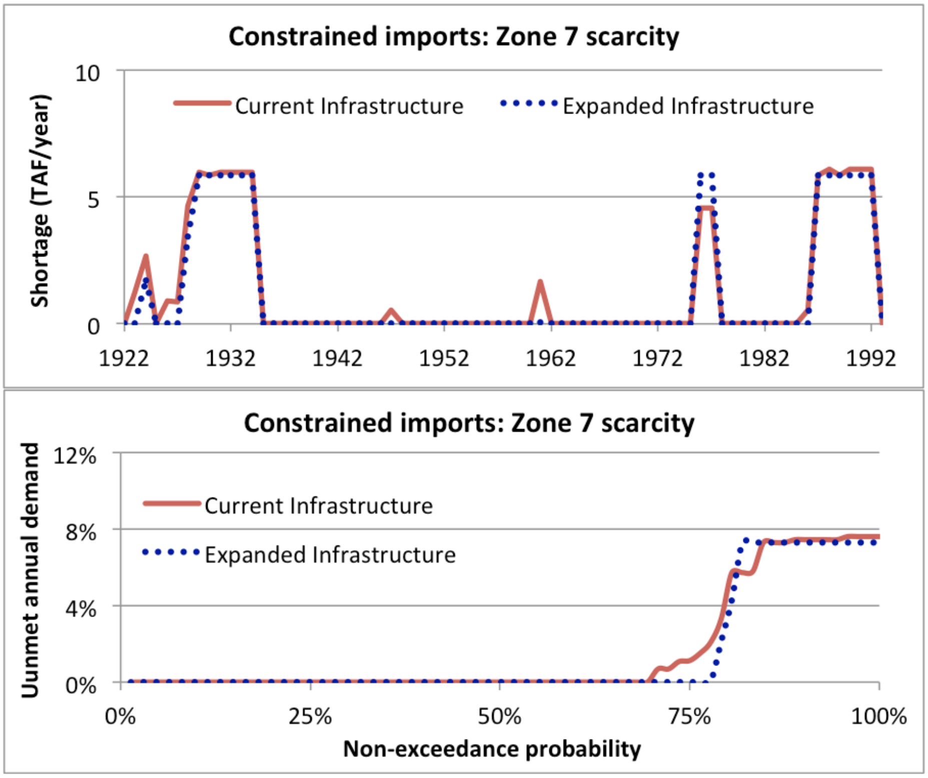


Figure 4-23. Zone 7 unmet demand.

Figure 4-23 shows the annual maximum willingness-to-pay to expand Zone 7's aquifer pumping capacity from 3.8 TAF/month. In the base case, the marginal value of expansion was low because the pumping capacity exceeded the natural recharge, and the direct use of SWP imports was less expensive than the recharging and pumping process. In run HE, the marginal value of expansion increased because contributions from EBMUD make artificially recharged groundwater less expensive. With constrained imports, the marginal value of expansion had value in periods of scarcity, and was near zero otherwise. In run CC, it was mainly during short periods of scarcity that expansion would have benefited Zone 7 and EBMUD, if it were allowed to access the aquifer. In run CE, with the addition of EBMUD's contributions and indirect potable reuse increasing aquifer supplies, there was also value in expanding the pumping capacity in the longer droughts to benefit both Zone 7 and EBMUD.

Figure 4-24 shows the annual maximum willingness-to-pay to expand Zone 7's aquifer recharge capacity from 1 TAF/month to 2 TAF/month. In the base case, there was no value in expanding recharge capacity because Zone 7 had access to adequate imported SWP water, and it was cheaper to use the supply directly than to go through the recharging and pumping process. When groundwater banking was allowed, the marginal value of recharge capacity increased to $90/AF because of access to additional supplies from EBMUD allowed a reduction in Zone 7's take from South Bay Aqueduct. With constrained imports, there was rarely value in expanding recharge capacity until groundwater banking was allowed. Again, access to additional supplies from EBMUD increased the value of expanding recharge capacity, but the value was intermittent, depending on import constraints. Overall, the MVs for expanding capacity on pumping and recharge suggested that the Zone 7 groundwater bank was not operating at its full potential due to capacity constraints.

