Economic Responses to Water Scarcity in Southern California

By

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THESIS

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Abstract

Revisions were made to CALVIN, a hydro-economic optimization model of California’s intertied water delivery system, to better reflect year 2050 operating capacities and improve model accuracy. Revisions include changing how penalty equations are calculated, updating urban water rates, splitting urban demand areas into indoor and outdoor water use components statewide, and updating urban and agricultural demands and the conveyance network in southern California. This revision significantly updates cost and scarcity estimates, but does not significantly change the physical operation of the system.

This updated model is used to examine the economic effects on southern California of reducing or ending the State Water Project deliveries to southern California in 2050. SWP contactors without access to Colorado River water are the most affected, with the MWDSC member agencies having increased scarcity and agriculture and urban areas near the Colorado River being unaffected.

Dedication

For my mother, Linnell, who gave me the habit of
doing things right.

Acknowledgements

Thanks firstly to Josué Medellín-Azuara for all of his help and technical and moral support in seeing this project through. He answered endless questions, located data, and provided invaluable assistance in setting up and debugging the model runs.

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Abbreviations

af – Acre-Foot
CRA – Colorado River Aqueduct
CVP – Central Valley Project
CVPM – Central Valley Planning Model
DAU – Detailed Analysis Unit
DWR – California Department of Water Resources
EBMUD – East Bay Municipal Utilities District
E&W MWD – Eastern and Western Municipal Water Districts
IID – Imperial Irrigation District
IRWMP – Integrated Regional Water Management Plan
LAA – Los Angeles Aqueduct
maf – Million Acre-Feet
MWDSC or MWD – Metropolitan Water District of Southern California
PVID – Palo Verde Irrigation District
SB-SLO – Santa Barbara-San Luis Obispo
SBV – San Bernardino Valley
SCV – Santa Clara Valley
SWP – State Water Project
taf – Thousand Acre-Feet
USBR – United States Bureau of Reclamations
UWMP – Urban Water Management Plan
WTP – Willingness-To-Pay

Chapter 1
Introduction

This research examines the water management and costs effects of reduced water imports over the Tehachapi Mountains to southern California. With the unreliability of the Sacramento-San Joaquin Delta as a conveyance system due to environmental, seismic, and climate risks, the likelihood of disruptions in imported water supply from northern California is increasing. The CALVIN model for southern California was revised and used to estimate the economical management of water scarcity and potential costs of five different water import levels.

Integrated hydro-economic modeling, like CALVIN, provides a versatile environment for statewide policy and planning exploration. While no model can perfectly reflect reality, for a large interdependent network such as California's water supply system, the model provides better, more defensible results than anyone's intuition and an ability to provoke more grounded and productive discussion of important water issues.

CALVIN

CALVIN, the CALifornia Value INtegrated Network model, is a hydro-economic model of California's intertied water supply and delivery system. 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). The CALVIN coverage area and network are shown in Figure 1.1.

The CALVIN model began in the late 1990s with professors and graduate students at UC Davis (Draper et al. 2003). The goal was to use optimization modeling to organize a quantitative understanding of integrated water supply management in California, examine the economic and supply effects of a wide variety of water management alternatives in a consistent and convenient way, and identify economically promising water market, infrastructure, and other water management actions within an integrated water supply management context. Like all modeling projects, CALVIN brings together a large amount of data on the system into an internally consistent framework. Like all large models, this objective can be mostly fulfilled without being completely achieved.

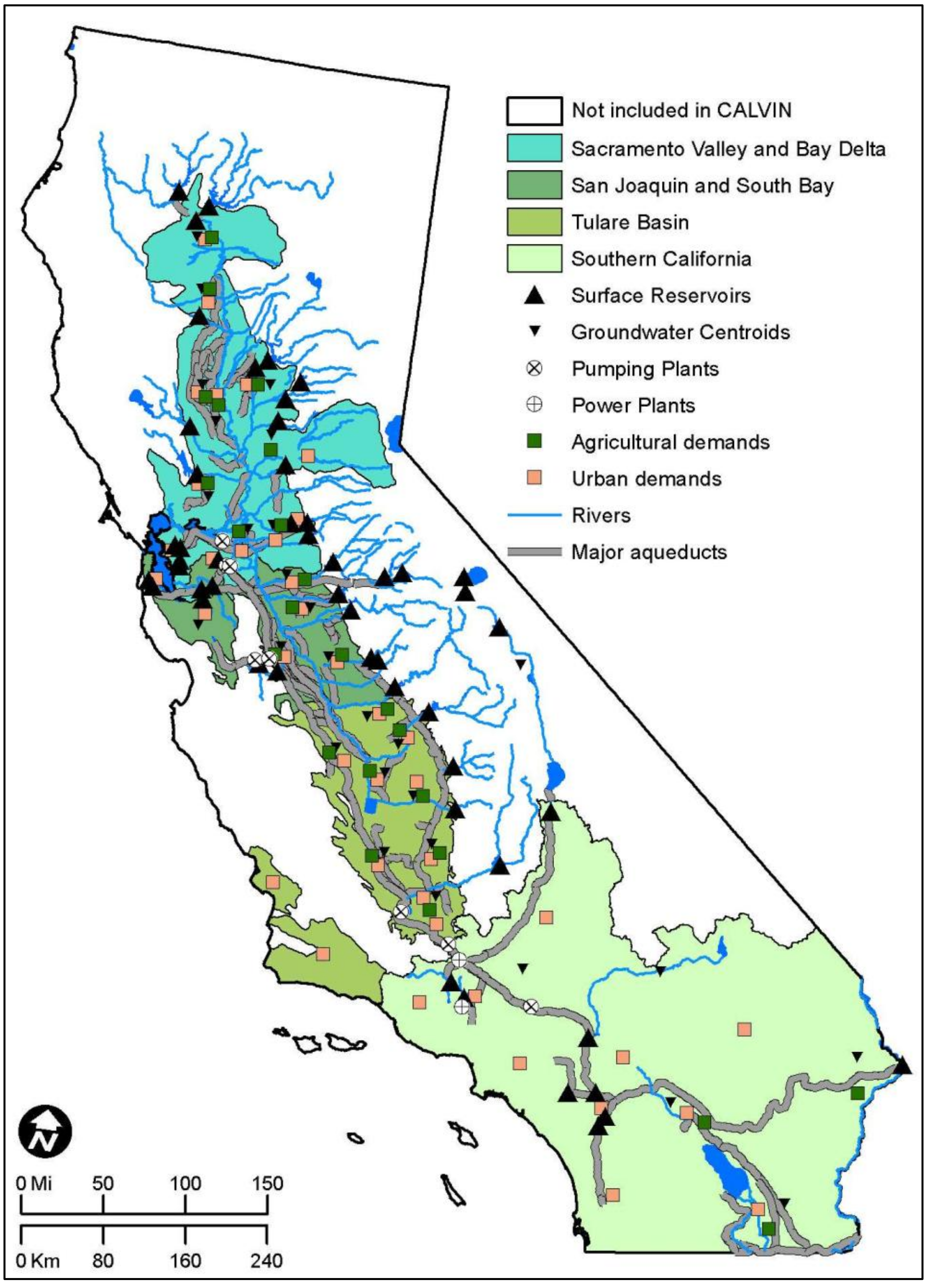
Model Description

CALVIN is an optimization model with an objective of minimizing statewide water supply operating and scarcity costs. Operating costs are specified in the network for every link and scarcity costs are derived from each area's estimated water delivery demand curve, as defined by the economic penalty equations described in Chapter 3.

The current network consists of 41 urban demand areas, 25 agricultural demand areas, 44 reservoirs, 31 groundwater basins, and 1,692 links. Typically, inflows simulate 72 years of monthly, unimpaired, historical hydrology (1922-1993) to represent natural hydrologic variability. The model is solved using the Army Corps of Engineers Hydrologic Engineering

Center's Prescriptive Reservoir Model (HEC-PRM) which uses a generalized network flow optimization solver (Draper et al. 2003).

Figure 1.1: CALVIN Coverage Area and Network



Each demand area in CALVIN corresponds to one or more DAU, or Detailed Analysis Unit, the smallest aggregate unit of area at which the California Department of Water Resources (DWR) processes data. Appendix 1 of this thesis lists all demand areas included in CALVIN, with their corresponding DAUs.

Since this type of optimization model has perfect hydrologic foresight (it knows in advance the future inflows for every timestep in the modeling period) model results are often the best case outcomes for water management rather than predictions of actual outcomes (Draper 2001). However, this still allows examination of how any change will affect all aspects of the system and can steer towards the most promising solutions. Comparison against model formulations with more limited foresight indicate that operations and cost often do not differ greatly, particularly when large amounts of surface and groundwater storage are available to dampen the effects of hydrologic uncertainly (Newlin et al. 2002; Draper 2001).

Table 1.1: Previous CALVIN Studies

Description	**Citation**
Integrated water management, water markets, capacity expansion, at regional and statewide scales	Draper et al. (2003); Jenkins et al. (2001; 2004); Newlin et al. (2002)
Conjunctive use and southern California	Pulido et al.(2004)
Hetch Hetchy restoration	Null (2004); Null and Lund (2006)
Perfect and limited foresight	Draper (2001)
Climate warming, wet and dry	Lund et al. (2003); Tanaka et al.(2006; 2008)
Climate warming, dry	Medellín-Azuara et al.(2008a; 2009)
Climate warming, dry and warm-only	Medellín-Azuara et al.(2008a; 2009); Connell (2009)
Severe sustained drought impacts and adaptation (paleodrought)	Harou et al. (2010)
Increasing Sacramento River outflows	Tanaka and Lund (2003)
Reducing Delta exports and increasing Delta outflows	Tanaka et al.(2006; 2008; 2011); Lund et al.(2007; 2008)
Colorado River delta and Baja California water management	Medellín-Azuara et al.(2006; 2007; 2008b)
Ending overdraft in the Tulare Basin	Harou and Lund (2008)
Cosumnes River restoration and Sacramento metropolitan area water management	Hersh-Burdick (2008)
Bay Area adaptation to severe climate changes	Sicke (2011)
Urban water conservation with climate change and reduced Delta pumping	Ragatz (2011)

(Adapted from Lund et al, 2010)

Previous CALVIN Studies

Since its creation, CALVIN has been used to examine a wide variety of different scenarios based on changes in policy, infrastructure, water use, and even climate. These previous CALVIN studies are summarized in Table 1.1.

Other Models of Southern California

Since this study is focused mostly on southern California, it is worthwhile to review some other major models of southern California. Among these other models, CALVIN fills a unique niche in modeling both the physical water conveyance system that links southern California with the rest of the state and its economically optimal adaptation to conditions.

CalSIM II

CalSIM II is a simulation model of Central Valley Project (CVP) and State Water Project (SWP) operations developed by the California Department of Water Resources (DWR) and the Bureau of Reclamations (Draper et al. 2004). It covers the Sacramento Valley and the Eastern San Joaquin Basin, with additional deliveries to parts of the Tulare Basin, Bay Area, and southern California which are supplied by the SWP and CVP. This model allocates water based on a series of weighted priorities set up by the user rather than based on economic considerations.

LCPSIM

LCPSIM (Least Cost Planning Simulation) is a priority-based, mass-balance model designed by DWR to be used with CalSIM II to minimize the expected costs and losses from shortages to urban areas in the Bay Area and southern California. LCPSIM helps CalSIM calculate water transfer and carryover storage operations and adjusts modeled State Water Project delivery targets based on undeliverable State Water Project quantities (DWR 2010).

WEAP

The Water Evaluation And Planning model (WEAP), is a simulation model available from the Stockholm Environmental Institute. Two main versions of this model have been developed for California. A high resolution model by Planning Area (PA model) that covers only the Sacramento and San Joaquin Hydrologic Regions, and a low-resolution model by Hydrologic Region (HR model) that covers all ten hydrologic regions in California. WEAP allocates water based on mass balance and a system of priorities. It includes a precipitation-runoff model (Sieber 2011).

IRPSIM

IRPSIM (Integrated Regional Planning Simulation Model) is Metropolitan Water District's (MWDSC) water allocation model. It was created by A & N Technical Services, and is a simulation model that runs Monte-Carlo simulations of MWDSC's potential supplies and demands in all historical hydrologies to estimate system reliability. It allocates water based on mass-balance and a set of predefined priorities. The model includes MWDSC member agencies (Chesnutt 1994).

RAND IEUA-WMM

The RAND Corporation's Inland Empire Utilities Agency – Water Management Model is a WEAP-based model. The model is not geographically referenced, but aggregates supplies and demands into broad categories including surface supplies, groundwater, urban demands, agricultural demands, and return flows. The model uses historical hydrology and simulated future hydrologies to assess the Inland Empire Utilities Agency's response to climate change. It uses linear programming to allocate water based on a system of demand priorities and supply preferences (Groves et al. 2008).

Confluence ™ and ISRM

The San Diego County Water Authority (SDCWA) uses two models, the Imported Supply Reliability Model (created by the same group that created MWDSC's IRPSIM) and the *Confluence* model. The *Confluence* model uses Monte-Carlo simulations to represent uncertainties in hydrology and demands. The model routes water through SDCWA's physical pipe infrastructure and is used to assess operations and supply reliability. The ISRM model works in conjunction with *Confluence* to analyze SDCWA's system and local supplies by incorporating data provided by MWDSC's IRPSIM (SDCWA 2002).

CALVIN Background

CALVIN has gone through several generations of updates and improvements since the original appendices were written (Jenkins et al. 2001). While these appendices remain the best source for all CALVIN-related information and essential reading for anyone starting a CALVIN project, they are no longer up to date, and the earlier documentation should always be checked against the current model and metadata (stored in the CALVIN input databases). The information that has changed most relates to infrastructure and model setup – such as the number of nodes and links in the network, the area covered, or pumping capacities. Information on methods used, hydrology, and pricing remains mostly valid, except for those aspects changed in this update.

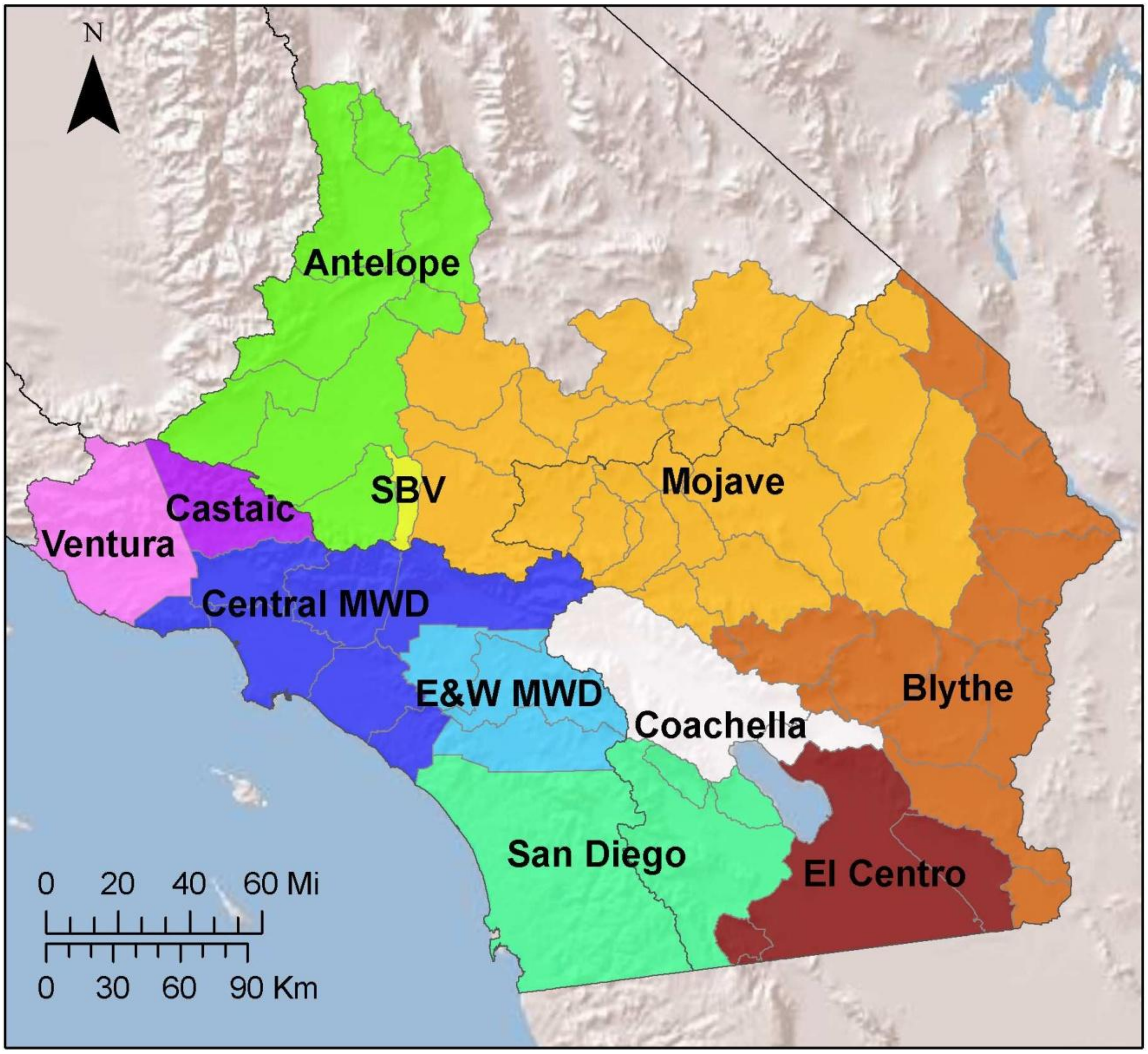
Objectives

This thesis research updated projected 2050 demands and infrastructure in the CALVIN representation of southern California and made several system-wide changes including updates to urban water rates, and the calculation of shortage penalties. Chapter 2 describes the changes made to the southern California portion of the model (Region 5) and some consequence of those changes. Chapter 3 describes the CALVIN urban economic penalty functions and the updates made to them statewide. Chapter 4 describes the division of urban residential demand areas statewide into separate indoor and outdoor demand areas based on water use with independent economic demand functions. This split allows more detailed examination of how scarcity is allocated. Chapter 4 also describes updating the penalty functions with the latest economic water demand data and bringing all costs and benefits to 2008 dollars. The last section of Chapter 4 shows the results of these changes. Chapter 5 compares some results from the updated model with earlier model results. Finally, Chapter 6 applies the updated model to examine the consequences of steep cuts in the supply of water imported over the Tehachapi Mountains to southern California.

Chapter 2
Southern California Update

This chapter documents the processes and results of updating the infrastructure and water demands for southern California (Region 5) to a set of 2050 projected conditions. It assembles all of the CALVIN data, old and new, on southern California as a reference.

Figure 2.1: CALVIN Southern California Urban Demand Areas



Description of the Region

Urban Demand Areas

CALVIN Region 5 is the portion of the state south of the Tehachapi Mountains. In the CALVIN model, it includes eleven urban and seven agricultural demand areas (expanded from three agricultural areas in earlier versions of the model), shown in Figures 2.1 and 2.2. Table 2.1 lists urban demand areas, populations, and projected 2050 target water deliveries.

Table 2.1: 2050 Projected Urban Population and Target Water Delivery

Urban Demand Area	2050 Population	Target Water Delivery (af/yr)
Antelope	1,573,750	356,034
Blythe	71,968	15,717
Castaic	543,497	159,480
Central MWD	16,980,730	3,100,520
Coachella	705,460	321,567
E&W MWD	1,348,470	792,570
El Centro	353,925	70,556
Mojave	988,644	223,664
San Bernardino	1,436,700	547,080
San Diego	4,296,800	798,825
Ventura	1,151,370	153,450
Total	**29,451,314**	**6,539,464**

The urban demand areas, alphabetically, are:

Antelope covers the Antelope Valley region including portions of Los Angeles, Kern, and San Bernardino Counties. Major cities include Boron, California City, Edwards Air Force Base, Lancaster, Mojave, Palmdale and Rosamond. The region is undergoing rapid population growth. It is supplied by the east branch of the California aqueduct, supplemented by scarce local supplies. Antelope Valley has an adjudicated groundwater basin with a long history of overdraft.