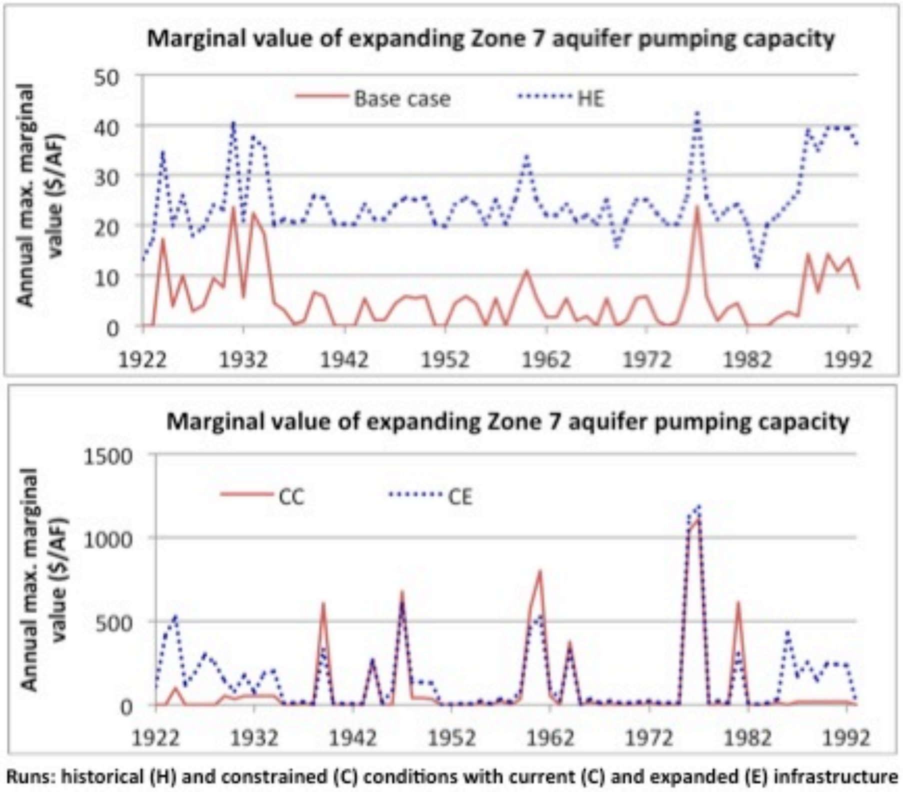
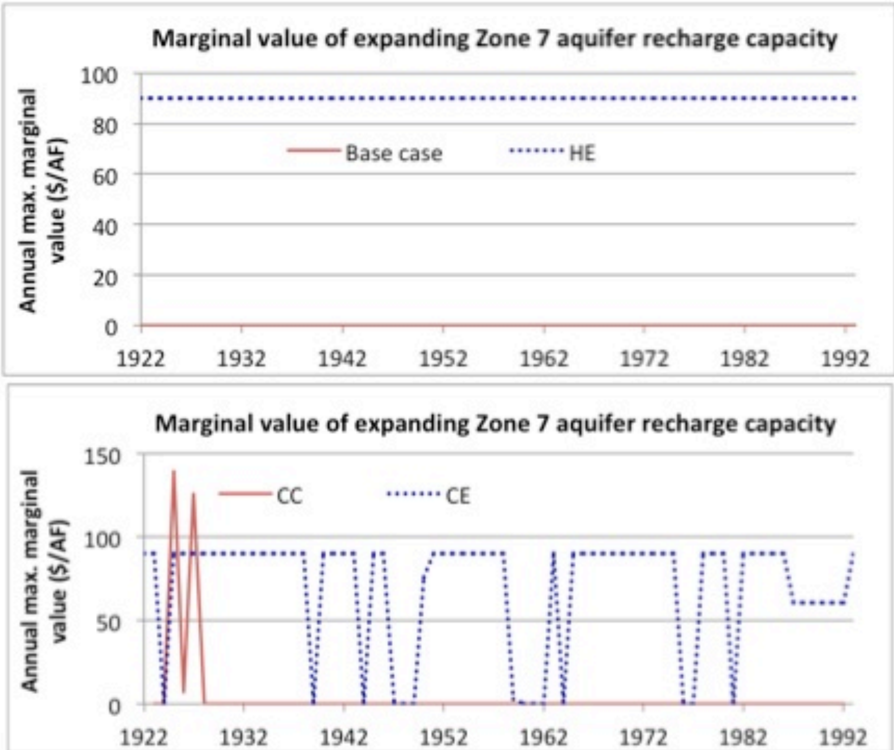


Figure 4-24. Marginal value of expanding Zone 7's aquifer pumping capacity.

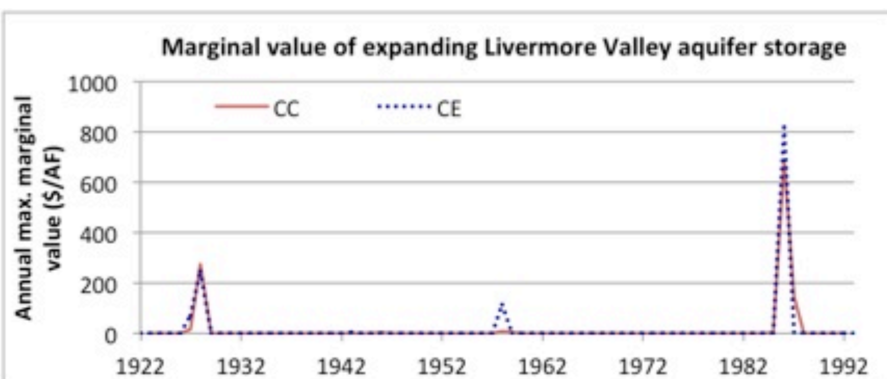
The maximum willingness-to-pay to expand Zone 7's capacity for artificial recharge with recycled water was all zeros, so it was not plotted. Zone 7's indirect potable reuse capacity was 2.8 TAF/month (30 MGD), but the agency only used it at a maximum rate of 1.2 TAF/month. There was no value in further expanding indirect potable reuse for Zone 7 under the water scarce conditions modeled. As was seen with SCVWD, the marginal value of introducing indirect potable reuse was zero in run CC, despite the scarce conditions. This suggests that Zone 7 would not have employed indirect potable reuse without the additional demands on its aquifer that came with becoming a groundwater bank.

Figure 4-25 shows the annual maximum willingness-to-pay to expand Livermore Valley Aquifer storage. Like with SCVWD's aquifer, the aquifer only hit its upper limit occasionally following wet periods. Only in these few instances was there value in expanding storage. Most of the time the marginal value of expanding storage was zero, reflecting limited supplies for recharging the aquifer. This result indicates that storage is rarely a limiting factor relative to supplies to refill the storage, and that Zone 7 would not gain much by expanding its storage, even when receiving groundwater bank contributions and employing recharge with recycled water.



Runs: historical (H) and constrained (C) conditions with current (C) and expanded (E) infrastructure

Figure 4-25. Marginal value of expanding Zone 7's aquifer recharge capacity.



Runs: constrained (C) conditions with current (C) and expanded (E) infrastructure

Figure 4-26. Marginal value of expanding Zone 7's aquifer storage capacity.

Conclusion

The model results indicate expanding the infrastructure improved Zone 7's supply reliability slightly in short-term moderate scarcity. However, being a supplier to EBMUD, which incurred great drought scarcity due to the modeled constraints, resulted in increased scarcity for Zone 7 during the droughts. Because EBMUD's drought-period need was greater, the model reallocated supplies to the detriment of Zone 7. While EBMUD and CCWD had contributed an average of 12 TAF/year (net) to the Zone 7 aquifer, these supplies did not serve as a store for the agencies to access in scarcer times. Instead, the model reduced Zone 7's take of South-of-Delta supplies by 13 TAF/year. The integrated sources and flexible operations were able to reduce both EBMUD's and Zone 7's scarcity (slightly) while using a little less water.

Being a groundwater bank could potentially benefit Zone 7 water agency more than the model results show. The operational costs under expanded infrastructure increased in large part because the model used the Zone 7 gains (mainly from EBMUD's supply) to reduce scarcity elsewhere in the state. Given Zone 7's reliance on a through-Delta import for most of its supply, a major benefit of setting up a groundwater bank with EBMUD and CCWD is the access to different water sources. Portfolio diversification reduces vulnerability to any particular supply being disrupted. Indirect portable reuse also benefits Zone 7, and EBMUD, for the same reason, and has the added benefit of being a drought-proof supply.

Zone 7 water agency has been considering some of these types of expanded infrastructure, as well as others (Zone 7 2011 WSE). An intertie with EBMUD has been proposed as part of the Bay Area Regional Desalination Project. The intertie could potentially give Zone 7 access to the Freeport Facility when excess capacity exists. Zone 7 is also studying the possibility of recharging groundwater with highly treated recycled water. The agency's main concern with indirect potable reuse is the potential for strong public opposition.

5 CONCLUSION

5.1 Modeling conclusions

This type of hydro-economic modeling provides a range of insights for water management and policy problem. This study focused on the value of expanded groundwater banking and indirect potable reuse capacity for the Bay Area under water stressed conditions.

Overall, the model showed that groundwater banking and indirect potable reuse could reduce water supply vulnerability in the San Francisco Bay Area, although at an increased operational cost. However, the savings from reduced scarcity (measured in terms of economic loss) offset increases in operational costs. The increased operational flexibility from groundwater banking within the Bay Area also could reduce scarcity elsewhere in the state if the Bay Area shifts imports to a more conjunctive use style of operations.

Groundwater banking was the most effective for reducing short-term scarcity. Total volume of aquifer storage available for banking, 660 TAF, limits ability to reduce scarcity for an area with forecasted demands of about 1,300 TAF/year. However, the aquifers' contribution to scarcity reduction was more limited by recharge supply than storage capacity. New supplies are needed to prevent significant shortages in long water-scarce periods, such as extreme drought or catastrophic Delta export reductions. Indirect potable reuse was effective for reducing the severity of intense, longer-term scarcity.

All Bay Area agencies having shortages under the modeled water scarce conditions saw their shortages reduced by the expanded infrastructure. But agencies did not benefit equally; some saw their scarcity reduced much more than others or operational costs increase much more than others. This largely resulted from using an optimization model with the objective of minimizing total system-wide costs and that lacks operational policy rules. Under standard groundwater banking operations, withdrawals would be limited to deposits (minus losses), and no agency could claim the contributions of other agencies to their detriment (although they might buy and sell stored water). The agency modeling results were interpreted with operational limitation in mind.