Blythe represents a spatially extensive, sparsely populated area along California's eastern border. The major cities in the region are Blythe and Needles with a combined population of less than 8,000. It receives water from the Colorado River via Palo Verde Irrigation District. The area is important despite the low population because it is a direct diverter from the Colorado River.

Castaic covers the service area of Castaic Lake Water Agency in the Santa Clarita Valley, including portions of Los Angeles and Ventura Counties and the cities of Castaic, Santa Clarita, and Valencia. It receives most if its water deliveries from the west branch of the California Aqueduct, supplemented by some local supplies.

Central MWD covers most of the member agencies of MWDSC, including Los Angeles, Anaheim, Burbank, Beverly Hills, Calleguas Municipal Water District, and Orange County. It is the largest single urban demand in CALVIN and has a high marginal scarcity cost. It receives water from the California Aqueduct, the Los Angeles Aqueduct, and the Colorado River Aqueduct (CRA), supplemented by scare local supplies and an extensive reservoir system.

Coachella covers the Coachella Valley, including the cities of Coachella, Indio, Palm Springs, and Thousand Palms. The upper part of the valley is a resort-based economy developed largely on groundwater. The lower valley is largely agricultural and supplied by the Colorado River via the Coachella branch of the All American Canal.

E&W MWD covers the area supplied by Eastern Municipal Water District and Western Municipal Water District, member agencies of MWDSC with access to all of MWDSC’s supply sources and storage facilities. The region is in rural Riverside County and includes the cities of Perris, Hemet, and Riverside. It supplements imported water with moderate local supplies.

El Centro is a conglomerate of all of the cities in Imperial Valley, including El Centro, Calexico, Brawley, and Imperial. These cities are customers of Imperial Irrigation District and are supplied from the Colorado River via the All American Canal. Outflows go to the Salton Sea.

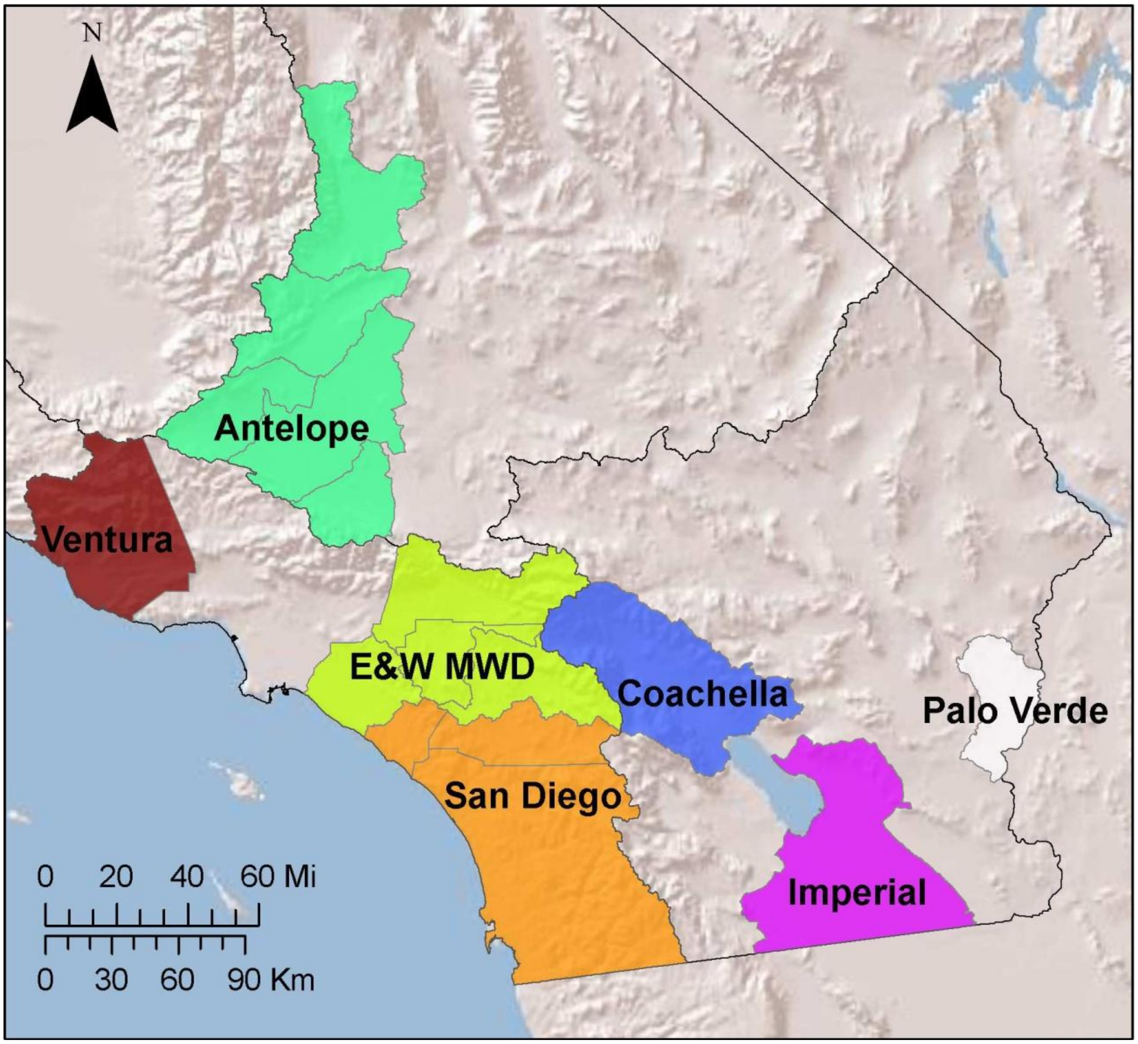
Mojave covers the service areas of the Mojave and Hi-Desert water agencies including the cities of Barstow, Victorville, and Twentynine Palms. It imports water from the west branch of the California Aqueduct, the majority of which is recharged directly to groundwater. This is another chronically overdrafted, adjudicated basin facing serious difficulties in procuring long-term water supplies.

San Diego covers San Diego County. It is a MWDSC member agency and is supplied by the California Aqueduct and the Colorado River Aqueduct and has almost no local supplies developed for urban use, although agriculture pumps heavily from private wells.

SBV covers the San Bernardino Valley including portions of Riverside and San Bernardino counties. San Bernardino is the largest city in the region and receives its water from the west branch of the California Aqueduct, supplemented by significant groundwater supplies. Due to its location at the foot of the San Bernardino Mountains, SBV is the only demand area in southern California with high groundwater levels. The water district pumps down the aquifer to avoid artesian wells and flooding in basements (SBV MWD 2007).

Ventura represents Ventura County including the cities of Ventura, Port Hueneme, Thousand Oaks, Simi Valley, and Oxnard. It receives a little water from the west branch of the California Aqueduct, 32 taf/year, but mainly uses extensive local supplies, particularly from groundwater. The groundwater basin is currently in overdraft but is being managed to alleviate this problem (FCGMA 2007).

Figure 2.2: CALVIN Southern California Agricultural Demand Areas



Agricultural Demand Areas

Projected agricultural acreage for 2050, shown in Figure 2.2, is assumed to decrease from current quantities by the conversion of agricultural land to urban uses. The acreages and applied water listed in Table 2.2 are the projected 2050 values. Cropping patterns are assumed to remain unchanged. Demand areas marked with an asterisk are new to this version of the model.

Table 2.2: 2050 Projected Agricultural Land Area and Applied Water

Agricultural Demand Area	Land Area (acres)	Applied Water Target Delivery (af/yr)
Antelope*	18,731	82,388
Coachella	61,006	333,350
E&W MWD*	38,573	90,015
Imperial	461,780	2,672,750
Palo Verde	90,100	748,410
San Diego*	62,847	169,607
Ventura*	87,288	175,183
Total	**852,119**	**4,271,703**

*New in this version of CALVIN

Agricultural demands, alphabetically, are:

Antelope Valley is a small, low value agricultural producer. Primary crops include carrots, sod, onions and potatoes. It draws water supply exclusively from groundwater.

Coachella Valley produces predominantly vegetables, grapes, and citrus. Its water supply comes from the Colorado River via the Coachella branch of the All American Canal.

E&W MWD represents agriculture in Riverside County. It produces nursery stock, table grapes, and vegetables supplied by groundwater, the SWP, and Colorado River water via the CRA.

Imperial Irrigation District (IID) produces predominantly vegetables and field crops. They hold second priority rights to California's share of the Colorado River and import it via the All American Canal.

Palo Verde Irrigation District (PVID) is the first priority, senior water rights holder on the Colorado River. Although PVID's applied water use is relatively high, their consumptive use is among the lowest in the region. The district is able to fallow more than 20,000 acres per year and sell the saved consumptive use to MWDSC. PVID grows a wide range of crops, the largest percentage of which is alfalfa and other fodder crops. In this version of the model, Palo Verde's demands were expanded to include the California portion of the Yuma Project which supplies Indian reservations along the California-Arizona border. The Yuma Project covers about 29,000 acres using 97 taf/year of applied water.

San Diego County produces nursery stock, avocados and tomatoes. Most of San Diego County's agriculture is supplied by private wells. Only rough estimates of total pumping volume are available.

Ventura County is the eighth-most valuable agricultural region in California, producing berries, stone fruits, nursery stock, and citrus. Agriculture irrigates mainly from private wells.

Data Sources

Much of the original CALVIN data came from DWR's reports, bulletins, and the California State Water Plan. While the Water Plan remains an important data source, unfortunately, its data often does not have fine enough resolution for regional and local modeling. Many of the reports and bulletins referenced in the original CALVIN documents have not been updated in the past decade thus could not inform this update. The primary sources of information for this update were municipalities' Urban Water Management Plans (UWMP) and regions' Integrated Regional Water Management Plans (IRWMP). These plans are submitted to the state every five years, so are kept up to date and are the best available data for many of these regions. However, since these contain self-reported data, the data lack significant independent review or development, may be skewed to try to justify a particular project, and are occasionally internally inconsistent.

Infrastructure

Existing CALVIN infrastructure capacities and connectivity were corroborated using agency reports or by speaking with people at the agencies. Individual sources are documented in the database metadata on each component. Measurements established with confidence and which do not need to be rechecked during the next update have been marked as final in the CALVIN database. Other data are marked as draft or provisional in the database depending on the reliability of the data source.

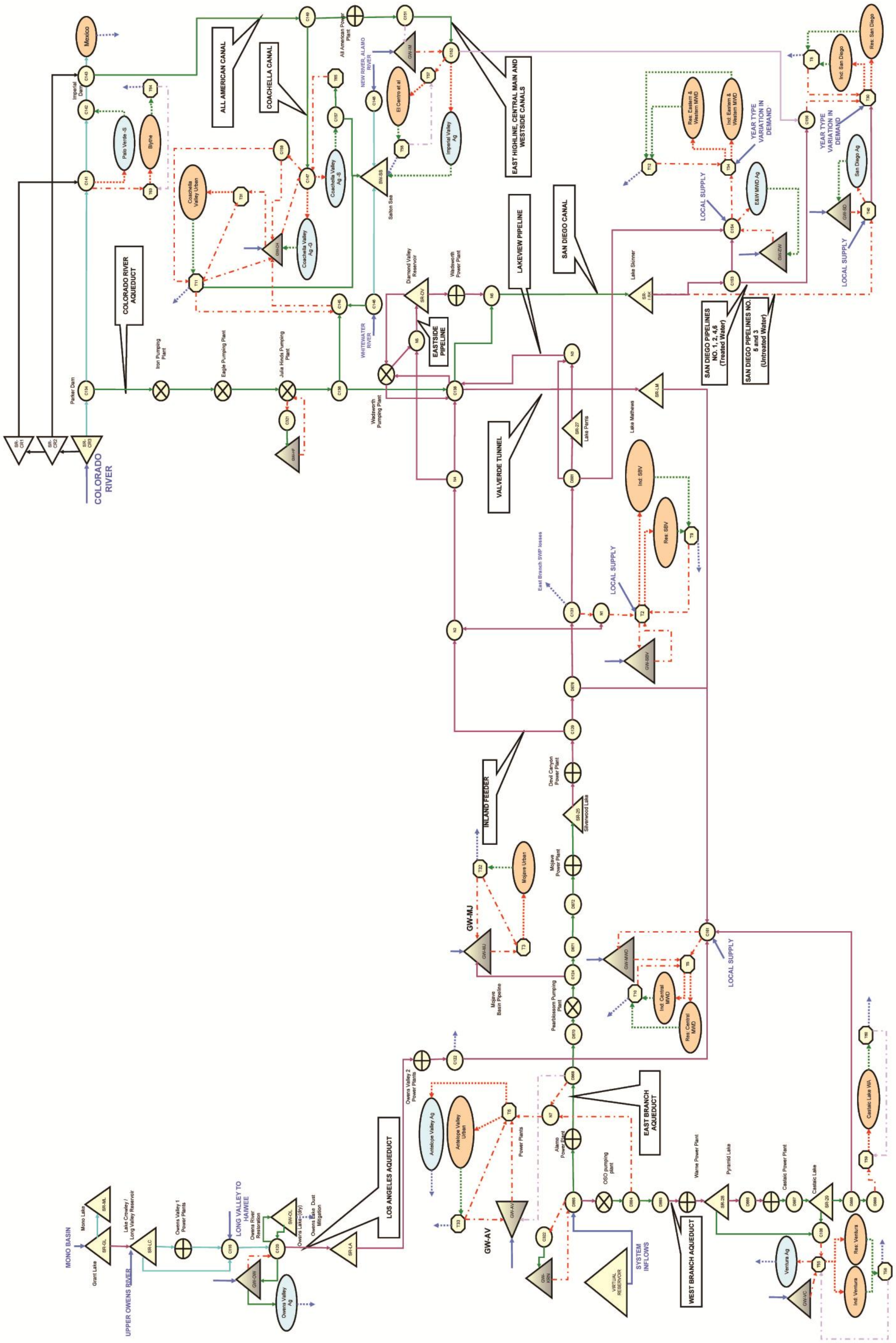
Reservoirs

Reservoir capacities were checked using information from DWR and MWDSC. Minimum capacities were set to either the dead pool or the emergency pool, following the original convention (Jenkins et al., 2001). Reservoir maximums changed very little from their original values. However, reservoir dead pools were often much lower than former CALVIN values. The largest change was at Castaic Lake where the lower bound was decreased from 294 taf to 4.1 taf. These changes may be due to physical modifications of the reservoir, erroneous original data, or calibration of CALVIN dead pool levels to match observed operations patterns, not physical realities.

Conveyance

Conveyance data were gathered from agencies, reports, legal documents, and maps. Information on the source for individual links is available in the database metadata. Almost all capacity data in southern California were rechecked against current information, but few major capacity changes were made. A few interties were added or removed, and the area around Diamond Valley Lake (formerly Eastside Reservoir) was reconfigured to reflect current operating capabilities. Also, the area around Owens Lake was altered to reflect the new Owens River restoration project and dust prevention measures. Figure 2.3 shows the new network connectivity.

Figure 2.3: Updated CALVIN Region 5 Schematic



Recycling

Regions' recycling capacity was derived from their most recent local UWMP or IRWMP. It is the regions' projected recycling capacity at their latest projection date (usually 2025 or 2030). These numbers change rapidly so should be reexamined for the next update. In general, these numbers increased from the original CALVIN values. Expanded recycling capacity, which carries a higher cost, was set at 50% of maximum projected wastewater return flows minus existing recycling capacity. Capacities are shown in Table 2.3

Table 2.3: Southern California Annual Recycling Capacities (taf/yr)

	Existing	Expanded
Mojave	25	25
Antelope	65	13
Castaic	0	18
Ventura	0.2	42
SBV	36	49
Central MWD	344	422
E&W MWD	43	114
San Diego	18	24
Total	**531**	**793**

Groundwater Recharge

Artificial recharge capacity was derived from each area's most recent UWMP or IRWMP. The current capacity was used unless realistic plans for expansion were indicated. Artificial recharge capacity was added for the San Bernardino region with the addition of a regional groundwater basin. In earlier versions of CALVIN, groundwater inflows were incorporated as part of the local inflows. Recharge capacities often change and so should be reexamined during the next update. About half of these numbers increased from the original CALVIN values while the rest remained constant.

Changes to the Network

Several elements were added to the network, Figure 2.3. Most of these are junction nodes to facilitate new aqueduct connections. Several nodes were removed as parts of the system were reconfigured. El Centro area urban demands were relocated from up near the Colorado River to down in Imperial, where it is actually located. El Centro area demands are supplied by Imperial Irrigation District and might be more consistently renamed as "Imperial Urban". The pipe connections around Diamond Valley Lake and Owens Lake were reconfigured to reflect current operating capabilities. Junctions connecting two pipelines with no changes in capacity or cost were deemed unnecessary and removed to simplify the network.

Appendix 2 contains a full list of added and deleted nodes. It also contains tables of major changes to node and link names, capacities, and connections. Major changes are defined as those that altered the shape of the network or where a constraint was changed by more than 20%. A list of all changes made to southern California as part of this update can be found in the software and data appendices of this report (Updated_Southern_CA_links.xls).

Agricultural demand areas (and associated hidden nodes incorporated to better represent losses) were added in places where the agricultural water demand exceeded 50 taf/year: Ventura, E&W MWD, San Diego, and Antelope Valley. These demands are split into ground and surface water demands. Additionally, hidden nodes were added before all existing southern California agricultural demands. These nodes separate the shadow value on the diversion from the shadow value on the delivery and are not displayed on the schematic or in the tables. Since all new agricultural demands are supplied at least 50% by groundwater, groundwater basins were added in Ventura, E&W MWD, and San Diego. A groundwater basin was also added in San Bernardino (SBV) for urban supply.

Operating Costs

The sources and values for operating cost data were not reexamined as a part of this update. Most costs are based on statewide averages for treatment, delivery, water quality, hydropower, etc. (Jenkins et al. 2001). Reevaluating those statewide averages was beyond the scope of this project. However, some local costs were changed where data was available. Original costs were presented in 1995 dollars. To make costs consistent with penalties, costs were inflated to 2008 dollars using a scaling factor of 1.48, taken from Engineering News Record's Building Cost Index, City of San Francisco, month of June (McGraw-Hill 1995 and 2008), as discussed in Chapter 4.

Supply and Demand

The original CALVIN demands were calculated from the 1998 State Water Plan, with the unit of analysis being the Detailed Analysis Unit (DAU). Unfortunately, DWR has not re-released data at that level of detail. Updated urban demands were taken from individual water agencies' UWMP or IRWMP and scaled out to 2050, if necessary. This provides projections by water agency or region.

Population Projections

Most agencies use Department of Finance figures for population projections though many also cited the Southern California Council of Governments. MWDSC and IID provide population projections to 2050; the rest provide projections only out to 2025 or 2030. Those projections were extended to year 2050 using the growth rate of the previous five year period. (For example, projections for 2030 were scaled using the growth rate from 2025-2030.) Total water use was scaled from the latest projection to 2050 by the population ratio, assuming constant per capita demand.

Dividing the region by water agency rather than by DAU produces some population shifts from the original CALVIN model. The total 2050 projected population is very similar, but the areas of population concentration shift, with some areas, such as San Bernardino, being assigned a larger population than in the previous projections and other areas, such as Mojave, a lesser population.

Indoor and Outdoor Demand Split

A major change in this version of the model was dividing urban residential demands into indoor and outdoor portions with separate economic cost functions. Indoor demand represents uses inside the home such as cooking, bathing, or laundry as well as commercial uses and industrial uses in those demand areas where industry is not modeled separately. Outdoor demands include uses outside of the dwelling such as yard and garden maintenance or car washing. Indoor and outdoor uses also have different price elasticity of demand (-0.15 for indoor, -0.35 for outdoor) and different rates and destinations for return flows (90% of interior use returns to a treatment plant; 10% of outdoor use returns to groundwater). Details of this split will be discussed in Chapter 4.