The model did not show SCVWD benefiting from being a groundwater bank for SFPUC and ACWD under water-scarce conditions, but both ACWD and SFPUC benefitted from the increased operational flexibility. SCVWD did not appear to benefit from the banking mostly because SCVWD's large local storage and diversified supply portfolio protected it from shortages during short water-scarce periods, when groundwater banking is most useful. Also, the banking infrastructure was small compared with the size of SCVWD demands. Finally, the groundwater banking did not provide supply sources that SCVWD did not already have access to. However, under historical water availability, SCVWD benefited from the groundwater contributions from SFPUC, suggesting that if SFPUC or ACWD had access to additional supplies, SCVWD could benefit from acting as a groundwater bank. Meanwhile ACWD benefitted directly from groundwater banking; access to a more diversified portfolio reduced shortages during short periods of scarcity. While SFPUC occasionally benefitted directly from groundwater banking (during a few short periods of scarcity), it also benefited indirectly because of reduced scarcity at other agencies, allowing SFPUC to keep more of its imported supplies.

The model showed Zone 7 benefitted from being a groundwater bank for EBMUD and CCWD under short periods of water scarcity while EBMUD benefited from the arrangement during short periods of water scarcity and during droughts[8]. CCWD's interactions with the groundwater bank were not properly tested because modeled constraints did not induce scarcity for CCWD. Interpretation of the impact of being a groundwater bank on Zone 7 was complicated by an underlying system re-operation to reduce Bay Area's South-of-Delta imports (and a partial reallocation of Zone 7's SWP supplies to SCVWD). The combination of reduced SWP supplies and EBMUD's greater need during droughts resulted in worse scarcity for Zone 7 during droughts. Without this reallocation of supplies, Zone 7 would have benefited more from its access to EBMUD and CCWD supplies. Given Zone 7's reliance on a through-Delta import for over 80% of its supply, a major benefit of establishing a groundwater bank with EBMUD and CCWD is the access to different water sources. Likewise, for EBMUD and CCWD, access to Zone 7's aquifer diversifies their water supply portfolios.

The model showed all of the agencies with access to indirect potable reuse employing it during long droughts. Indirect potable reuse (through groundwater recharge) served as a useful portfolio diversification tool, and specifically a drought-proof one. However, the agencies' rare use of full indirect potable reuse capacity and low willingness-to-pay for expansion indicated that capacities (ACWD: 10 MGD; SCVWD: 100 MGD; Zone 7: 30 MGD) probably were oversized in the model.

Implications & Challenges

The model results suggest that Bay Area groundwater banking (or methods of pooling resources) and indirect potable reuse are worth investigating in more detail. Comparing the outcomes of two different groundwater banks highlighted the gains from integrating multiple supply sources as well as potential losses of benefit due to competition. As new storage (e.g., reservoirs) or infrastructure to expand existing storage (e.g., increased recharge/pumping capacity) is planned, maximizing effectiveness of regional storage should be considered. Storage that can take advantage of multiple sources or that does not directly compete with other storage for supplies can be especially advantageous.

Of course, many challenges exist for actually implementing groundwater banking. The costs of infrastructure and operations will be significant, although likely less than other supply alternatives. Water rights can be a significant barrier; unless the banked surface water is held under a pre-1914 appropriative right, it is subject to a "change order" from the State Water Resources Control Board, authorizing the transfer from a surface source to the groundwater bank

[8] These results suggest that Zone 7 and EBMUD would both benefit from the proposed intertie between their systems. Zone 7 would particularly benefit from being more tied into the regional system and having access to a source that does not depend on the Delta.

(Thomas 2001). To obtain such an order, it is necessary to establish that the recharge and withdrawal of water will not adversely affect other legal users of water. Additionally, host agencies may run into public acceptance barriers with existing groundwater pumpers concerned about their water being taken by others or their extractions being limited. EBMUD's attempt to set up groundwater banking in Eastern San Joaquin County (a program designed to help mitigate local overdraft) failed because of landowners' fears of an outside agency taking their groundwater (Thomas 2001). Finally, enforcement of one's rights to imported water against unauthorized withdrawals by other users of the aquifer is difficult.

Indirect potable reuse also has many implementation challenges. Among them are cost and waste disposal (especially brine from reverse osmosis), but the biggest challenge is likely to be public acceptance. Both SCVWD and Zone 7, in conjunction with their local wastewater agencies, are considering artificial recharge with highly treated recycled water, and both agencies state that public acceptance is the potential limiting factor for such projects to proceed (SCVWD 2010 UWMP; Zone 7 2011 WSE). SCVWD is looking ahead to direct potable reuse (DPR); they plan to build indirect potable reuse systems that can be converted to DPR when public acceptance and regulatory structure allow (WateReuse Association panel, Sept. 27, 2013).

5.2 Limitations

As with any model, CALVIN is an imperfect representation of a real system and has its limitations. A major caveat with this type of optimization model is that it has perfect foresight. The model optimizes with perfect knowledge of future inflows, building up stores in advance of droughts and allowing depletion as wet periods approach. In reality, water managers do not have forecasts years out, and cannot perfectly allocate supplies, so the results likely underestimate actual scarcity and scarcity cost. Recharge of groundwater banks would likely be more continuous than appears in the model. In evaluating the model results it is important to note that perfect foresight understates the value of new storage and conveyance capacity (Draper 2001).

A major limitation with CALVIN's representation of groundwater banking is the inability to limit extractions to contributions. The model representation of groundwater banking is capacity-limited interagency transfers via aquifers. The results still show the value of pooled resources, but this limited model representation complicated the interpretation of agency-specific results.