Agriculture

New agricultural demands were added for Ventura, E&W MWD, San Diego, and Antelope Valley. Agriculture in southern California was modeled using the Statewide Agricultural Production Model (SWAP) (Howitt et al. 2010; Howitt et al. 2001). The SWAP model includes agriculture in Coachella, Palo Verde, Imperial Valley, Ventura, San Diego, Antelope, the Los Angeles area, and Yuma, California. SWAP uses positive mathematical programming or PMP (Howitt 1995), a method in which agricultural production for different regions and crops are calibrated to observed production factors such as land, water, labor, and supplies. Farmers aim to maximize profits from farming by considering land and water availability in each region as well as budgetary constraints.

SWAP employs DWR estimates of land use and applied water for nineteen crop groups including alfalfa, almonds and pistachios, corn, cotton, cucurbits, dry beans, fresh and processing tomatoes, grains, onions and garlic, truck crops, pasture, potatoes, safflower, sugar beet, citrus and subtropical fruits, and vine crops. Irrigated land areas correspond to DAU boundaries.

Agricultural production modeled for year 2050 is estimated in SWAP using 2005 base data but takes into account technological improvements in crop yields (Brunke et al. 2004), urbanization (Landis and Reilly 2002), and estimated shifts in crop demand by year 2050 (Howitt et al. 2008). SWAP assumes an average 29% increase in yields for all crops by 2050. Based on Landis and Reilly (2002), 20% of current agricultural land in the South Coast hydrological region (including Ventura, MWDSC, and San Diego) is expected to be converted to urban uses by year 2050. Agriculture in Coachella, Palo Verde, Imperial, and Yuma is expected to stay about the same size in terms of irrigated land area (with less than 2% reduction), and Antelope Valley is expected to have 10% conversion of current agricultural land to urban uses. Projected cropping patterns are driven by the profit-maximizing behavior of farmers considering improved yields, decreased land availability and changes in crop prices.

Derived water demand functions for SWAP regions are obtained by gradually constraining water availability and calculating the corresponding Lagrange multiplier on the water constraint. Lagrange multipliers are used as a measure of the marginal economic value (or shadow value) of water for all crops within a region. Medellín-Azuara et al. (2010) provides details on PMP optimization programs and a comparison of shadow values at farm and regional levels. SWAP provides CALVIN with economic values of water shortage in agriculture for every region, calculated by numerical integration of the piecewise linear derived water demand functions. Monthly estimates of evapotranspiration by crop group are employed to obtain monthly water shortage costs for CALVIN as sets of penalty functions.

Revisions to SWAP in the Colorado River and South Coast hydrologic regions developed for this study increased CALVIN agricultural water supply coverage by more than 250 thousand acres with the inclusion of agriculture in Ventura, San Diego, the Antelope Valley, Los Angeles and Riverside Counties and small areas in the Colorado River region.

Losses

Losses are represented in CALVIN through the link amplitude. The amplitude represents the fraction of the water going into the link which comes out the other end. The rest is lost to consumptive uses, such as or evapotranspiration. Most loss rates were not reexamined due to a lack of any better data. The loss rate on the All American Canal was adjusted to reflect the savings with the new canal lining project, based on information from IID. Total conveyance losses in the Colorado River hydrologic region were estimated at 360 taf/year (DWR 2009).

Inflows

Very little new data were available from water agencies on inflows into the region, nor were any metadata available on the original Region 5 inflow data. Appendix I of the original CALVIN report implies that inflows for Region 5 were developed from US Geologic Survey (USGS) stream gauge data and precipitation data (Jenkins et al. 2001). However, no information could be found on which gauges were used for each inflow or how the inflow time series were constructed from the raw data. These data were accidentally deleted after the initial project was completed.

All previous inflow data appear to have a logical basis (the inflows vary monthly and year to year with more water in the wet years and less in the dry years). Consequently, inflow patterns were preserved, but the time series was rescaled so that annual average inflow matches the annual average surface or groundwater inflows reported by the agencies in their IRWMP/UWMP. Changes are shown in Table 2.4.

Table 2.4: Average Annual Inflows (taf)

	Initial	**Revised**
Mojave	70	68
Antelope	54	135
Castaic	50	57
Ventura	203	311
SBV	217	317
Central MWD	1,487	1,408
E&W MWD	316	142
Coachella	139	123
Imperial	192	25
San Diego	150	165
Total:	**2,880**	**2,752**

For MWDSC member agencies (Central MWD, E&W MWD, and San Diego), MWDSC provided data on local surface and groundwater use by year from 1975 to 2009. For the period 1975 to 1993, these data were used directly to form the inflow time series. For years outside this range, an average value by year-type was substituted. The monthly split was done following an average hydrograph for the region. San Diego groundwater inflows also had an additional 219 taf/year added to the reported local supplies to supply previously unmodeled agriculture drawing from private wells.

Formerly, E&W MWD, San Diego, Ventura, and San Bernardino's groundwater had been modeled as part of local supplies. E&W MWD, San Diego, and Ventura's groundwater basin capacities are set to 10,000 taf. This preliminary estimate should be improved as better data become available. San Bernardino's basin has a capacity of 11,620 taf (SBV MWD 2007). For all four basins, initial storage is constrained to match ending storage. Inflows to the E&W and San Diego basins are based on data from MWDSC (Nevils personal communication).

A new inflow set was added for Ventura groundwater basin. This inflow provides the reported safe yield of the basin every year, split monthly in proportion to monthly rainfall. It doesn't reflect inter-annual variations in hydrology, and should be improved as better data become available. Fox Canyon Groundwater Management Agency in Ventura has a 50+ year model of the largest groundwater basin in the county, but that information is not currently in the public domain. A complete list of the current inflows and how they were calculated is in the software and data appendices (Recalculated_Inflows.xlsx).

The original macro that generates the piece-wise linear approximations to the penalty curves, included a procedure for subtracting local supplies not explicitly modeled in CALVIN from the demands. This practice was discontinued several updates ago as it distorted the total demand amounts, confused the elasticities, and made accurate reporting difficult. Now all inflows are explicitly represented in CALVIN. The obsolete procedure has been removed from the updated macro to avoid confusion.

Year Type Variations in Demand

MWDSC's simulation model, IRPSIM, calculates demand based on the historical hydrology. Therefore MWDSC was able to provide an estimate of their 2050 demands under a repeat of each past water year's historical hydrology. This number was used to calculate a year type variation in demand for the MWDSC member agencies. Indoor, industrial, and commercial demands were assumed to remain constant and were based on an average annual demand level and the DWR water use by sector percentages. Outdoor use (including large landscape uses) was calculated as the area's maximum annual demand level over the 72 years of hydrology minus the previously calculated indoor, industrial, and commercial uses. This maximum use is modified by local inflows coming in to a hidden node before the outdoor demand area. The local inflows are calculated as the maximum annual demand minus the actual annual demand, split monthly by the average hydrograph. This local inflow will slightly distort the margins controlled by these areas, but the distortion should be inconsequential for small shortages, and allows inter-annual variation in demand. These variations were applied only to MWDSC member agencies: Central MWD, E&W MWD, and San Diego.

This type of year type variation in demand had been previously implemented in early CALVIN models but was removed prior to the current generation of model. This type of manipulation of inflows and demands might cause some problems with evaluating marginal costs or total demand.

Year type variation in demand essentially applies a combination of real and time-varying virtual water to meet a maximum demand every year. When processing the return flows, the real water must be separated from the virtual water, so that the real water can be sent to groundwater, and the virtual water can be sent to sink, preserving true mass-balance. To do this, the locations where year type variation in demand has been applied have a time series of upper bounds on their return flows to groundwater. These upper bounds are 10% of the demand. The remaining return flows go to a sink and are lost to the system. The link to groundwater has no cost while the sink has a small cost, $1/af, so that the model prefers to send return flows to groundwater, up to capacity. As demands are updated, these times series should be updated as well.

Penalties

Penalties were calculated as described in Chapters 3 and 4, with one minor change. New data for non-industrial monthly demand fractions were provided by MWDSC for Central MWD, and these data were used to generate new penalties.

Calibration

Because the original CALVIN model was already well-calibrated, very little additional calibration was needed for this update.

Correcting Some Old Errors

While examining the model outputs in detail as a part of calibration, some errors were found outside of southern California. In CVMP3 and CVPM12 agricultural demand areas, small recurring shortages occurred in August. These shortages were due to a mismatch between the groundwater pumping capacity upper bound and agricultural groundwater demand. Since no new data were available on pumping capacities, it was assumed that pumping capacity had expanded with water demand. The expansion at each location is recorded in the database metadata.

Sicke (2011) found that several urban wastewater recycling expansion links had been turned off. These links were reactivated. Some groundwater pumping inaccuracies near Napa also were resolved. A list of these changes can be found in the software and data appendices (Infrastructure_changes.txt).

Calibration Links

Little calibration was needed to make the updated southern California model feasible. A calibration link was added from GW-IM to sink to account for extensive agricultural and urban return flows to groundwater in the Imperial Valley and the lack pumping due to poor water quality. Without the sink, the groundwater basin overflows. Representation of outflows and losses from this basin should be improved as better data become available. Calibration links from El Centro to sink and from Silverwood Lake to sink were removed as unnecessary. The capacity of both links had been set to zero previously. A calibration link from T2SBV to sink, representing SBV agricultural deliveries was updated and retained. SBV agricultural deliveries remain too small (less than 50 taf/ year) to model economically.

Future Southern California Improvements

In southern California, existing urban recycling and groundwater recharge capacities are constantly changing, and while the values in the model accurately represent current and planned expansions to capacity, this could change in a few years. One use of the model is to estimate the value of continuing to expand these facilities.

Groundwater data, particularly capacities and recharge rates, are difficult to obtain. All of the new groundwater basins and many of the existing ones have estimated capacities. Natural inflow rates are based on estimates of annual safe yield, divided into monthly increments by annual precipitation pattern. This is relatively accurate when averaged over a long time horizon but does not necessarily reflect the hydrology of any one year. Updated values for Owens Valley groundwater were unobtainable and the original values lack metadata. Surface water inflows are also based on average annual values, not observed data. The lack of metadata on the original sources for these flows causes some uncertainty. Again, these values are likely to be accurate over the 72-year average, but do not necessarily accurately reflect the hydrology of any one year.

Post-Processing

The splitting of urban demands and the expansion in the number of sampling points for the linear approximations of outdoor water scarcity penalties, required some modifications to old post-processors. Flow finder, urban scarcity, and agricultural scarcity post-processors have been developed for this model. Changes to the macros are documented within the code.

Results

The southern California update changed demands, inflows, and infrastructure in CALVIN Region 5. These updated demands were used to calculate new penalties based on the same equations and 1995 reference prices and quantities as those used in the Penalty Update run (Pen Updt) described in Chapter 3. All prices are calculated and displayed in 1995 dollars.

Demands and linkages in Regions 1 through 4 were not changed during this southern California update process, and should be identical between the two models - except for the calibration changes mentioned above. All CALVIN regions have a 2050 level of projected demand. This projection was revised in Region 5 to better reflect current projections of 2050 population and water demand. Because Regions 1 through 4 were not a part of this update and their results were largely unaffected by it, they are not discussed. In the base case, the southern California Update model demonstrates reasonable scarcity levels for all urban and agricultural demands areas.

Capacity Constraints

Water shortages in CALVIN have three possible causes. The first is economic – the water is available to the demand area, but users are not willing to pay enough to supply all demands, considering operating costs and the opportunity cost of supply. The second cause is insufficient capacity – the demand area lacks sufficient incoming conveyance capacity to take delivery of their target demand level at any price. The third cause is that there is simply no water available. To distinguish between economically driven shortages and capacity issues, Table 2.5 lists average annual supplies and demands for areas in Region 5. Imported supplies are the maximum amount of water that could be delivered by an agency’s incoming conveyance links. Groundwater supplies reflect the lesser of inflows to the groundwater basin or pumping capacity. Water recycling and desalination capacity are not accounted for in Table 2.5.

Table 2.5: Annual Water Supply and Target Delivery (taf/yr)

	Average Demands*				**Maximum Supplies***			**Net #**
	Out	In	Industry	Ag	Surface	Ground	Imports	**Water**
Mojave	117	103	0	0	0	68	289	137
Antelope	248	102	0	80	7	110	662	349
Castaic	83	78	0	0	57	0	1267	1163
Ventura	77	71	7	175	37	258	32	-3
SBV	371	168	7	36	39	277	270	4
Central MWD	1493	1666	113	0	102	1456	4630	2916
E&W MWD	569	311	6	69	11	235	1173	464
Coachella	149	172	0	214	0	329	1280	1074
Palo Verde & Blythe	10	6	0	481	0	0	4400	3903
El Centro & Imperial	44	26	0	2122	0	0	7352	5160
San Diego	490	343	3	172	28	339	1293	652

* Out – outdoor water uses; In – indoor water uses (residential and commercial)

Net Water – Maximum supply minus average demand

From Table 2.5, only Ventura has shortages induced by a lack of delivery capacity. All other shortages are economic. Ventura has only 0.5 taf/year of existing recycling capacity, not enough to cover the shortfall, and the potential to add an additional 42 taf/year at higher cost. In reality, Ventura accommodates this shortfall by overdrafting groundwater. However, in this model run, overdraft is prohibited, causing persistent shortage. The Ventura County water agencies' long-term plan for alleviating this shortage is to build an expanded SWP connection to enable delivery of SWP water that they already hold contracts to (Watersheds Coalition of Ventura County 2007). Outside of Region 5, Santa Barbara-San Luis Obispo (SB-SLO) also has capacity issues due to high growth projections for 2050 demand. This explains why SB-SLO consistently has scarcity and desalination in every model run, despite a high willingness-to-pay (WTP). The model also under-represents many of the local water supply management options available to the SB-SLO region, which receives only a modest proportion of its supplies from the SWP.

Urban Scarcity

Outside of Region 5, there is very little change in urban scarcity when compared to the Penalty Update base case described in Chapter 3. This is reasonable, as little was changed for those areas. The two changes observed are a 2 taf shortage in Napa-Solano where the groundwater correction was applied and a 0.3 taf increase in scarcity for SB-SLO.

Table 2.6: 2050 Average Annual Urban Scarcitiy Analysis

	WTP ($/af)		Scarcity Cost ($k)		Scarcity (taf)		Target (taf)	
	Pen Updt	SC Updt	Pen Updt	SC Updt	Pen Updt	SC Updt	Pen Updt	SC Updt
Mojave	0	1,093	0	17,684	0	21	809	221
Antelope	0	1,278	0	33,853	0	28	252	350
Castaic	627	977	3,935	9,460	6	10	144	161
Ventura	916	1,349	10,409	8,876	12	7	236	155
SBV	0	801	0	30,051	0	36	238	547
Central MWD	0	0	0	0	0	0	3,298	3,279
E&W MWD	432	981	34,429	36,516	38	30	817	886
San Diego	398	0	31,061	0	35	0	1,076	836
Coachella	0	919	0	35,662	0	28	985	321
Blythe	390	411	668	317	2	0.6	54	16
El Centro	390	0	1,362	0	4	0	118	70
	Max		**Total**		**Total**		**Total**	
	916	1,349	81,864	172,419	96	161	8,027	6,842

Table 2.6 shows the urban scarcity results within Region 5. Since in the southern California Update case (SC Updt), urban demands were split into indoor and outdoor sub-areas, the values are combined for display. WTP values are the maximum of indoor and outdoor WTP. All other values are sums.

Contrary to what might be expected, the 2050 Region 5 urban target demand decreases by 15%, 1.2 maf/year, from the projected 2050 levels of earlier versions of CALVIN. Some of this change might be caused by reduced estimates of population growth in some areas, but much of it can be accounted for by conservation, reducing average per capita use in southern California from 0.25 af/person/year to 0.22 af/person/year. Many conservation measures such as low flow toilets and water efficient sprinklers provide permanent water demand reductions.

Total urban and agricultural demands in southern California decreased by 10% with this southern California update. Comparing the two models, the total urban scarcity increased by 67% and the total scarcity cost increased by 111%. This increase in scarcity is caused in part by the slight reduction in inflows (128 taf/year) and an increase in agricultural demands (nearly 1 maf/year). However, taking into account the overall reduction in demand, the change in total scarcity and scarcity costs seems primarily driven by regional shifts in demand.

Demand Changes by Supply Source

Two major sources of water imported to southern California are from northern California over the Tehachapi Mountains in the SWP's California Aqueduct and from the Colorado River via the Colorado River Aqueduct, All American Canal, or direct diversion. Urban demand areas can be grouped into three categories depending on their supply source.

Table 2.7: Changes in Urban Demand (initial vs. revised)

	(taf)	(%)
MWDSC	-190	-4%
Non-MWDSC SWP	-245	-15%
Colorado River	-654	-71%
Total	**-1,089**	**-67%**

The non-MWDSC SWP contractors: Antelope Valley, Mojave, Castaic Lake, Ventura County and San Bernardino Valley, depend solely on the California Aqueduct for imported water. The Colorado River region: Coachella, El Centro (a conglomerate of Imperial Valley cities), and Blythe, receive only Colorado River water. MWDSC member agencies: Central MWD, E&W MWD and San Diego, can receive water from both sources. From Table 2.7, while all regions have less projected urban demand with the update, the decreases in projected demands for the Colorado River region are significantly larger than the decreases for the non-MWDSC SWP contractors, both in magnitude and percentage. MWDSC demands remain relatively constant. This change in demand pattern drives changes in water use and scarcity in the remaining chapters of this thesis.

Indoor-Outdoor Split

A major innovation in this revision was separating urban residential demands into in-home, indoor uses, and yard and other outside, outdoor uses with separate economic demand functions. This allows examination of how water users allocate shortage in more detail. In Table 2.8, in almost every case, shortages were split between indoor and outdoor demands so that the marginal cost of scarcity, represented by WTP, was equal. This can be interpreted as people eliminating the lowest value uses of water first, both inside and outside.

This balancing of WTP leads to outdoor shortages two to six times larger than indoor shortages. The ratios of indoor to outdoor shortages aren’t the same as the ratios of indoor to outdoor uses, however they follow the same ranking (the highest ratio of outdoor to indoor uses). Antelope Valley has the highest ratio of both outdoor to indoor water use and scarcity. In total, 75% of all scarcity is allocated to outdoor uses in this case. This confirms that the most, but not all, low-value residential consumptive uses of water are outside the home.

Table 2.8: 2050 Annual Indoor-Outdoor Scarcity Split

	WTP ($/af)	**Scarcity Cost ($k)**	**Scarcity (taf)**	**Target (taf)**
Out: Mojave	892	10,042	13	117
In: Mojave	1,093	7,642	8	104
Out: Antelope	1,278	28,878	24	248
In: Antelope	1,263	4,975	4	102
Out: Castaic	977	7,131	8	82
In: Castaic	962	2,329	2	78
Out: Ventura	1,215	5,436	5	77
In: Ventura	1,349	3,440	3	71
Out: SBV	817	24,459	29	371
In: SBV	868	5,592	6	168
Out: Central MWD	0	0	0	1,500
In: Central MWD	0	0	0	1,666
Out: E&W MWD	765	25,664	22	569
In: E&W MWD	883	10,852	8	311
Out: San Diego	772	23,634	19	490
In: San Diego	919	12,028	9	343
Out: Coachella	0	0	0	149
In: Coachella	0	0	0	172
Out: Blythe	340	228	0	9
In: Blythe	458	88	0	6
Out: El Centro	0	0	0	44
In: El Centro	0	0	0	26
	Max	**Total**	**Total**	**Total**
Outdoor	1,278	125,472	120	3,656
Indoor	1,349	41,354	34	2,879
Combined	1,349	166,826	154	6,535

Agriculture

Agricultural results outside of Region 5 showed little change in scarcity or WTP with the southern California Update. In the base case, the only areas outside of Region 5 with agricultural scarcity are CVPM 3 and 12, despite efforts to correct that as part of calibration. The correction reduced average annual scarcity in CVPM 3 from 93 taf to 1 taf. Scarcity in CVPM 12 remained the same despite adding groundwater pumping capacity, suggesting that it may be economically driven.

Table 2.9 compares agricultural scarcities between the Penalty Update model and the southern California Update model. Blank cells in the Penalty Update columns represent new agricultural areas absent in the earlier model. Total agricultural applied water demands represented in southern California increased by 56%. This is partly due to adding four new agricultural areas, and partly expanded Colorado River region agricultural demands. The demands for southern California agricultural areas previously represented increased by 17%, with only Coachella decreasing. This decrease is a correction to the previous overestimate of agricultural water use in the Coachella region.