A shortcoming of CALVIN's representation of capital-intensive hypothetical supplies, like proposed recycling and desalination, is that fixed costs are ignored. The ideal model for evaluating the usefulness of indirect potable reuse would be two-stage, where the initial investment in infrastructure would be taken into account. Again, recharge of groundwater banks would likely be more continuous than appears in model results.

5.3 Future Work

Groundwater banking modeling

To pursue the evaluation of regional groundwater banking further would require moving to a modeling platform which could set rules like groundwater banking withdrawals must be less than or equal to deposits. For example, Water Evaluation and Planning system (WEAP) software has been employed for several groundwater banking modeling studies (Purkey et al. 1998; Lempert and Groves 2010; Sandoval-Solis et al. 2010). Having policy restrictions on operations would give a more realistic assessment of the potential benefits of groundwater banking. The results from this study were likely optimistic because of the overly flexible operations. However, the benefits were evaluated relative to an optimistic base case with perfect hedging. The benefits of groundwater banking may be greater for a non-optimized system. An ability of groundwater banking participants to buy and sell water should ease this limitation considerably; the model essentially represents this condition.

Indirect potable reuse modeling

Further evaluation of a proposed capital-intensive supply such as artificial recharge with highly treated reclaimed water should be done in a two-stage optimization model. A two-stage model would set up a decision on investing in infrastructure, before allowing use of it. Because of the computational requirements, the model would likely have to be limited to the Bay Area. Unfortunately, this would lose the statewide context of the intertied California water supply system.

Comparative regional studies

This study examined two approaches to reducing water supply vulnerability in the San Francisco Bay Area, groundwater banking and indirect potable reuse. A comparative study with other approaches being considered could be useful. For example, the Bay Area Regional Desalination Project (BARDP) is a joint project by CCWD, EBMUD, SFPUC, SCVWD, and Zone 7 to evaluate the feasibility of building a shared desalination plant (BARDP 2013). The proposed 10-20 MGD brackish desalination plant would divert water from the Delta through an existing CCWD intake. After treatment, the water would be delivered through intertied agency conveyance systems, or stored at CCWD's Los Vaqueros Reservoir for later use. It could be informative to compare centralized brackish desalination as proposed by the BARDP against decentralized indirect potable reuse as proposed here. Another option being considered to improve Bay Area water supply reliability is an expansion of Los Vaqueros Reservoir from 160 TAF to 275 TAF with a potential connection to South Bay reservoirs (Los Vaqueros Reservoir Expansion Project EIS/EIR 2010). Again it could be informative to compare the gains from this proposed storage and conveyance expansion to the gains from regional groundwater banking.

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7 APPENDIX: Drought Portfolios and Costs by Agency

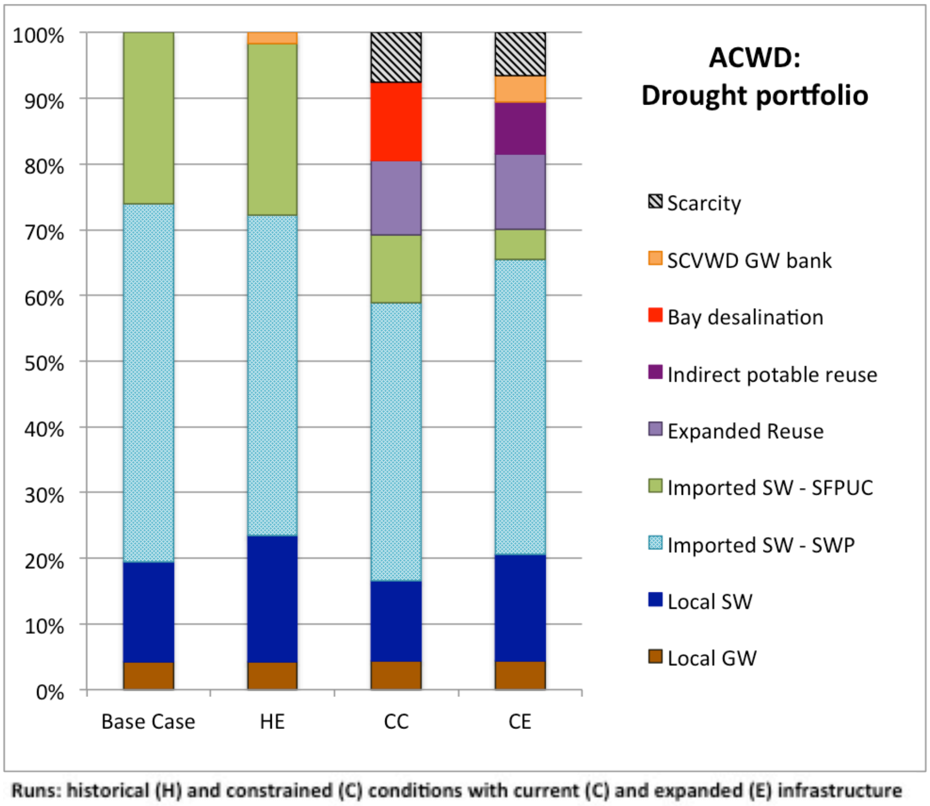


Figure 7-1. ACWD drought supply portfolio.

Table 7-1. ACWD drought-period costs ($M/year).

	Historic water availability		Constrained Bay Area imports	
Runs:	**Baseline**	**HE**	**CC**	**CE**
ACWD Scarcity Costs	$0	$0	$9.6	$8.0
ACWD Operating Costs	$59	$56	$70	$73
Total Cost	**$59**	**$56**	**$80**	**$81**
Runs: historical (H) and constrained (C) conditions with current (C) and expanded (E) infrastructure				

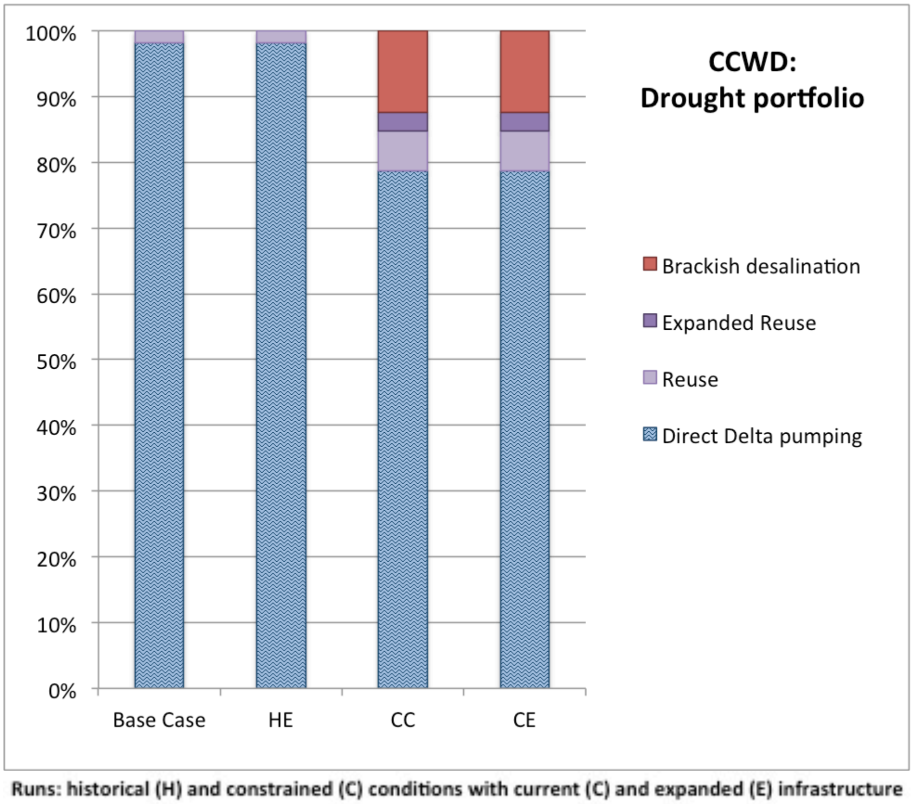


Figure 7-2. CCWD drought supply portfolio.

Table 7-2. CCWD drought-period costs ($M/year).

	Historic water availability		Constrained Bay Area imports	
Runs:	**Baseline**	**HE**	**CC**	**CE**
CCWD Scarcity Costs	$0	$0	$0	$0
CCWD Operating Costs	$88	$88	$127	$127
Total Cost	**$88**	**$88**	**$127**	**$127**
Runs: historical (H) and constrained (C) conditions with current (C) and expanded (E) infrastructure				