Palo Verde Irrigation District diverts and applies significantly more water than their consumptive use. According to the US Bureau of Reclamations (2005-2009), their recent average consumptive use has only been 345 taf/year. However, CALVIN penalties are based on applied water, not consumptive use, so the larger number is used here. Additionally PVID has an active fallowing program and sells a portion of their consumptive use to MWDSC.

Table 2.9: 2050 Average Annual Agricultural Scarcity Analysis

	WTP ($/af)		**Scarcity Cost ($k)**		**Scarcity (taf)**		**Target (taf)**	
	Pen Updt	SC Updt	Pen Updt	SC Updt	Pen Updt	SC Updt	Pen Updt	SC Updt
Antelope	-	145	-	15,407	-	80	-	80
Ventura	-	0	-	0	-	0	-	175
E&W MWD	-	389	-	6,058	-	23	-	69
San Diego	-	0	-	0	-	0	-	172
Coachella	321	153	17,195	4,527	153	26	554	333
Imperial	208	141	148,862	146,852	622	814	2,187	2,673
Palo Verde	0	57	0	1531	0	19	494	784
	Max		**Total**		**Total**		**Total**	
	321	389	166,057	174,375	775	963	2,741	4,286

The amount of water demanded by MWDSC urban users (Central MWD, E&W MWD, and San Diego) has remained nearly constant between the two models. The shifts in demand pattern are due to changes in demand between the other SWP contractors and the Colorado River region. In the Penalty Update model, the thirstier region was the Colorado River Region, which could be easily satisfied by transfers from nearby agricultural areas. Now, with the significant drop in projected urban demand in that region, the thirstier region is the South Coast. However, the Colorado River Aqueduct is already operating at capacity to supply MWDSC member agencies and has no connectivity to the other SWP contractors, so there is no way for agricultural users on the Colorado River to transfer more water west to the areas of high demand.

Since Colorado River water cannot physically be transferred to where it is economically more valuable, the Colorado-based agricultural regions receive more water, though not their full demand. Agricultural regions like E&W MWD and Antelope Valley that have capacity to transfer water to South Coast urban users do so and thus have higher levels of scarcity. Overall, relative agricultural scarcity decreases in the southern California Update model from 28% to 22% of target water delivery.

Ventura County is a South Coast agricultural region that does not transfer water to urban uses. It is largely self-sufficient, receiving 98% of its supplies from local groundwater. Agriculture in Ventura County is also so high-valued, with a marginal cost of $1,608/af for the first unit of scarcity, that it is actually economically preferable to short local urban uses (with a marginal cost of $881/af for the first unit of indoor scarcity) before agriculture. The region's primary crops include table grapes, stone fruit, and pistachios. San Diego's agriculture was also unaffected by scarcity, despite some urban scarcity and a moderate WTP in San Diego's urban areas. It is another high value ($1,460/af marginal cost for the first unit of scarcity) agricultural area with significant groundwater pumping. Most agriculture in San Diego County is supplied by private wells.

Table 2.9 shows Antelope Valley agriculture is being deprived of 100% of its water in the base case – the most optimistic case examined in this thesis. Antelope Valley produces primarily sod and potatoes, and comparing the low marginal WTP for the last, and thus highest cost, unit of agricultural water ($145/af) with the WTP of Antelope Valley's urban uses ($863/af), continuing agricultural production in this location in 2050 may be economically unviable unless the current crop mix is shifted towards higher value crops.

Industrial

Industrial uses have a much higher marginal cost for the first unit of scarcity than residential or agricultural uses. Consequently, there was no industrial shortage in the low scarcity, base case.

Conclusions

Increases in scarcity and scarcity cost in the southern California Update model are driven by shifts in urban demand from the Colorado River region to the South Coast. Cities on the South Coast tend to be larger and have a higher scarcity cost than their inland counterparts. Due to limitations in east to west conveyance capacity, it is also significantly more difficult for the largest southern California agricultural regions, located near the Colorado River, to transfer water to these urban demand areas, increasing urban scarcities and reducing agricultural scarcities with corresponding changes in scarcity cost.

Chapter 3

Urban Penalty Equation Update

While employing the original penalty function equations (Appendix B2 of Jenkins et al. 2001) to update CALVIN urban demands for year 2050 in the southern California Region, penalties and marginal willingness to pay were observed to display counterintuitive trends and disproportionally high values for some locations. When no calculation error could be found, the set of governing equations was revisited. It was realized that the quantity ratio (2050 versus 1995 total water demand), rather than the population ratio, was the appropriate scaling ratio to preserve the marginal values of the demand curve. This chapter discusses how this update to the penalty equations affects penalties, water distribution, and shortage costs statewide. Information in this chapter is based on the original 2050 demands, infrastructure, and the following assumed seasonal elasticities: winter = -0.15, summer = -0.35, intermediate = -0.25.

Penalty Equations

Following Appendix B2 of the original CALVIN report (Jenkins et al. 2001), the penalty equations in CALVIN were determined as follows:

The price elasticity of demand η is defined as:

$\eta = (\Delta Q/Q)/(\Delta P/P) = (dQ/Q)/(dP/P)$ (1)

where P is the price at which the observed quantity Q is demanded. Assuming constant elasticity (as assumed here), equation 1 is re-arranged and integrated to produce the following demand function:

$P = \exp[\{\ln(Q)/\eta\} + C]$ (2)

where C is the integration constant. With an observed price (Pobs), observed level of water use (Qobs) at that price, and an estimated η, the constant is defined as:

$C = \ln(Pobs) - \{\ln(Qobs)/\eta\}$. (3)

First, the 1995 residential demand functions are generated by computing an integration constant (equation 3) from the 1995 retail price, the 1995 level of residential water use, and the appropriate elasticity estimate. The curve is then scaled by the 2050 population increase. An adjusted constant for the scaled 2050 demand curve is calculated from the 1995 constant and the 2050 to 1995 population ratio PR(2050/1995) as follows:

$C2050 = C1995 + \{\ln(1/PR(2050/1995))/\eta\}$ (4)

The final residential penalty function derived by analytically integrating equation 2 over the specified limits is:

$PEN(QR) = [\exp(C2050)/\{1+(1/\eta)\}] \times [Q2050\ \hat{}\{1+(1/\eta)\} - QR\ \hat{}\{1+(1/\eta)\}]$ (5)

Where Q_{2050} is the target 2050 demand and Q_R is the actual delivery.

Scaling Ratio

Discussions with Prof. Pierre Merrel of the Agricultural and Resource Economics Department at UC Davis indicated that scaling by the demand ratio ($QR=Q_{target20}/Q_{target95}$)

produces more accurate results than scaling by the population ratio ($PR=Pop_{2050}/Pop_{1995}$). Scaling by the population ratio neglects changes in per capita use and thus distorts the shape of the penalty curves.

Figure 3.1: Penalty vs. Delivery for Various Scaling Ratios

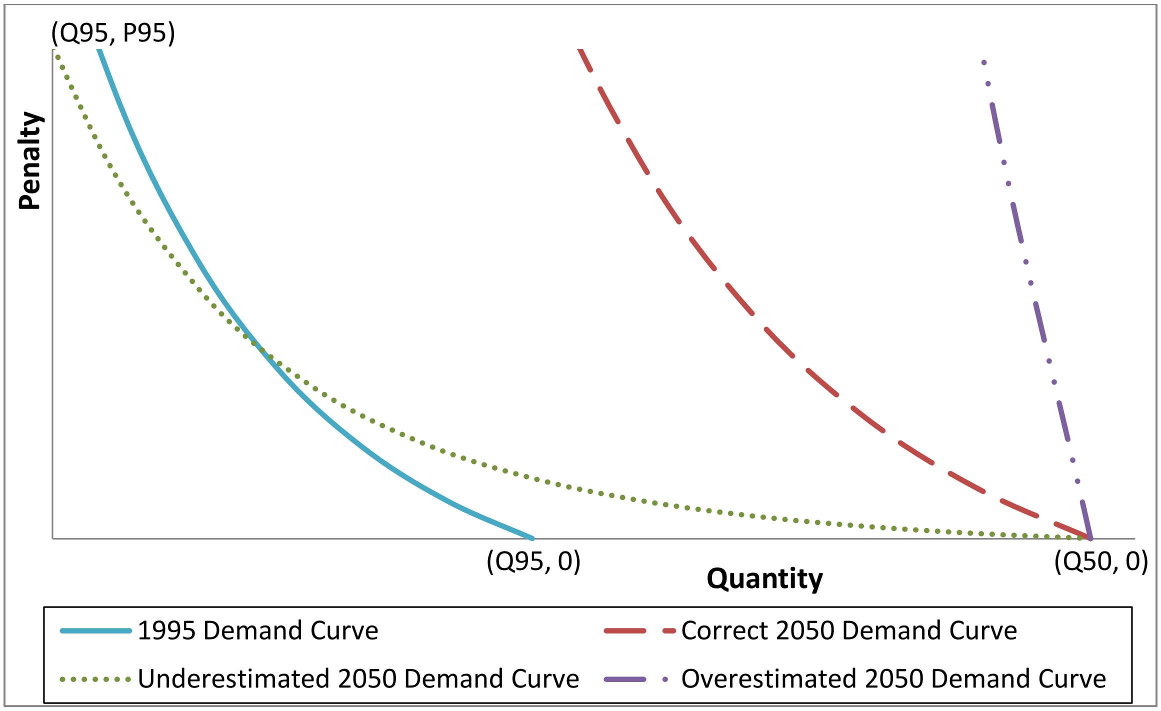


Figure 3.1 illustrates the observed 1995 demand curve [solid blue] scaled up to 2050 target deliveries by the quantity ratio [red dashed], a population ratio larger than the quantity ratio [purple dash-dot] (decreasing per capita use) and a population ratio smaller than the quantity ratio [green dotted] (increasing per capita use). The different scaling factors affect the slope of the curve, the distance between points on the 1995 curve and the 2050 curve, and the value of the penalty at a given delivery quantity.

The original penalty curve is defined by two known (Quantity, Penalty) points: (Q_{target}, 0) and the point calculated from P_{obs} and Q_{obs}: (Q_{95}, P_{95}). At any level of consumption, X, $Q_{targetX}$ is a clearly known user input. However (Q_X, P_X) is arrived at by scaling (Q_{95}, P_{95}) by the scaling factor being used. $Q_{target20}$ is $Q_{target95}$ multiplied by QR, but when (Q_{95}, P_{95}) is then scaled up by PR, the two fixed points on the curve are being scaled up by different factors, thus changing the slope. If PR > QR, as is the case for almost all demand areas (due to water conservation reducing per capita use), the slope becomes steeper than it should. If QR < PR, the slope will be flatter. Thus, the updated penalties will mostlybe less than the original penalties. This concept is illustrated graphically above and in tabular form below.

Table 3.1: Margin vs. Percent Delivery for Various Population Ratios ($/af)

PR/QRactual	1/3	2/3	1	4/3	5/3	2
100%	0	0	0	0	0	0
95%	1	55	824	5,607	24,822	83,697
90%	1	67	997	6,789	30,051	101,328
85%	1	82	1,231	8,377	37,079	125,028
80%	1	104	1,552	10,561	46,751	157,639
75%	1	134	2,005	13,648	60,413	203,707
70%	2	179	2,665	18,140	80,296	270,751
65%	2	245	3,659	24,902	110,230	371,685

Table 3.2: Margin vs. Percent Delivery for Various Quantity Ratios ($/af)

QR	0.5	1	1.5	2	2.5	3
100%	0	0	0	0	0	0
95%	824	824	824	824	824	824
90%	997	997	997	997	997	997
85%	1,231	1,231	1,231	1,231	1,231	1,231
80%	1,552	1,552	1,552	1,552	1,552	1,552
75%	2,005	2,005	2,005	2,005	2,005	2,005
70%	2,665	2,665	2,665	2,665	2,665	2,665
65%	3,659	3,659	3,659	3,659	3,659	3,659

The margin is the slope of the penalty curve at different delivery levels. Table 3.1 illustrates how scaling by PR < QR will very quickly flatten the curve while scaling by PR > QR steepens it. Thus when scaling by PR, the slope of the curve depends on the relationship between PR and QR. Table 3.2 illustrates that by scaling by QR, the slope of the penalty curve correctly remains constant for any quantity ratio.

Discussion

These changes resolve some limitations and issues discussed by Jenkins et al. in Appendix B2 of the original CALVIN report, including the limited range of applicability (Jenkins et al. 2001). Appendix 1 of this document demonstrates graphically the more logical and consistent behavior of various aspects of the penalty equations after the update, especially at the margins.

Table 3.3: Underestimated Penalties (increasing per capita use)

Urban Area	% Change
Blythe	27%
CVPM8	2%
CVPM12	119%
Mojave	19%
Redding Area	17%

Table 3.4: Overestimated Penalties (decreasing per capita use)

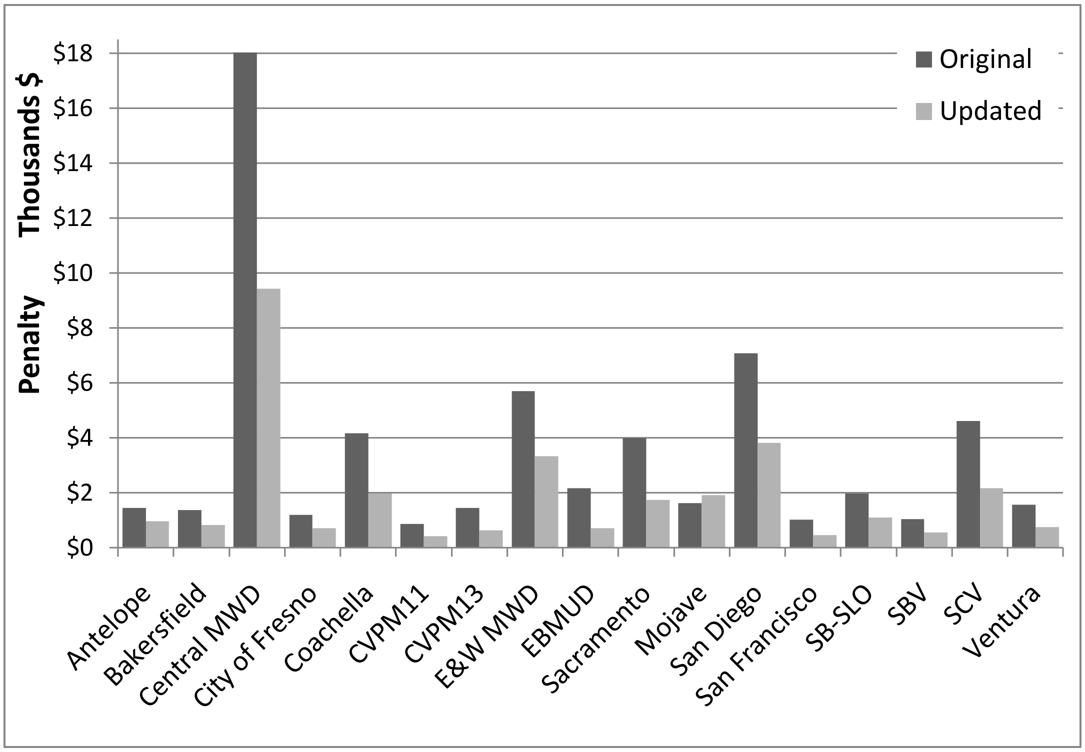
Urban Area	% Change	Urban Area	% Change
Antelope Valley	-34%	CVPM3	-60%
Bakersfield	-40%	CVPM4	-56%
Castaic Lake	-32%	CVPM5	-91%
Central MWD	-48%	CVPM6	-15%
City of Fresno	-41%	CVPM9	-26%
Coachella Urban	-53%	E&W MWD	-42%
Contra Costa	-82%	EBMUD	-68%
CVPM10	-22%	El Centro	-53%
CVPM11	-51%	Sacramento	-57%
CVPM1	-57%	Napa-Solano	-23%
CVPM14	-41%	San Diego	-46%
CVPM15	-39%	San Francisco	-56%
CVPM17	-76%	SB-SLO	-44%
CVPM18	-38%	SBV	-47%
CVPM19	-94%	SCV	-53%
CVPM20	-49%	Stockton	-38%
CVPM21	-67%	Ventura	-52%
CVPM2	-6%	Yuba City	-38%

The original penalty equations overestimated the shortage costs for most urban demand areas. Overall, 36 of the 41 urban demand areas had penalty overestimates (Tables 3.3 and 3.4). The average change per demand area in urban penalty after the update was a decrease of 38%, while the sum of urban penalties statewide decreased by 49%. Since the only term in the equation which changed was the scaling factor, these percentages remain constant at all delivery levels. Thus for a very low penalties the magnitude of the overestimate was relatively small, while at greater shortage levels the magnitude of the overestimate becomes significant.

The total change in urban penalties is distributed fairly evenly throughout the state with no single area bearing most of the changes. The magnitude of changes in the penalties range from only 2% in CVPM8 to 119% in CVPM12. The amount of change depends on the disparity between PR and QR. Places where per capita use is increasing had underestimated penalties, and areas with decreasing per capita use had overestimated penalties and negative changes.

The update also reduced the standard deviation among urban residential penalties at any delivery level by 53%, resulting in more comparable willingness to pay (WTP) across demand areas and a more even distribution of shortages, Figure 3.2. For example, if all areas receive 95% of their target delivery, the standard deviation among the penalties calculated at that point will be the same as if they all received 50%, or any other delivery level.

Figure 3.2: Urban Penalty for Major Water Users at 90% Delivery

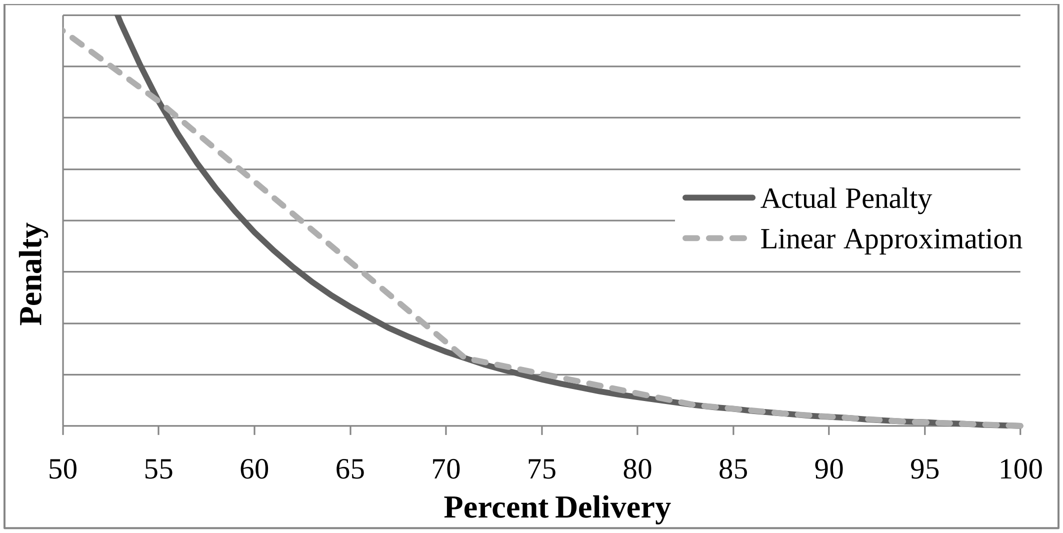


By correcting the oversteepening of the penalty curves for the largest water users, the updated penalty set removes the highest peaks of Figure 3.2 and produces a more even penalty spread. Major water users were defined as those demanding more than 200 taf/ month during the summer.