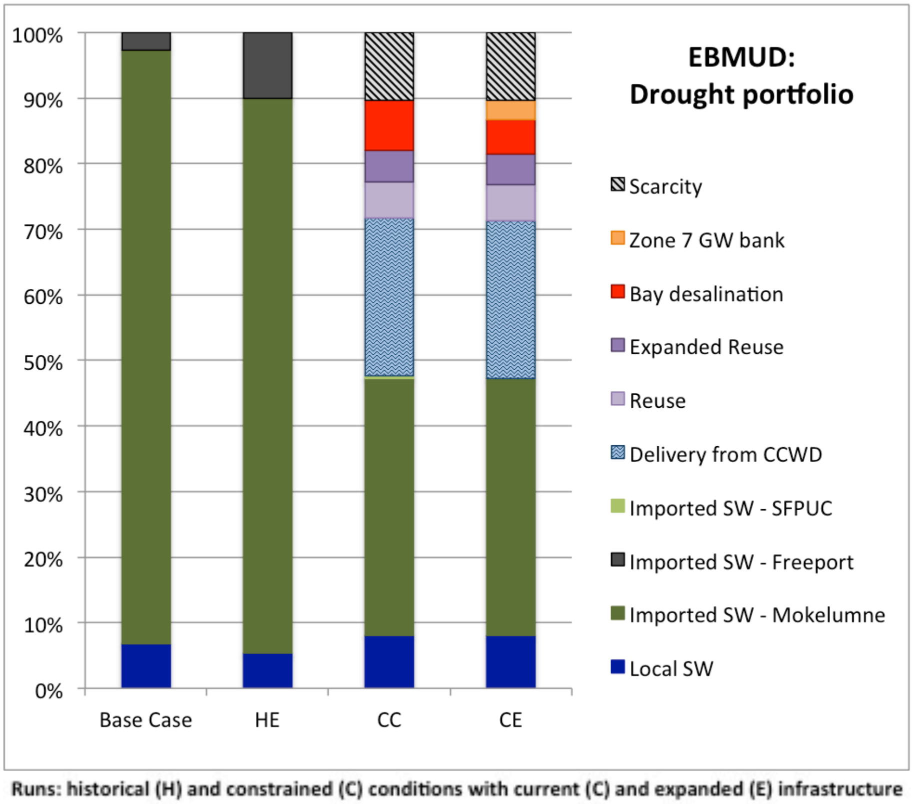


Figure 7-3. EBMUD drought supply portfolio.

Table 7-3. EBMUD drought-period costs ($M/year).

	Historic water availability		Constrained Bay Area imports	
Runs:	**Baseline**	**HE**	**CC**	**CE**
EBMUD Scarcity Costs	$0	$0	$46	$46
EBMUD Operating Costs	$67	$74	$122	$111
Total Cost	**$67**	**$74**	**$168**	**$157**
Runs: historical (H) and constrained (C) conditions with current (C) and expanded (E) infrastructure				

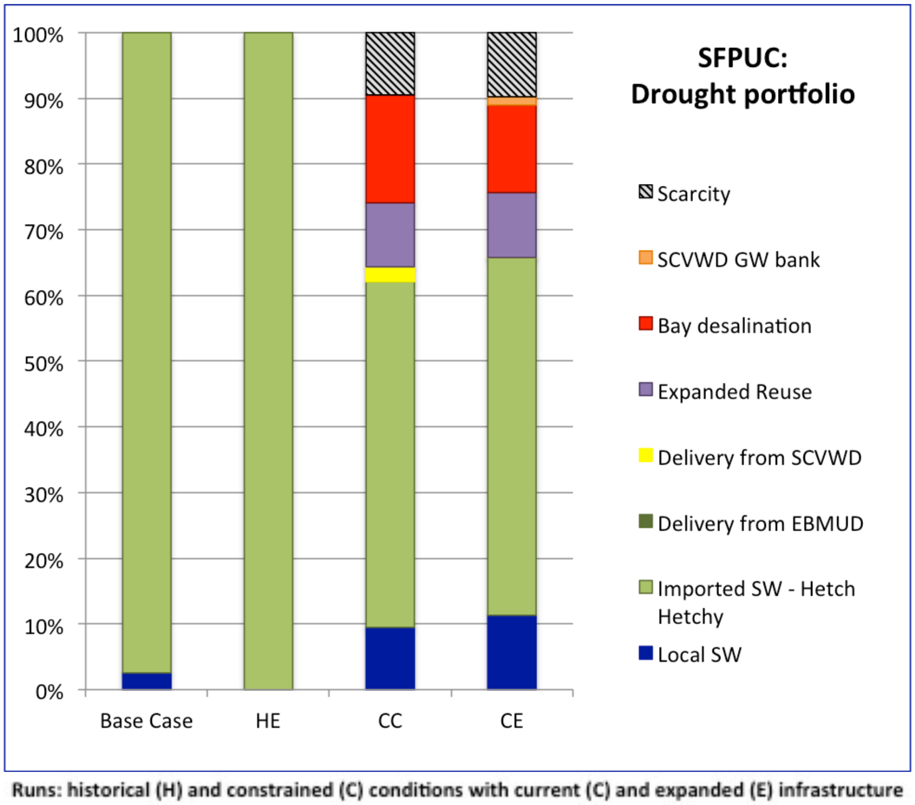


Figure 7-4. SFPUC drought supply portfolio.

Table 7-4. SFPUC drought-period costs ($M/year).

	Historic water availability		Constrained Bay Area imports	
Runs:	**Baseline**	**HE**	**CC**	**CE**
SFPUC Scarcity Costs	$0	$0	$36	$36
SFPUC Operating Costs	$44	$45	$151	$133
Total Cost	**$44**	**$45**	**$187**	**$169**
Runs: historical (H) and constrained (C) conditions with current (C) and expanded (E) infrastructure				