Application

CALVIN, as mentioned previously, uses a linear generalized network flow optimization solver. This means that the exponential penalty equations described above in CALVIN require a piece-wise linear approximation. This is done by sampling different points along the curve. Five points per month are used for the summer months (April to October), and eight points per month for the rest of the year. As seen in Figure 3.3, these points are concentrated at the higher delivery levels, providing an excellent approximation of the penalty for delivery levels up to approximately 85%, a respectable approximation for deliveries greater than around 70%, and a poor approximation for deliveries less than 70%. The exact range of each approximation varies with each month and location. The final sampling point of the linear approximation is at approximately 50% delivery. Up to this last sampling point, the linear approximation provides varying degrees of overestimate to the actual penalty. For deliveries less than the last sampling point, HEC-PRM extrapolates the approximation out based on the slope at the last sampling point. This means that at extreme levels of scarcity, the linear approximation can significantly underestimate the penalty calculated from the equations. Such high shortage levels are also far outside of the range of calibration data for what are essentially empirical demand functions.

Figure 3.3: Sample Linear Approximation



This selection pattern was chosen because it is extremely rare for urban scarcities to exceed 15% (deliveries 85% of target) in normal CALVIN operations. The marginal costs beyond that point are too high to be economically justifiable in anything but the most desperate of circumstances. Concentrating the sampling points allows formation of an acceptable approximation of the most relevant part of the curve and save computing effort by neglecting the unused portion. The rough nature of this approximation at high scarcity levels makes it difficult to estimate costs for extremely water scare scenarios, such as modeling the failure of a major piece of infrastructure. However, since urban penalties are typically the highest cost component of the system, system behavior is still captured accurately in these scenarios. Some examples of this will be seen in Chapter 6.

Consumer Surplus, Marginal Willingness-To-Pay, and Scarcity Cost

The primary function of the penalties is to provide the shortage component of system-wide costs to the objective function, which the HEC-PRM solver minimizes. The water demand penalty functions also define scarcity costs and marginal willingness-to-pay (WTP) for water at each demand area, as illustrated in Figure 3.4.

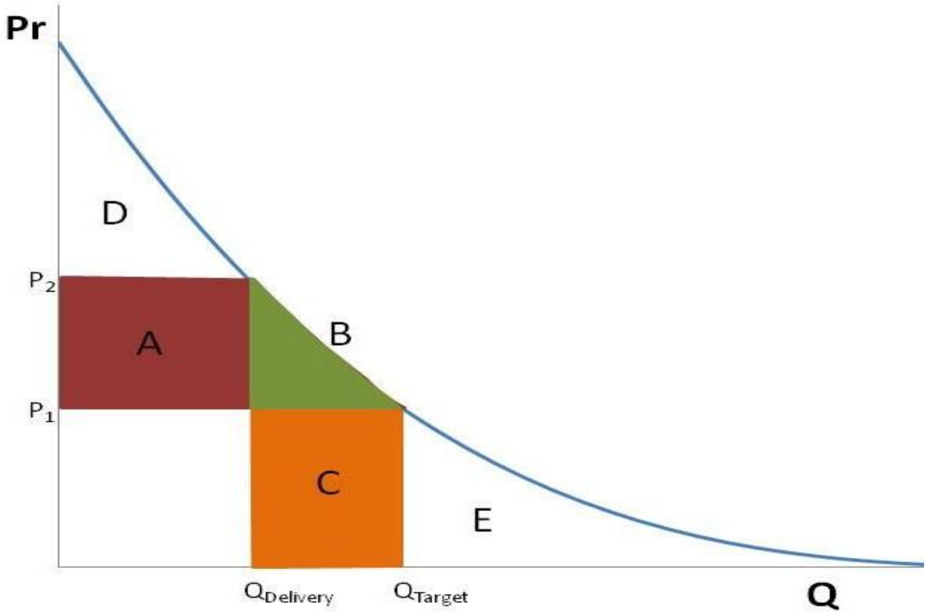
The scarcity cost is defined as the integral of the penalty curve from $Q_{Delivery}$ to Q_{Target}, the shaded area in Figure 3.4. Total scarcity is the sum of all the penalties in the 72-year period. Marginal WTP is the maximum slope of the penalty curve that is incurred in that period, marked with a star in Figure 3.4. This slope is also the marginal cost of water scarcity.

Figure 3.4: Illustration of WTP and Scarcity Cost

The method illustrated above is mathematically accurate. But it is not a measure of consumer surplus. The urban penalty equations calculate a location’s WTP as area B + C under the demand curve shown in Figure 3.5. In Hicksian economics this area is known as the compensating surplus (McConnell and Brue 2005). It doesn’t appear to have a formal name in Marshallian economics, but represents a similar concept.

The standard method of calculating total consumer surplus is as area A + D for partial deliveries and A + B + D for target deliveries, and to approximate change in consumer surplus is just area B, the change in welfare due to water shortages.

Figure 3.5: Consumer and Compensating Surplus



Compensating surplus, the welfare measure associated with rationing, shows that the cost to water users of being able to consume only $Q_{Delivery}$ instead of Q_{Target} is area B, which is the loss of consumer surplus to the demand area (McConnell and Brue 2005). With Q_{Target} available, the demand area's total consumer surplus is A +B + D, and with $Q_{Delivery}$ available the consumer surplus is A + D, so the change in consumer surplus is area B. Area B + C is the total willingness-to-pay for the increment Q_{Target} - $Q_{Delivery}$, including consumer surplus and producer revenue (assuming a very small marginal cost of supply). C would be the lost water revenue to the provider and B the net value of the water to users if that increment were made available at price P_1. It would not be appropriate to use WTP as a proxy for the cost of full supply as it mixes up the two sides of the water market (Larson, personal communication). So while the penalty functions provide the correct feedback for the objective function (how much each location is willing to pay for a specified amount of water), this is not necessarily the same value as the cost of shortage. However, the cost of scarcity must be less than or equal to the amount an area would be willing to pay for that water. Thus, willingness to pay serves as an upper bound for the total cost of scarcity.

Results

To examine how this change in the penalty functions affects CALVIN results, results from the model run with the updated penalties were compared to results from earlier studies. These changes affected only urban penalties. Agricultural and industrial penalties were unchanged. The first scenario is Connell’s (2009) corrected base case, a low shortage scenario depicting current operating conditions in California. The second was Sicke’s (2011) warm-dry, climate change scenario, a high scarcity case depicting California’s response to a warmer, dryer future where sea level rise prevents water exports from the Delta. Results are summarized in Table 3.5.

Table 3.5: Summary of Scarcity Analyses

	Original Penalties		Updated Penalties	
	Urban	Agriculture	Urban	Agriculture
	Scarcity (taf/year)			
Base Case	0.04	1.01	0.12	1.01
Warm-Dry	660	9,114	1,084	9,081
	Scarcity Cost $1000/year			
Base Case	$37	$233	$102	$234
Warm-Dry	$677,000	$2,937,000	$1,019,000	$2,917,000
	Max WTP $/af			
Base Case	$381	$232	$1,026	$232
Warm-Dry	$2,400	$570	$2,070	$570
	Average WTP $/af			
Base Case	$25	$11	$95	$11
Warm-Dry	$336	$128	$465	$127

These results show how changing the slopes of the penalty functions changes the optimal distribution of water throughout the state. Overall, the updated penalties slightly decrease the amount of water transferred from agriculture to urban uses and reduce the use of more expensive supply options such as desalination and water recycling. This results in more urban scarcity. However, since most locations have less steeply sloped penalty functions in the updated version, total scarcity cost does not increase proportionately. In the warm-dry scenario a 39% increase in scarcity from the original penalties to the updated penalties only increases total cost by 34%. In the base case, a 216% increase in scarcity increases total cost by 179%. The reduced spread of the penalties results in a higher average WTP. Shortage is split among more demand areas, 31 as opposed to 27 for the warm-dry case. The behavior of maximum WTP is difficult to generalize as it depends on the marginal values of scarcity throughout the state.

Results by Demand Area

Comparing urban results in Table 3.6, no northern California demand areas have scarcity in the base case. All of the locations in Table 3.6, with the exception of Blythe, have higher WTP and scarcity in the Penalty Update model. This is because these locations all had penalties were previously overestimated. Blythe was the single location in this list that had an underestimated penalty, and its scarcity and scarcity cost decreased. Scarcity cost and WTP are in 1995 dollars.

Table 3.6: Average Annual Base Urban Water Scarcity Analysis

	WTP ($/af)		Scarcity Cost ($k)		Scarcity (taf)	
	Original	Pen Updt	Original	Pen Updt	Original	Pen Updt
SB-SLO	0	1,026	0	6,317	0	5
Castaic	227	627	1,267	3,935	2	6
Ventura	3	916	2	10,409	0	12
E&W MWD	343	432	20,821	34,429	19	38
San Diego	154	398	8,366	31,061	7	35
Blythe	381	390	1,177	668	3	2
El Centro	0	390	0	1,362	0	4
	Max		**Total**		**Total**	
	381	1,026	31,633	88,181	31	102

In the warm-dry scenario, Table 3.7, many more locations have water scarcity, including some in northern California, though none north of the Delta. Since most of California's precipitation falls north of the Delta and the Delta is the major hub for north-south water delivery, it is logical that north-of-Delta demands should receive full deliveries in almost any case – especially when impaired transport through the Delta prevents that water from being delivered to higher value uses in southern California.

Table 3.7: Average Annual Base Agricultural Scarcity Analysis

	WTP ($/af)		Scarcity Cost ($k)		Scarcity (taf)	
	Original	Pen Updt	Original	Pen Updt	Original	Pen Updt
CVPM 3	13	13	12,745	12,745	93	93
CVPM 12	8	8	577	577	6	6
Coachella	232	232	39,946	39,945	154	154
Imperial	208	208	147,813	148,862	618	622
	Max		**Total**		**Total**	
	232	232	201,081	202,129	871	875

The only change in base case agricultural scarcity, Table 3.7, is in Imperial, with an additional 4 taf of scarcity and $1 million in scarcity costs annually after the update. Agricultural penalties did not change with this update and agricultural scarcity was not greatly affected by the change in urban penalties.

Table 3.8: Average Annual Warm-Dry Urban Scarcity Analysis

	WTP ($/af)		Scarcity Cost (k$)		Scarcity (taf)	
	Original	Pen Updt	Original	Pen Updt	Original	Pen Updt
Contra Costa	0	1,311	0	6,819	0	5
EBMUD	460	1,129	4,284	21,872	3	22
San Francisco	721	932	12,749	14,425	11	18
SCV	751	1,229	31,415	66,034	26	65
Turlock-CVPM12	153	0	1,938	0	12	0
Fresno	899	708	42,199	34,580	63	66
Sanger-CVPM17	0	445	0	5,095	0	8
Visalia-CVPM18	0	403	0	2,992	0	7
Delano-CVPM20	369	614	4,566	9,283	7	17
Bakersfield	1,663	1,366	59,863	49,300	54	57
SB-SLO	0	1,322	0	7,578	0	6
Mojave	1,191	1,041	118,150	105,340	153	137
Antelope	2,028	1,721	61,136	56,513	43	46
Castaic	2,409	2,070	65,441	61,845	36	40
Ventura	3	916	2	10,409	0	12
SBV	1,046	811	17,287	15,228	19	23
Central MWD	702	1,202	156,180	349,169	142	356
E&W MWD	1,274	1,237	47,902	89,881	42	88
San Diego	735	1,188	52,325	109,814	44	105
Blythe	389	407	1,244	980	3	2
El Centro	0	408	0	2,003	0	5
	Max		**Total**		**Total**	
	2,409	2,070	676,681	1,019,160	658	1,085

Table 3.8 shows differences between urban locations whose penalties had been overestimated and those whose penalties had been underestimated. For the former, scarcity and scarcity costs increase while for the latter these values decrease. Overall, since more urban locations were overestimated than underestimated, urban scarcity and costs increased.

Similar to the base case, agricultural scarcity and scarcity cost change very little with the urban penalty update in the warm-dry case. In the warm-dry case, the update decreased overall agricultural scarcity and scarcity costs. Scarcity in eleven of the seventeen agricultural demand areas changed by less than 1 taf. The largest changes were in CVPM 17, 18, and 20 where scarcity decreased 12 to 13 taf annually.

Table 3.9:Annual Average Warm-Dry Agricultural Scarcity Analysis

	WTP ($/af)		Scarcity Cost ($k)		Scarcity (taf)	
	Original	Pen Updt	Original	Pen Updt	Original	Pen Updt
CVPM 1	18	18	1,111	1,111	14	14
CVPM 3	40	40	32,326	32,325	218	218
CVPM 4	18	18	6,612	6,612	63	63
CVPM 10	176	176	146,752	146,880	558	558
CVPM 11	98	98	89,189	89,279	540	540
CVPM 12	178	180	63,254	64,484	359	363
CVPM 13	176	177	107,389	107,841	619	621
CVPM 14	570	570	514,082	513,612	912	911
CVPM 15	169	170	62,493	63,396	319	323
CVPM 16	243	244	53,499	53,499	183	183
CVPM 17	494	494	278,393	269,666	638	625
CVPM 18	202	202	298,168	294,318	1,202	1,190
CVPM 19	358	357	302,075	301,663	788	787
CVPM 20	496	492	403,678	395,591	796	784
CVPM 21	320	320	363,995	364,406	1,040	1,041
Coachella	251	251	53,873	53,873	200	200
Imperial	216	215	159,843	158,890	665	662
	Max		**Total**		**Total**	
	570	570	2,936,733	2,917,446	9,114	9,081

Conclusions

The governing equations described in Appendix B2 of the original CALVIN report (Jenkins et al. 2001) are appropriate and have increased accuracy when the population ratio is replaced by a quantity ratio. The penalty, which is the area below the demand curve between the demanded, target water quantity and the delivered water quantity, represents a functional, if unconventional, upper bound for total shortage costs or the total willingness to pay to attain water deliveries at the target levels. Although the model has increased urban scarcity and scarcity costs in all cases after the update the structure of the optimal solution remains comparable.

Chapter 4

Statewide Residential Demand Split and Cost Update

Another set of CALVIN updates divided all urban residential water demands into indoor and outdoor components, updated the penalty functions with the most recent water cost and demand estimates, and brought operating costs into 2008 dollars statewide.

Urban Demand Split

Split Demand Area Creation

Urban demand areas in CALVIN were split to represent indoor and outdoor demands with separate penalty functions. This allows for better resolution of water shortages and examination of water conservation, non-potable reuse, and allocation of shortages between indoor and outdoor uses under economically optimal conditions.

Urban demands include residential and commercial water uses as well as industrial water uses in those areas without a separate industrial demand component. Table 4.1 shows the change in how demands are divided in the initial and revised models. Naming conventions for the new split demand areas are described in Appendix 4.

Table 4.1: Interior-Exterior Split Demand Nodes

Initial	Revised
Residential*	Indoor Residential Outdoor Residential
Industrial #	Industrial

*Commercial demands are preprocessed within residential

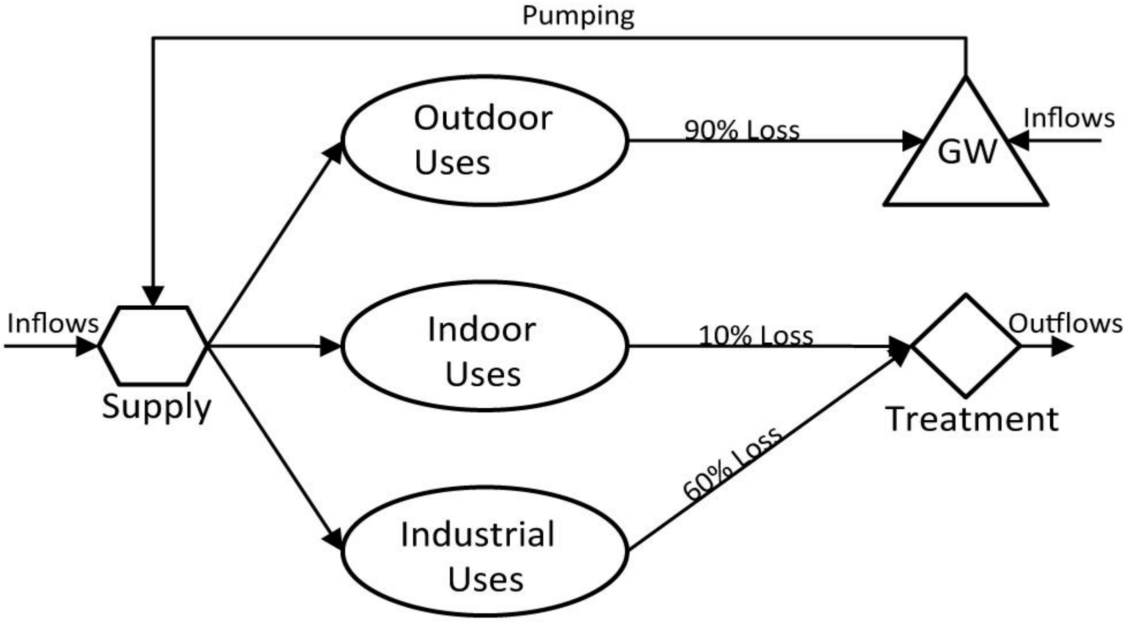
#In those demand areas without a separate industrial component, industrial demands are preprocessed within residential

While creating the separate indoor and outdoor demand portions, four urban demand areas, Sacramento, Stockton, Bakersfield, and City of Fresno, were found to include separate industrial areas without associated penalty functions or data to generate those functions. These dummy industrial demands were deleted and the split areas were named following the convention of non-industrial areas. Industrial components for areas can be included in the model as data becomes available.

Connectivity

The split indoor-outdoor demand areas are connected to the network in the same way as the original areas. Both indoor and outdoor receive inflows from the original source, and indoor return flows go to the original treatment plant. Outdoor return flows are assumed to percolate to groundwater where a groundwater basin exists and to go to sink elsewhere. This connectivity is shown in Figure 4.1, below.

Figure 4.1: Indoor-Outdoor Urban Demand Connectivity



<u>Return Flow Amplitude</u>

The amount of return flow is represented by the link amplitude. The amplitude represents the fraction of the water going into the link which comes out the other end. The rest is lost to consumptive uses or evapotranspiration. In the original CALVIN standard urban demands had return amplitudes of 40% (60% consumptive use), a statewide average based on data described in Appendix B1 of the original CALVIN report (Jenkins et al 2001). Central Valley urban demand areas each had individual return amplitudes based on data from the CVGSM model (USBR 1997).

Diverging from Appendix B1, the return flow rate for the new standard urban outdoor areas was set at 10% (90% consumptive use), representing deep percolation of outside applied water, while the return flow for urban indoor areas was set to 90% (10% consumptive use), representing the percent of indoor applied water sent to treatment plants. These numbers represent our best judgment as no hard data was available.

For Central Valley demands and other non-standard return flows, the return amplitudes were set as close to the above values as possible while preserving the original amplitude through a weighted average. For example, if an area had 40% indoor uses and 60% outdoor uses, with original return amplitude of 50%, the new amplitudes might be assigned as shown in Table 4.2.

Table 4.2: Central Valley Return Flows

	Use %	Amplitude	Product
Indoor	40	95%	38%
Outdoor	60	20%	12%
		SUM	**50%**

Calculating Penalties

Penalty functions were calculated using the revised and updated penalty macro. The major change is rewriting the portions of the macro to divide residential demands into separate indoor and outdoor penalty functions. These changes are documented in the code and are mainly computational. The macro is included in the software and data appendices of this report (URBAN4_v3.xlsx).

Outdoor penalty functions were set up to have seven segments in summer and ten in winter, instead of the five and eight used previously. This allows for better resolution at larger percentage shortages – anticipating that urban users will short outdoor use before indoor and to a higher degree due to the higher economic value of indoor uses. This expands the range of good approximation out to around 80% delivery. However, due to this change and to the links added as part of the demand split, older post-processors will require some modification to be compatible with this model.

Price Elasticity of Demand

Formerly, values for price elasticity of demand were split by season, with the highest elasticity in the summer and the lowest in the winter. The low winter elasticity reflected inelastic indoor demands, while the higher summer elasticity reflected more flexible outdoor demands (Jenkins et al 2001). The intermediate season was a combination of the two. Now, with split indoor and outdoor residential uses, indoor uses have been assigned the former winter elasticity (-0.15), and outdoor uses have been assigned the former summer elasticity (-0.35). These elasticities are assumed to remain constant across all seasons. More recent estimates of price elasticity of water demand for urban uses in California were not available.

Industry

Industrial use fractions and loss data were not changed as no new data were available. Industrial losses are based on the expected loss due to a 30% shortage as reported by the California Urban Water Agencies (CUWA 1991).

Monthly Demand

Indoor residential use was split evenly across the 12 months, with outdoor residential use being monthly total use minus monthly indoor use.

A minor error was found in the original penalty calculations where the overall monthly use fractions in the original summed to more than one for some locations. This was corrected by reducing every month's use proportionately so results summed to one.

Water Use by Sector

The percentage of water used by each sector was updated using data from the 2009 State Water Plan (DWR 2009) which gives percent water use by sector for each Detailed Analysis Unit (DAU). For regions containing several DAUs, percentages were determined by a simple average. Generally, water use in adjacent DAUs was so similar that the difference between a simple average and a population weighted average would be trivial. CALVIN penalty functions divide urban uses into residential indoor (which includes commercial), residential outdoor, and industrial. The 2009 DWR water use data divide water use into indoor residential, outdoor residential, commercial, industrial, and large landscape. Whereas DWR's old data sets from the 1998 State Water Plan and earlier, divided use into: residential, commercial, industrial, and municipal/government. In the new DWR categorization municipal/government uses are split between commercial and large landscape uses. The new DWR category, large landscape use, is added to outdoor residential usage in most cases. In southern California regions, like Coachella, where the landscape water use percentage was very high and the region is known to have many golf courses, GIS was used to calculate the land area in golf courses. Golf course water use was assumed as 3.84 af/acre/year (Templeton, Zilberman and Henry 2010). The golf course water use was then subtracted from the large landscape use and added to commercial use, as CALVIN considers golf courses as a commercial use. For most locations, golf course water use was insignificant.

The average percentage of industrial water use has dropped significantly from the original to the 2005 estimates. The average southern California industrial water use in the original CALVIN was roughly 8% of total urban use, but with the new data it has dropped to roughly 1.5%. This drop may be due to reduced levels of industry, greater industrial water conservation, or DWR employing a different accounting scheme. Regardless, since industrial cost data remains unchanged and industrial water penalties are calculated based on economic losses due to a 30% shortage, higher margins on industrial penalties are expected because a much smaller magnitude of shortage will be a higher percentage of total use. No new data was available on the cost of industrial shortages.

Cost Update

All operating and scarcity costs in CALVIN were converted to 2008 dollars using costs indexes. Agricultural penalties were already in 2008 dollars, and updating the urban penalties provided a convenient opportunity to bring them into 2008 dollars as well. Time and resources were not available to replicate the original effort to recreate statewide average operating costs from outside data (Appendix G; Newlin 2000), so existing operating costs were simply scaled up to 2008 dollars from their original values in 1995 dollars using a conversion factor of 1.48, taken from the Engineering News Record's San Francisco Building Cost Index for the month of June (McGraw-Hill 1995 and 2008).

Recalculating Penalties

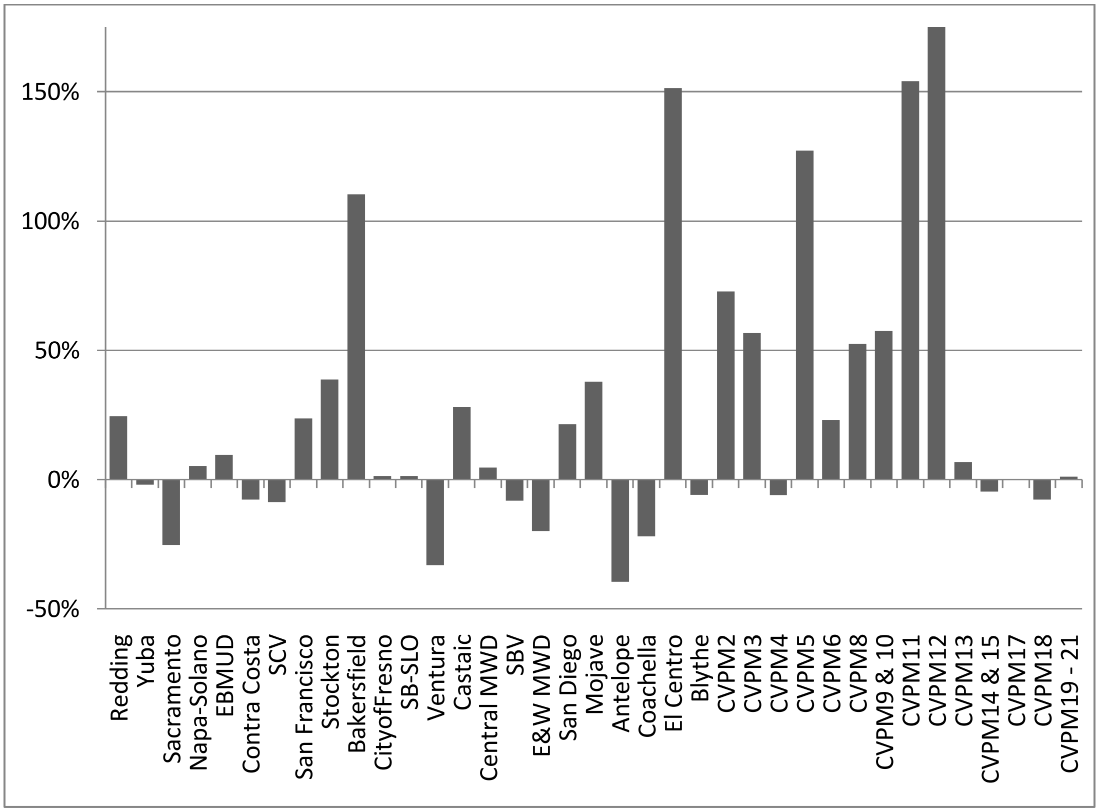
The original penalty functions were generated from 1995 pricing data given in the 1995 Black & Veatch "California Water Charge Survey" and water use data from DWR. More recent data are available from both these sources. In the most recent Black & Veatch survey (2006), some water agencies have significantly changed their pricing. Incorporating this data into the model changes the relative slopes of the penalty functions and thus the optimal economic allocation of water and makes the model more accurately represent current pricing practices. (Of course 2050 pricing practices remain somewhat uncertain.)

Updated water rate data for each urban demand area was calculated from the 2006 Black & Veatch "California Water Rate Survey" using the original convention of population weighted averages (Jenkins et al. 2001). Details are in Appendix 5. It was matched with 2005 water use data from DWR, as 2006 data was not available. The 2006 dollars were scaled up to 2008 dollars using a conversion factor of 1.09, taken from the Engineering News Record's (ENR) San Francisco Building Cost Index for the month of June (McGraw-Hill 1995 and 2008).

Industrial penalty functions are established based on an estimated loss for a 30% shortage. This value was in 1995 dollars and was scaled up to 2008 dollars using a conversion factor of 1.48. Agricultural penalty functions calculated from SWAP were already in 2008 dollars.

Figure 4.2 shows the changes in reported urban water rates by demand area derived from the 1995 and 2006 Black & Veatch data. Details of this calculation are in Appendix 5. Both rates were converted into 2008 dollars. These rates are calculated as a population weighted average of the reported rates of all the surveyed cities within each demand area. Many urban water agencies' rates are rising less than inflation. Using data from ENR, the inflation in their building cost index from 1995 to 2006 was 39%. The agency with the largest negative change in inflation-corrected rates, Antelope Valley, saw their effective rate drop by -40%, implying that they haven't raised their rates in those ten years. The largest rate hikes were in urban CVPM11 and 12 (Manteca, Modesto and Turlock) and greater El Centro (Imperial Irrigation District's urban customers). Based on the 2006 Black & Veatch survey, nearly 40% of all CALVIN urban demand areas had a decrease in their inflation-corrected rates compared to the reported 1995 values.

Figure 4.2: Percent Change in Urban Water Rates 1995 to 2006
(adjusted for inflation)



Results

The only change in the new split model which would have affected model results was the update of urban water rates from 1995 to 2006 values. The process of splitting the demand areas did not change the total target demand, economic costs, or any part of the conveyance network; it just allows more detailed accounting of water use. Scaling the operating costs and urban water values to 2008 dollars did not change the relative magnitude of those costs. However, since agricultural values were always in 2008 dollars while the operating and urban costs were still in 1995 dollars, the relative value of agricultural water decreased slightly with this update. Thus any change in results is due purely to economic shifts.

Since changes were implemented statewide, results are examined for the whole state. All results are shown in 2008 dollars. Results from the southern California Update model (SC Updt) were scaled up from 1995 dollars using the conversion rate of 1.48 discussed above. As before, no industrial shortages occurred, so industrial demand areas are not listed explicitly, though their demands are included in the total for each urban area. Areas with no scarcity in either model are not listed for simplicity. Water scarcity results are compared for the base case.

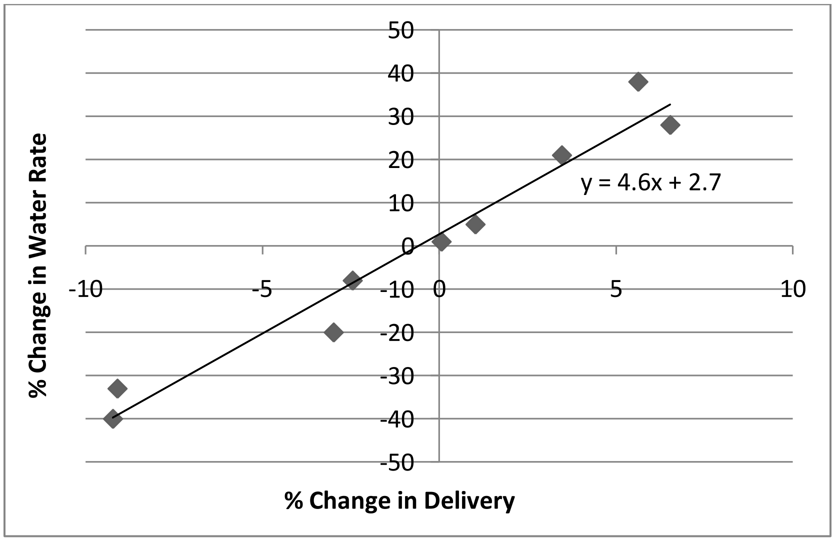
Urban Scarcity

Table 4.3: Average Annual Urban Scarcity Analysis

	WTP ($/af)		Scarcity Cost ($k)		Scarcity (taf)		Target (taf)
	SC Updt	Split	SC Updt	Split	SC Updt	Split	Both
Napa-Solano	313	99	2,557	342	2	0.3	176
SB-SLO	1,704	1,549	10,283	9,622	5	5	205
Mojave	1,093	1,013	17,684	9,035	21	9	221
Antelope	1,278	1,036	33,853	47,407	28	58	350
Castaic	977	79	9,460	113	10	0.1	161
Ventura	1,349	1,226	8,876	19,915	7	20	155
SBV	868	801	30,051	34,853	36	47	547
E&W MWD	883	981	36,516	54,683	30	56	886
San Diego	919	0	35,662	0	28	0	836
Blythe	458	411	317	133	0.6	0.3	16
	Max		**Total**		**Total**		**Total**
	1,704	1,549	185,258	176,103	168	196	3,553

In Table 4.3, in the base case most of northern California receives full delivery in both runs, so the effect of the changes in urban water rates is not apparent. A higher scarcity run might be more illustrative. However, north-of-Delta urban demand areas tend to receive full deliveries even in high scarcity cases. Overall, urban scarcity increases by 18% and scarcity cost decreases by 5%. This indicates the model is using less of the more expensive supply options in favor of more short-term water conservation.

Figure 4.3: Change in Delivery vs. Change in Water Rate



Seeing how deliveries changed with changes in water rates, Figure 4.3, increasing rates yielded increased deliveries and vice versa. Looking at the trendline for this data set, each unit percent change in water rates yields an average 4.6% change in delivery. The trend is clearly linear, with an excellent fit ($R^2 = 0.96$). CALVIN models the supply side of the market where an increase in price incentivizes an increase in deliveries rather than the demand side where an increase in price generally results in a decrease in consumption. These results explain why some cities saw increases or decreases in total scarcity.

Decreasing rates also explain why many urban areas with increased scarcity had lower WTP. Urban areas with decreased scarcity also generally had lower WTP due to normal market forces.

Agricultural Results

Agricultural scarcity results, Table 4.4, help to better understand the urban scarcity results. With the updated costs, agricultural deliveries decrease by 13% and agricultural scarcity costs rise by 20%. As mentioned above, the relative value of agricultural water decreased in this run. Higher relative costs of operations and delivery mean that agriculture pays more for water. This change results in more water transferred from agricultural to urban uses and higher scarcity costs for agriculture. Since urban users are now getting less expensive water from agriculture, they use less of the higher cost supply options (desalination, recycling etc.).

Table 4.4: Average Annual Agricultural Scarcity Analysis

	WTP ($/af)		**Scarcity Cost ($k)**		**Scarcity (taf)**		**Target (taf)**
	SC Updt	Split	SC Updt	Split	SC Updt	Split	Both
CVPM3	1	15	152	1,941	1	15	2,196
CVMP12	8	16	581	2,123	6	22	772
Antelope	145	145	15,407	15,407	80	80	80
Ventura	0	123	0	74	0	0.1	175
E&W MWD	389	544	6,058	9,419	23	27	69
Coachella	153	153	4,526	4,527	26	27	333
Imperial	140	141	146,852	147,364	814	817	2,673
Palo Verde	57	57	1,531	1,531	19	20	784
	Max		**Total**		**Total**		**Total**
	389	544	175,108	182,386	970	1,008	7,082

Most agricultural scarcity is still in southern California. However, there is a slight increase in agricultural scarcity in northern California (possibly to alleviate urban scarcity in Napa-Solano). Since the CRA is already operating to capacity, scarcity doesn’t change in the Colorado River region.

Other things worth noting about Table 4.3 are that Antelope Valley agriculture is still completely uneconomical in 2050, despite a 40% decrease in Antelope Valley's effective urban water rates. Antelope Valley's agricultural WTP for a 100% shortage is comparable to Ventura County's agricultural WTP for a 0.03% shortage, illustrating the differences in agricultural value between those two regions.

Conclusions

Changes to urban water rates and relative value of agricultural water result in slight increases to urban and agricultural scarcity. Total urban scarcity costs decreased as higher cost supply options were replaced by lower cost transfers from agriculture. Urban deliveries shifted from areas where there was a decrease in the effective water rates to areas where there was an increase. Agricultural scarcity and scarcity costs increased as the value of agricultural water decreased relative to its delivery costs and urban water values.

Chapter 5

Comparing New and Old CALVIN

CALVIN model representations of California are never perfect but do tend to improve over time. This chapter provides a detailed comparison of the revised CALVIN model with the pre-revision version of the model. Both models are run for the same base case. The earlier model is Connell's (2009) corrected base case model as analyzed Ragatz (2011).

Scarcity and Costs

Table 5.1 compares the urban scarcity results from Connell's (2009) corrected base case with the final revised model, discussed in Chapter 4. Throughout this chapter, all results are in 2008 dollars. Overall, urban demands decrease by 1.5 maf/year in the revised model. Total 2050 residential, commercial, and industrial demand for the revised model is 11.3 maf/year, as compared to a 2050 residential, commercial, and industrial demand of 12.8 maf/year in the initial model.

Table 5.1: Average Annual Urban Water Scarcity Analysis

	WTP ($/af)		**Scarcity Cost ($k)**		**Scarcity (taf)**		**Target (taf)**	
	Initial	Revised	Initial	Revised	Initial	Revised	Initial	Revised
Napa-Solano	0	99	0	342	0	0.3	176	176
SB-SLO	0	1,549	0	9,622	0	5	205	205
Mojave	0	1,013	0	9,035	0	9	809	221
Antelope	0	1,036	0	47,407	0	58	253	350
Castaic	336	91	336	113	2	0.1	142	161
Ventura	4	1,226	3	19,915	0	20	246	155
SBV	0	801	0	35,853	0	47	238	547
E&W MWD	508	981	30,815	54,683	19	56	856	886
San Diego	228	0	12,382	0	7	0	1,109	836
Blythe	564	411	1,742	333	3	0.3	55	16
Other Urban	0	0	0	0	0	0	8,720	7,751
	Max		**Total**		**Total**		**Total**	
	564	1,549	45,278	177,303	31	196	12,809	11,303

Despite lower demands, urban scarcity increases by over 500% and scarcity costs increase by almost 300% in the revised model, as shown in Figure 5.1 and Table 5.1. Agricultural scarcity is discussed below. Only areas with scarcity are shown. Causes for this shift include changes to urban demand penalties due to adjustments to the equations and urban water rates, shifts in the areas of highest demand, and infrastructure changes. However, the predominant forces are economic.

Figure 5.1: Average Annual Urban Water Scarcity

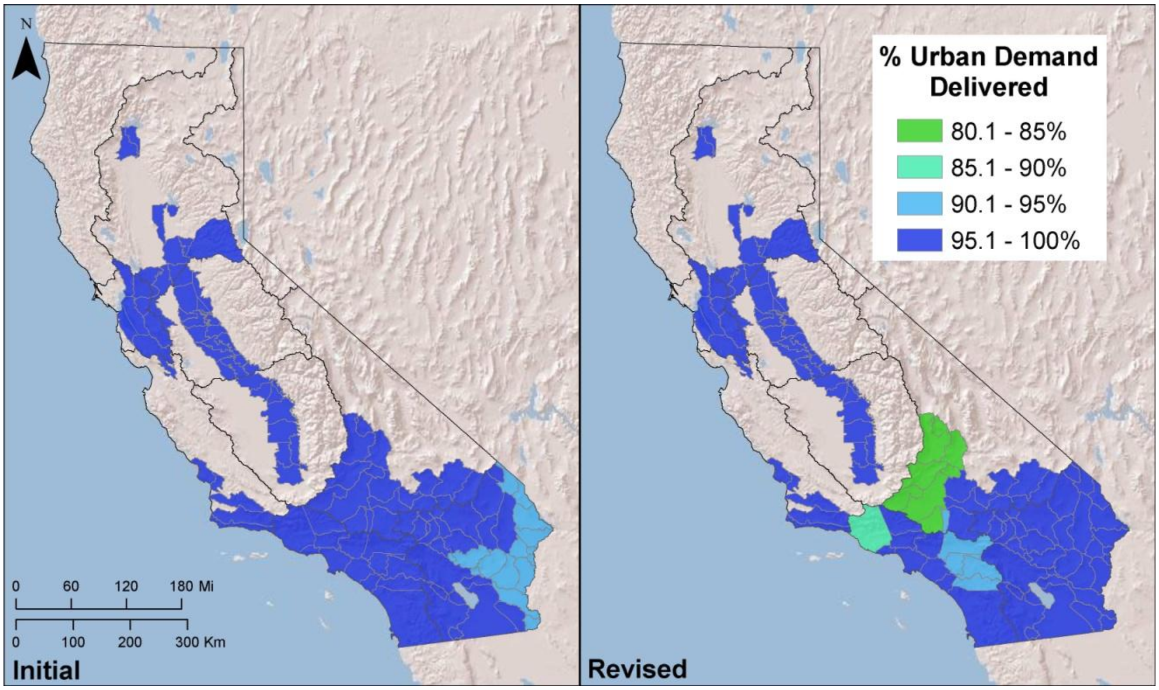
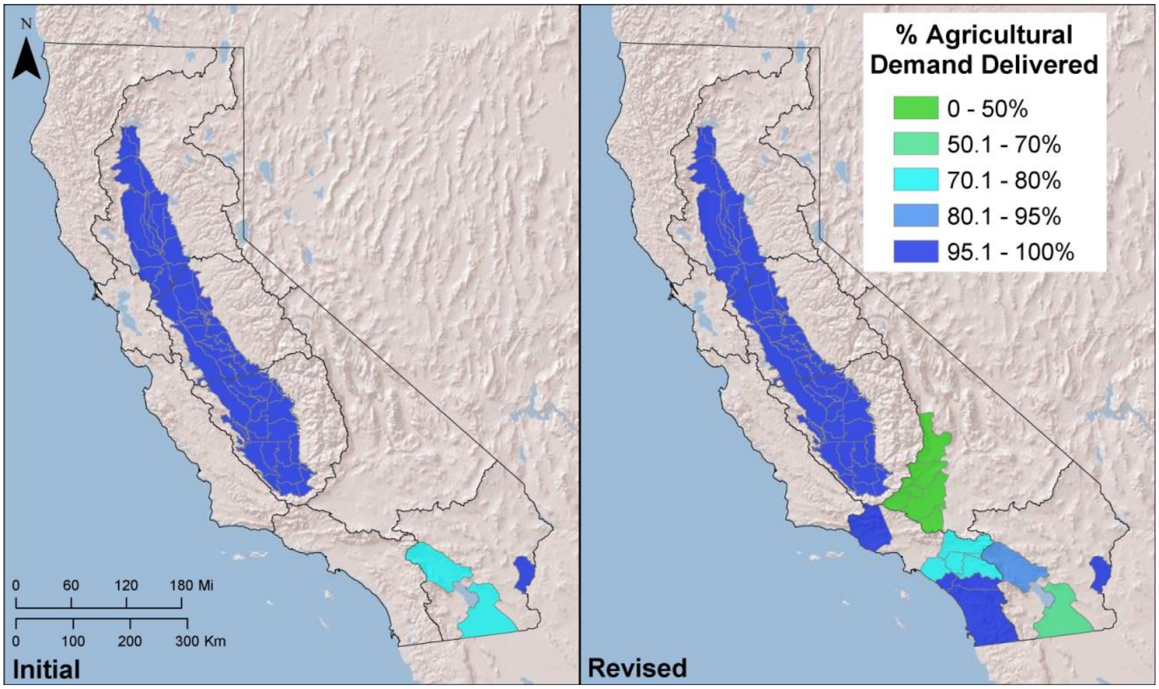