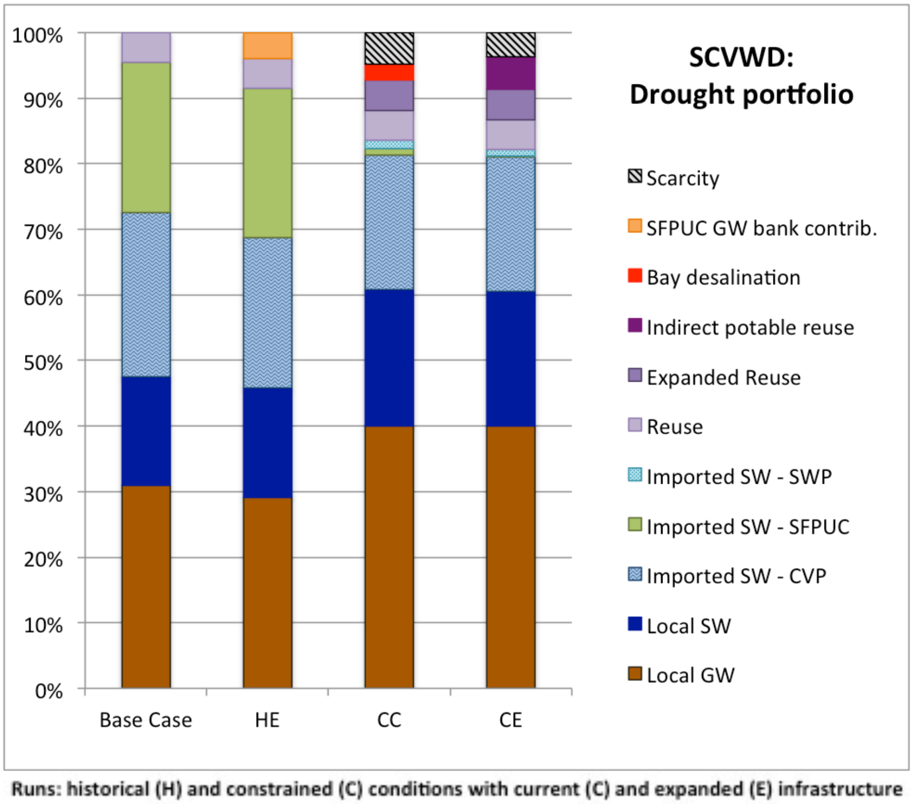
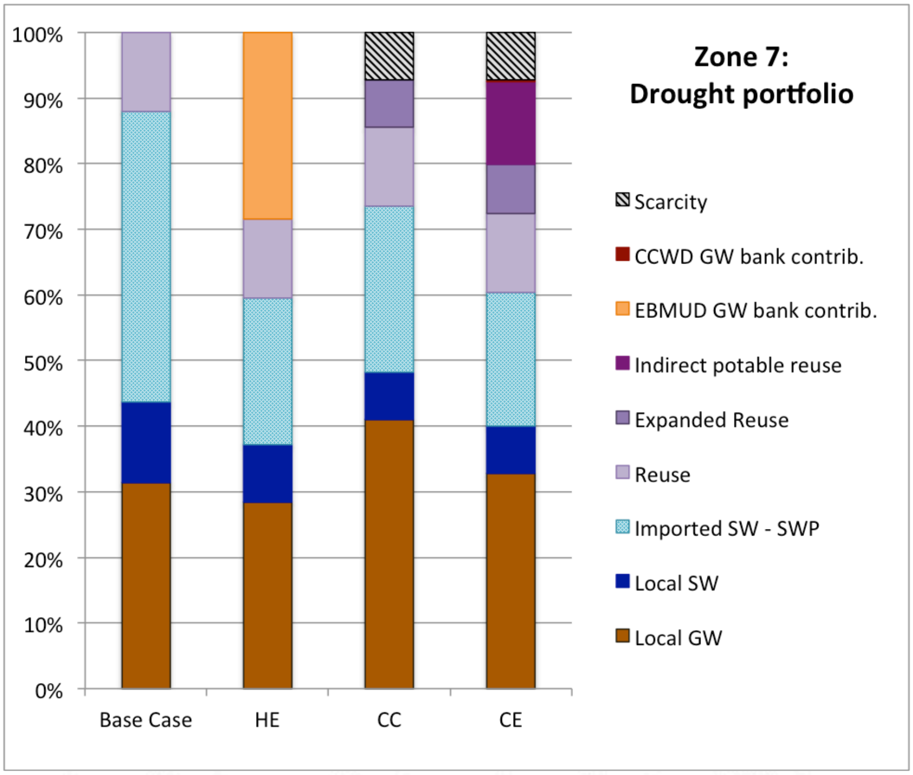


Figure 7-5. SCVWD drought supply portfolio.

Table 7-5. SCVWD drought-period costs ($M/year).

	Historic water availability		Constrained Bay Area imports	
Runs:	**Baseline**	**HE**	**CC**	**CE**
SCVWD Scarcity Costs	$0	$0	$33	$25
SCVWD Operating Costs	$131	$128	$168	$183
Total Cost	**$131**	**$128**	**$201**	**$208**
Runs: historical (H) and constrained (C) conditions with current (C) and expanded (E) infrastructure				



Runs: historical (H) and constrained (C) conditions with current (C) and expanded (E) infrastructure

Figure 7-6. Zone 7 drought supply portfolio.

Table 7-6. Zone 7 drought-period costs ($M/year).

	Historic water availability		Constrained Bay Area imports	
Runs:	**Baseline**	**HE**	**CC**	**CE**
Zone 7 Scarcity Costs	$0	$0	$8.7	$8.8
Zone 7 Operating Costs	$39	$44	$36	$56
Total Cost	**$39**	**$44**	**$45**	**$65**
Runs: historical (H) and constrained (C) conditions with current (C) and expanded (E) infrastructure				