Table 5.2: Average Annual Agricultural Water Scarcity Analysis

	WTP ($/af)		Scarcity Cost ($k)		Scarcity (taf)		Target (taf)	
	Initial	Revised	Initial	Revised	Initial	Revised	Initial	Revised
CVPM3	13	15	12,745	1,941	93	15	2,196	2,196
CVMP12	8	16	577	2,123	6	22	772	772
Antelope	-	145	-	15,407	-	80	-	80
Ventura	-	123	-	74	-	0.1	-	175
E&W MWD	-	544	-	9,419	-	27	-	69
Coachella	232	153	39,946	4,527	154	27	500	333
Imperial	208	141	147,813	147,364	618	817	2,187	2,673
Palo Verde	0	57	0	1,531	0	20	494	784
Other Agric.	0	0	0	0	0	0	17,974	18,014
	Max		Total		Total		Total	
	232	544	201,081	182,386	871	1,008	24,123	25,096

Figure 5.2: Average Annual Agricultural Water Scarcity



Agricultural scarcities have the opposite trend as urban scarcities, Figure 5.2 and Table 5.2. Total agricultural 2050 target deliveries increased by nearly 1 maf from 24.1 maf/year in the original model to 25.1 maf/year in the revised model.

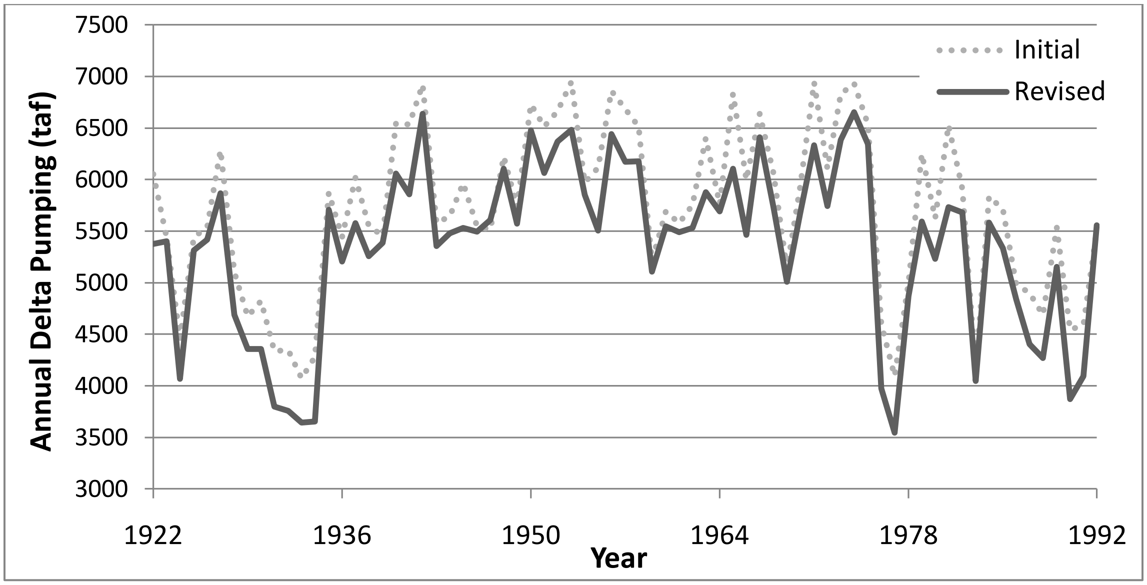
Despite increased agricultural demands, agricultural scarcity costs decreased by 9% in the revised model. Agricultural scarcity increased slightly in magnitude but remained nearly constant as a fraction of total demand. This is caused primarily by shifts in the areas of highest urban demand from the Colorado River region where agricultural transfers can alleviate that scarcity to the South Coast where it cannot.

Operations and Costs

Another major difference between the two models is in the amount of through-Delta pumping, Figure 5.3. Delta export pumping decreased slightly from an annual average of 5.7 maf in the initial model to 5.3 maf in the revised model, because less water is being demanded south of the Delta.

Examining the inter-basin transfers, the two models are nearly identical except in two areas: through-Delta pumping, discussed above, and pumping over the Tehachapi Mountains. Pumping over the Tehachapi Mountains decreased by 14% in the revised model, from 2.3 maf/year to 2.0 maf/year.

Figure 5.3: Annual Through-Delta Pumping



Operation costs also decreased, Table 5.3. Benefits include hydropower and are negative because they subtract from the total system cost. With reduced target deliveries, less water is being moved and treated. (Water treatment can cost as much as $400/af in southern California.) Also, with the addition of several groundwater basins and local supplies in southern California, the water that is being moved isn't moving as far and often requires less treatment when it arrives. (The cost of pumping and treating groundwater is often much less than the cost of treating high salinity imported water.)

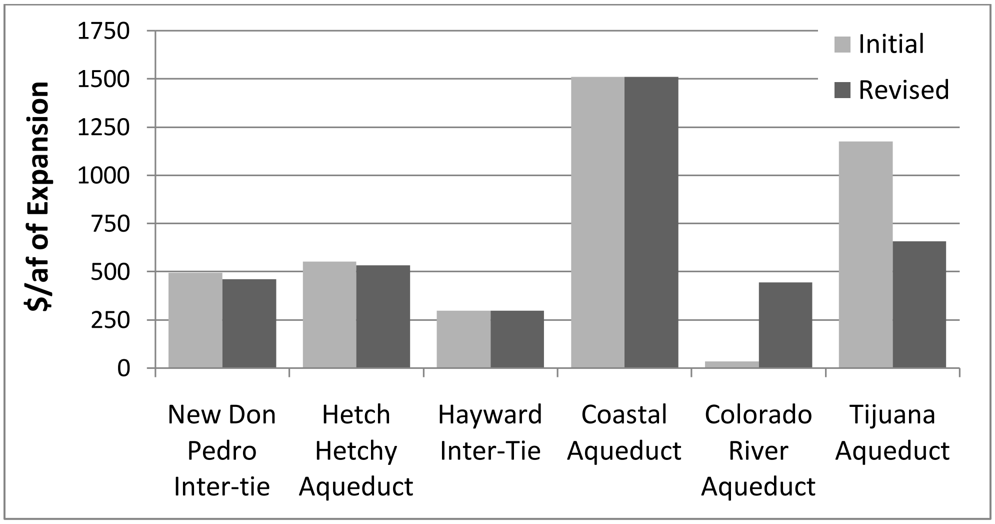
Table 5.3: Annual Operation Costs ($millions/yr)

Annual Operations Cost	**Initial**	**Revised**	**Change**
Groundwater Pumping	544	548	1%
Surface Pumping	1,323	1,116	-16%
Water Treatment	1,410	971	-31%
Recycled Water	231	172	-25%
Seawater Desalination	52	20	-62%
Hydropower Benefits*	-303	-290	-4%
Total ($M/year)	**3,257**	**2,538**	**-22%**

*Hydropower benefits are negative costs

Table 5.3 shows decreased costs in every area of operations except groundwater pumping, which remains nearly constant. The largest differences are in the most expensive sectors: desalination, recycling, and water treatment. Ninety-eight percent of the change in total treatment costs occurs in southern California. No single demand area causes the change. San Diego and E&W MWD, areas with high target demands and newly modeled groundwater basins, have significant reductions in water treatment costs while smaller demand areas like Blythe and Coachella contribute smaller reductions. However, not all southern California demand areas have decreasing water treatment costs. Areas where demand or reliance on imported supplies has increased, such as Ventura and SBV, have greater water treatment costs.

Figure 5.4: Marginal Value of Expanded Conveyance ($/af)



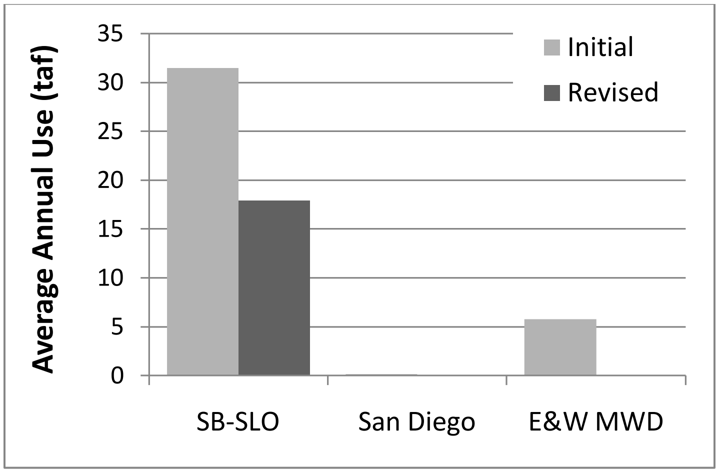
Since less water is moving, the marginal values of conveyance decrease slightly across most of the state, Figure 5.4. However the marginal value for east-west conveyance in southern California, such as the Colorado Aqueduct, has increased significantly in the revised model, although the Coastal Aqueduct still has the highest marginal value of expansion.

The proposed Tijuana Aqueduct also provides east-west conveyance, but since it only serves San Diego, an area without scarcity in the revised model, its marginal value decreased. Current conveyance cost estimates for the Tijuana Aqueduct account for salinity damage, but not for pumping costs. Since in its current configuration, the Tijuana Aqueduct runs over the San Pedro Martír Mountains, just south of the Mexican-California border, pumping costs are likely to detract $450 - $600/af from the value of that connection (Medellín-Azuara et al. 2009; CEA 2010).

The revised model uses considerably less of the most expensive supply options, such as seawater desalination and recycling. Seawater desalination has never been a major source of supply in the base case (Ragatz 2011), but results in Figure 5.5 show that total use of seawater desalination is reduced even further in the revised model, from 37 taf/year to 18 taf/year. San Diego averages 0.17 taf/year of seawater desalination in the initial model, which is not enough to be visible on the graph below.

Santa Barbara-San Luis Obispo (SB-SLO) is the only demand area using seawater desalination in the revised model. SB-SLO does not have enough incoming pipe capacity to take delivery of its projected target demand in any circumstances, so it must resort to more expensive supply options. In reality their options may also include transfers from local agriculture not included in this model.

Figure 5.5: Average Annual Seawater Desalination (taf)



Unlike seawater desalination, the revised model uses more water recycling than the initial, Figure 5.6. Recycling use increases from 198 taf/year to 231 taf/year. The areas with more recycling are Antelope Valley and Mojave – thirsty urban areas dependent on SWP water – and SB-SLO. Recycling use decreases in northern California and for the MWDSC member agencies. The addition of local supplies in Ventura also alleviates its need to recycle. SB-SLO has replaced some of its sweater desalination with less expensive recycling.

Figure 5.6: Average Annual Water Recycling (taf)

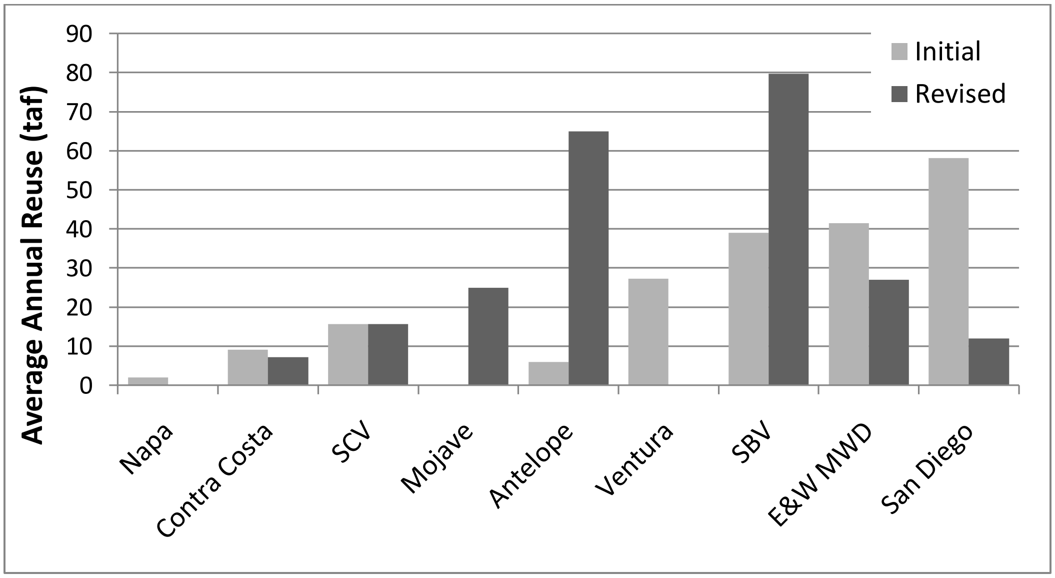


Table 5.3 showed that the total cost of recycling has decreased despite increases in the amount of recycling, indicating that most of the new recycling is within the existing low-cost

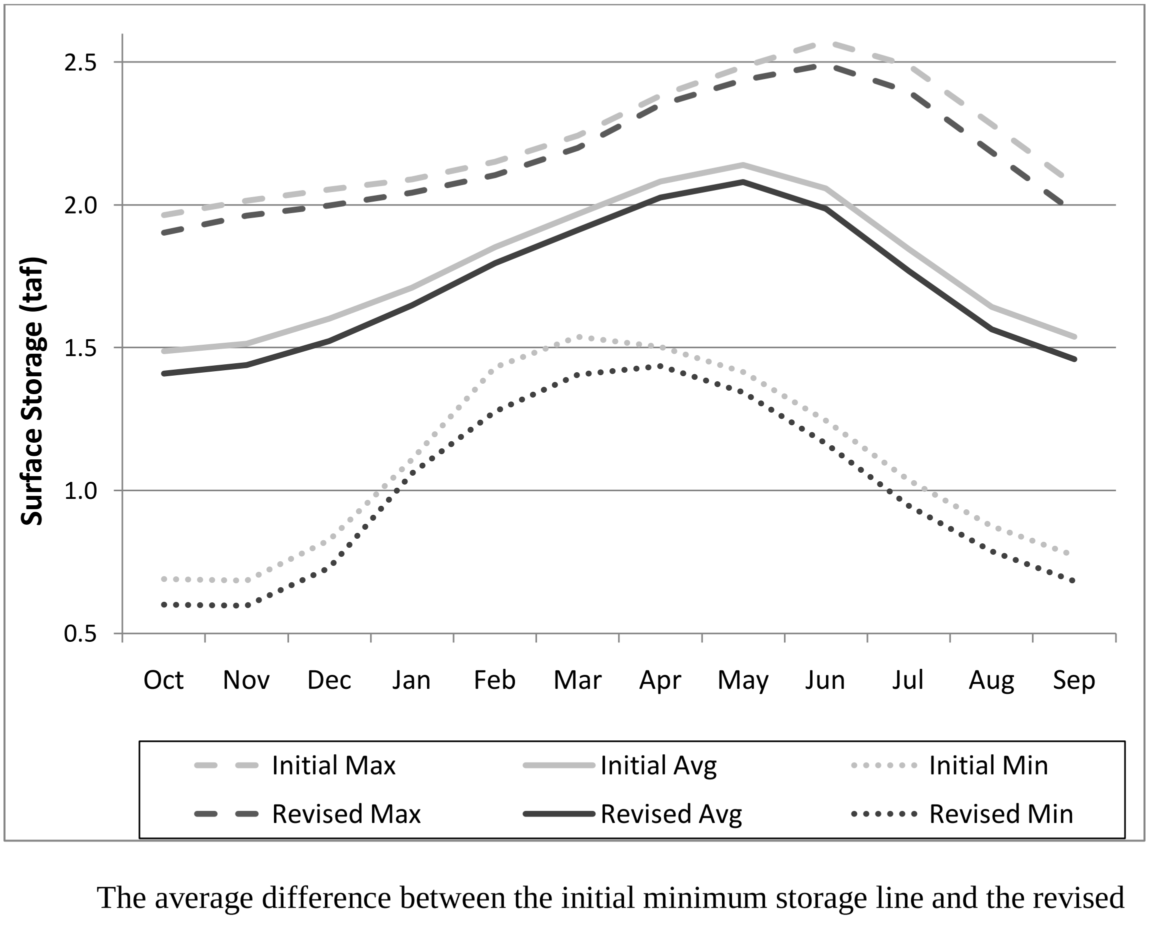
recycling capacity ($445 to $1200 per acre-foot) not the expanded high-cost recycling capacity ($1480 per acre-foot).

Reservoir Operations

These two model versions differ in how they use and value their reservoirs. Figure 5.7 shows average, maximum, and minimum monthly total storages for all reservoirs statewide. Total surface storage is calculated as the sum of all reservoirs in each month. The maximum and minimum are the highest or lowest total storage observed in that month over the entire 72-year period, and the average is the average total storage in that month. In the revised model, the maximum, minimum, and average storage decrease in all months.

The decrease in minimum storage is caused by reduced lower bounds for Silverwood Lake, Lake Perris, Pyramid Lake, Castaic Lake, and Diamond Valley Lake - the major reservoirs in southern California. The lower bounds were reduced to match data from DWR and MWDSC. This change decreased the minimum feasible total storage by 0.60 maf.

Figure 5.7: Average Statewide Monthly Surface Storage (maf)



The average difference between the initial minimum storage line and the revised minimum storage line in Figure 5.7 is 0.91 maf, indicating that not all of the decrease in minimum storage shown in Figure 5.7 is due to the change in southern California reservoir lower bounds. The average difference between the initial and the revised maximum storage lines in

Figure 5.7 is 0.63 maf, and the difference between the average storage lines is 6.9 maf. So while most of the downward shift in total reservoir storage is due to reduced lower bounds for reservoirs in southern California, there is an economic component as well, most likely driven by reduced southern California urban target deliveries.

Storage Amplitudes

Comparing amplitudes of storage illustrates if there is actually a change in reservoir use or if the same usage pattern just shifted downwards. The amplitude refers to the amount of seasonal or drought storage typically used and is calculated as the difference between the median high and the median low annual storage values over the 72 year period. The larger the amplitude, the more aggressively the reservoir is being operated. Tables 5.4 and 5.5 show amplitudes of total seasonal storage.

Table 5.4: Median Total Seasonal Surface Storage Amplitudes (taf)

	Average	Drought Year	Non-Drought Year
Initial	7,986	5,488	8,716
Revised	8,112	6,058	8,882

Table 5.5: Average Total Seasonal Surface Storage Amplitudes (taf)

	Average	Drought Year	Non-Drought Year
Initial	8,510	5,916	9,136
Revised	8,692	6,210	9,291

The median surface storage amplitude is less than the average in both drought and non-drought years indicating that there are more years with smaller amplitudes, but the magnitude of the large amplitudes is significant enough to shift the average.

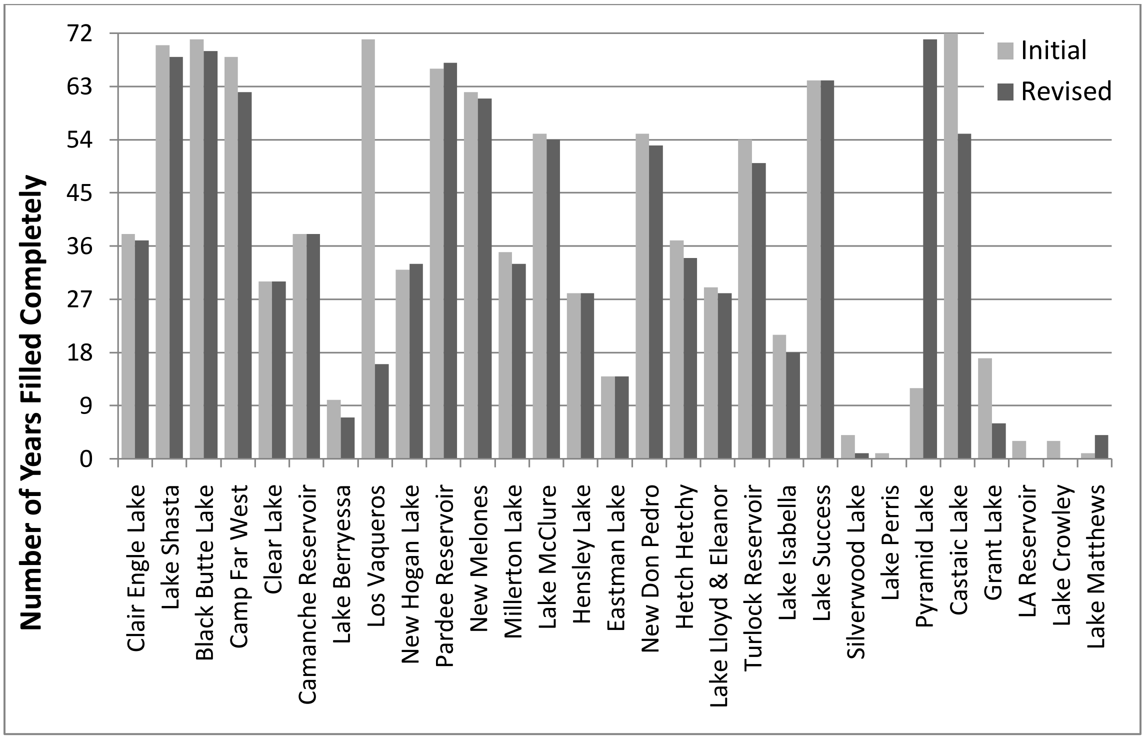
Changes in amplitude indicate that surface storage is being used slightly more aggressively in the revised model, despite decreases in average filling frequency and marginal values of expansion, discussed below. The changes in use patterns, Figure 5.7, showed that the decrease in the average minimum storage was greater than the decrease in average maximum storage, allowing the reservoirs to have higher storage amplitudes without filling the reservoir more frequently.

Filling Frequency

Figure 5.7 shows in how many years of the 72-year period each reservoir is filled to capacity. Large reservoirs that never fill, like San Luis Reservoir and Lake Del Valle and small reservoirs that fill every year, like Lake Skinner, are not displayed.

Of the twenty-nine reservoirs in Figure 5.7, twenty fill less frequently in the revised model, four fill more frequently, and five are unchanged. The average change for most reservoirs is small. Two reservoirs with dramatic changes in use are Los Vaqueros, going from filling in 71 out of 72 years to filling in only 16 out of 72 years, and Pyramid Lake, going from filling in 12 out of 72 years to filling in 71 out of 72 years.

Figure 5.8: Years Reservoirs Filled to Capacity



Pyramid Lake is the northern-most SWP reservoir south of the Tehachapi Mountains in southern California. It is on the west branch of the California Aqueduct, which provides the only source of imported water to Ventura County and Castaic Lake Water District, then goes on to serve Central MWD. With the shift in southern California urban demand from the Colorado River region to the South Coast, Pyramid Lake becomes a more important part of that regions water supply system.

Los Vaqueros Reservoir is a small reservoir (approximately 30 taf of useable storage) belonging to Contra Costa Water District (CCWD). It is located just south of the Delta. It serves Contra Costa WD and in these runs also EBMUD and parts of San Francisco via the CCWD-EBMUD intertie. With reduced southern California urban water demands, a larger share of the water exported through the Delta each month can go directly to the Bay Area, so there is less need to store water locally. Also, Los Vaqueros is an off-stream reservoir; water must be pumped up into it. So when through-Delta pumping and conveyance capacity are not limiting, it is economically preferable to store the water in cheaper locations upstream.

Two Northern California reservoirs, New Hogan Lake and Pardee Reservoir each filled in one additional year. New Hogan Lake is north of the Delta. Water from this reservoir can be exported to anywhere connected to the Delta. Pardee Reservoir serves EBMUD and parts of San

Francisco via the Mokelumne River Aqueduct, with the ability to transfer water to Contra Costa WD. Both are large reservoirs (combined useable storage of 300 to 500 taf, varying seasonally).

North-of-Delta reservoirs decrease filling frequency. Because less water is being exported through the Delta there is less need to store water upstream for dry season exports. Reservoirs in the Tulare Basin also decreased filling frequency, as with less water being exported over the Tehachapis more is available for their use, resulting in less need to store. Southern California reservoirs' filling frequency generally decreases with the exception of Pyramid Lake and Lake Matthews. Lake Matthews is the only reservoir in the Figure 5.8 capable of receiving Colorado River water, and transfers from the Colorado River to the South Coast are increasingly valuable.

The average change in filling frequency (excluding Los Vaqueros and Pyramid Lake as outliers) was three fewer years for those reservoirs filling less frequently (northern California and Tulare) and one extra year for those reservoirs filling more frequently (the Bay Area and Lake Matthews).

Marginal Value of Expansion

The tendency not to fill the reservoirs is confirmed by looking at the marginal values for expanding storage facilities. CALVIN has always shown low marginal values for expanded surface storage (Connell 2009; Ragatz 2011, Jenkins et al. 2004). This revision reduces the average annual value per acre-foot of expansion from \$26.64 to \$11.45. Reservoirs only have a positive marginal value of expansion when they fill. Since the reservoirs are filling less often in the revised model, there is less value to expanding them. Table 5.6 shows the number of reservoirs with marginal values of expansion in each category.

Table 5.6: Count of Reservoirs by Marginal Value of Expansion

	$ 0 - 9	**$ 10 - 24**	**$ 25 - 49**	**$ 50 - 99**	**$ ≥ 100**
Initial	34	8	2	2	1
Revised	36	6	1	3	1

For most reservoirs, the marginal value of expansion changed by only a few dollars. The only significant change is the marginal value of expansions to Lake Skinner, which decreased from \$862/af to \$529/af.

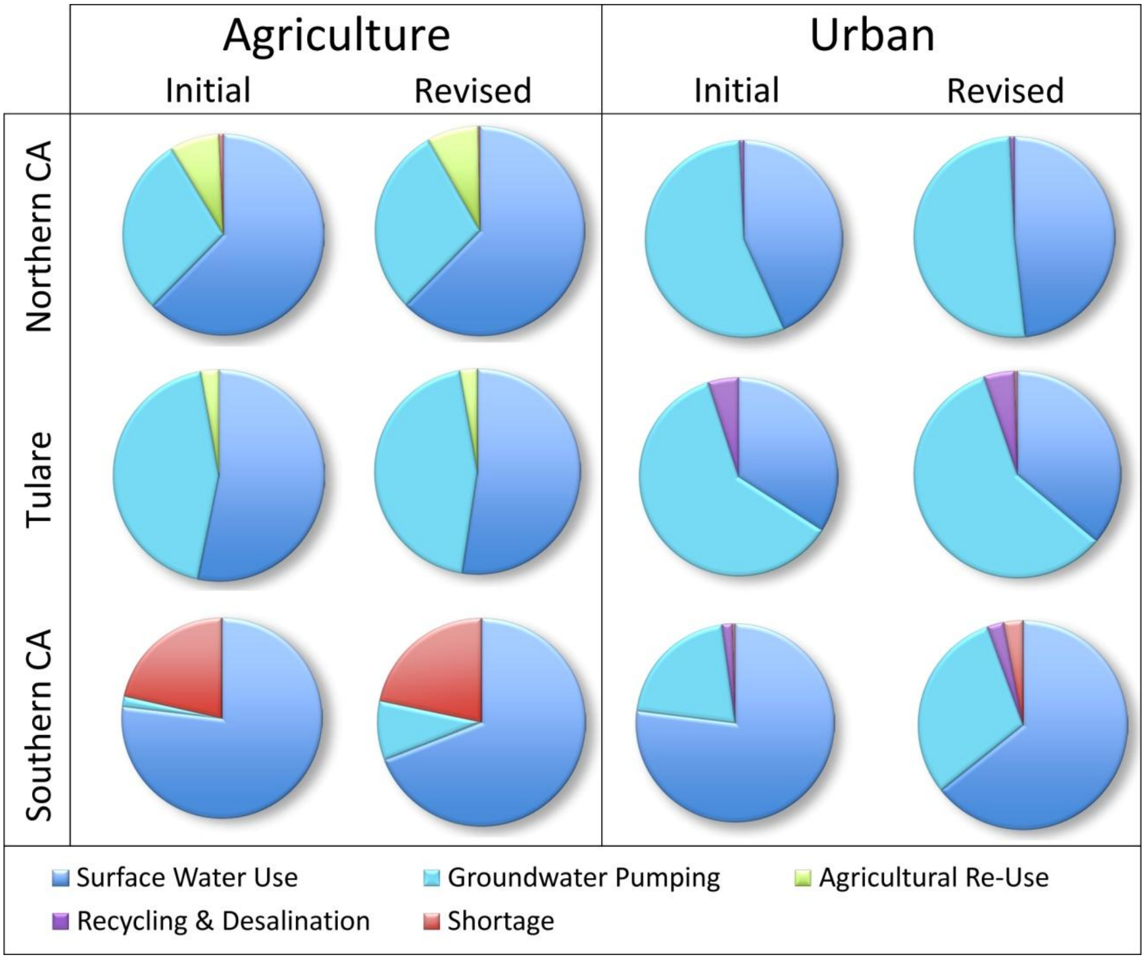
Supply Portfolios

A region's supply portfolio shows where its water supplies are coming from. Figure 5.9 and Table 5.7 compare supply portfolios by region and use type. While these figures show the percent of supply coming from each source, the total amount target delivery is not necessarily the same between the two models.

The overall statewide water supply portfolio had few changes. Two percent of total supply shifts from surface water to groundwater; everything else remains unchanged. However, differences appear regionally. For agricultural users in northern California (including the San

Joaquin Valley, the Bay Area and North-of-Delta) and the Tulare Basin, supply sources remain largely unchanged, though calibration corrections slightly reduced scarcity for northern California agriculture.

Figure 5.9: Agricultural and Urban Supply Portfolios



Southern California, where most changes were made in this update, has the largest supply shifts. No existing southern California agricultural demands had notable changes to their supply portfolios, as all are basically single source Colorado River exporters. However, the three new agricultural demand areas are completely groundwater dependent, adding a significant to new groundwater component to the southern California agricultural supply portfolio. Also, increased agricultural demands increase total agricultural scarcity in southern California.

Table 5.7: Average Annual Supply Portfolios by Region

	North CA Ag		Tulare Ag		South CA Ag	
	Initial	Revised	Initial	Revised	Initial	Revised
Surface Water	62%	62%	53%	52%	77%	69%
Groundwater	29%	29%	44%	45%	2%	9%
Re-Use	8%	8%	3%	3%	0%	0%
Scarcity	1%	0%	0%	0%	21%	22%

	North CA Urban		Tulare Urban		South CA Urban	
	Initial	Revised	Initial	Revised	Initial	Revised
Surface Water	43%	48%	34%	36%	77%	64%
Groundwater	56%	51%	61%	59%	21%	30%
Recycling / Desal	1%	1%	5%	5%	2%	3%
Scarcity	0%	0%	0%	0%	0%	3%

In the urban areas, northern California users shift 5% of their supplies from groundwater to surface water while Tulare Basin urban shifts 2%. Southern California urban users draw 13% less surface water, 9% more groundwater, and have 3% more scarcity in the revised model.

Overall, reduced dependence on surface water and reduced demands in southern California allows the rest of the state to shift their supply portfolios away from groundwater and draw more surface water.

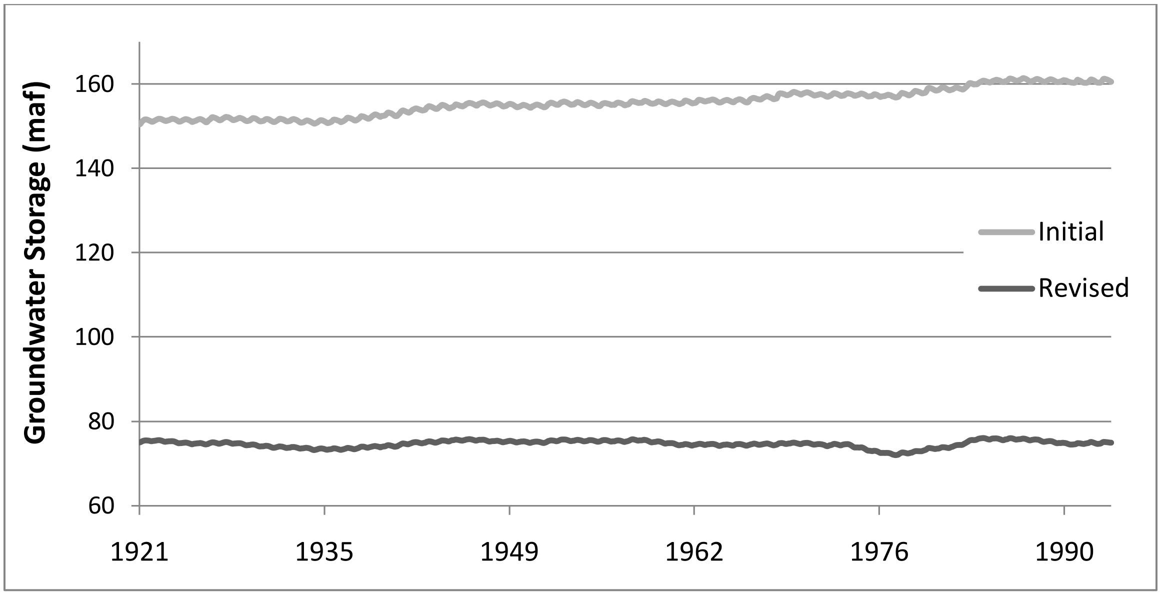
Conjunctive Use

Conjunctive use is the process of using surface water in years when it is available, allowing the groundwater basin to recharge, and pumping groundwater only in years when surface water is insufficient. Conjunctive use is explored by graphing groundwater storage through time. Despite the shifts in supply portfolio seen above, the only region that shows a visible change groundwater use is southern California, Figure 5.10.

Southern California has 57.4 maf less groundwater storage space in the revised model. Four new groundwater basins added 41.6 maf of additional storage, but reductions in the size of the groundwater basins for Imperial, Antelope, and Owens Valleys to match reported data removed 99 maf of storage.

The pattern of use also differs slightly. The groundwater storage for the initial model has a gently rising slope while the revised model stays almost flat with slight dips marking the major droughts. Looking back at the supply portfolios, Table 5.6, groundwater has increased from 2% to 9% of agricultural supply and from 21% to 30% of urban supply. This increase in groundwater use removes the upward trend in groundwater storage.

Figure 5.10: Southern California Groundwater Storage



Future Improvements

Every model has room for improvement. The most important change that should be made is to update urban and agricultural demand projections across the rest of the state. The original CALVIN demand projections were put together in the late 1990s, a period of strong economic growth when California's future population growth looked almost exponential. Population projections today are significantly more conservative, perhaps too much so given the recession. Also, statewide average per capita gross water use has decreased as water saving devices become more efficient and people become more conservation conscious. Updating the southern California demand projections resulted in a 1.5 maf/year reduction in gross urban demands. That is extremely significant. Updating urban demands in the rest of the state is likely to have a significant effect. If CALVIN results are to provide useful insights into the future of the state, the model needs to accurately reflect current projections of what that future will look like.

Another important issue is groundwater. In a nearly complete version of this model, an error in the network allowed eleven Central Valley groundwater basins to dump unwanted groundwater to sink at no cost or benefit. These basins collectively dumped an average of 2 maf/year of groundwater in favor of imported surface water. Under current constraints, the basins must pump and use this water or violate infeasibility constraints on groundwater storage. This error caused a significant shift in water supply portfolios in the San Joaquin and Tulare regions, an additional 1 maf of through-Delta pumping, and reduced annual operations costs throughout the state by $1 billion. Comparing the 1997 Central Valley Groundwater and Surface water Model (CVGSM), from which CALVIN groundwater data was developed, with more recent groundwater models shows that CALVIN groundwater supplies are likely greater than they should be, resulting in potentially significant underestimates of water demand from the

Sacramento-San Joaquin Delta. There should not often be excess groundwater in the San Joaquin and Tulare basins. Details are discussed in Appendix 6.

Comparison with IRPSIM

Because CALVIN and MWDSC's IRPSIM operate so differently, it is dificult to quantitatively compare results between the two models. IRPSIM is a simulation model running on an annual timestep and assigns water from the State Water Project, the Los Angeles Aqueduct, the Colorado River, and storage to its demands based on mass-balance and a user specified set of priorities. It does not route the water through any type of pipeline infrastructure or model local supplies. Local supplies are already subtracted from the demands entered into the model. IRPSIM divides MWDSC's demands up into three groups: demands that can only be met from the Colorado River, those that can only be met from the SWP, and those that can be met from either source. So while IRPSIM calculates the anticipated shortage in any given year, it does not allocate it to a specific user.

Inflows from the SWP are calculated based on the DWR reliability reports. Inflows from the LAA use a weather based regression, and inflows from the CRA are based on MWDSC's allocation and can be supplemented by toggling the Palo Verde fallowing program. The output of IRPSIM is the overall level of system reliability. In agreement with the findings in this modeling set, IRPSIM finds that areas solely dependent on the SWP consistently have lower levels of system reliability than areas dependent on the Colorado River or mixed supplies.

Conclusions

Overall, some interesting shifts occur with the revised model. Reservoir storage is used less aggressively and valued somewhat less. Seawater desalination is unused or is replaced by recycling, and recycling decreases except in parts of southern California. Pumping through the Delta, supply portfolios, and groundwater storage do not change significantly except in southern California where groundwater replaces surface water for urban uses and surface water replaces scarcity for agriculture.

Chapter 6

Responses to Reduced Water Imports to Southern California

This set of CALVIN model runs examines the effects of decreasing water availability on water management and costs for southern California. Five cases restricted flows over the Tehachapi Mountains from full availability (100%, 2.5 maf/year) to no imports from northern California. The full capacity of Edmonston Pumping Plant, the pumping station which lifts water over the Tehachapi Mountains, is 3.2 maf/year, but average pumping is only 2.5 maf/year (DWR, 2009). Economic effects were compared at these delivery levels. Physically and environmentally-constrained, but optimized, deliveries were also made from the Colorado River and from the Mono Lake and Owens River systems.

Model Setup

This model application is based on the revised model described in Chapters 5. All links, demands, capacities, and penalties are unchanged, unless otherwise stated. To create the southern-California-only model for this study, everything north of the Tehachapi Mountains was deleted except for the Kern groundwater bank. Demand areas in southern California are described in Chapter 2.

Capacity, recharge, and extraction rates for the Kern groundwater banks remained unchanged to allow for some over-year storage of northern California Water. These facilities have a storage capacity of 950 taf, a recharge capacity of 202 taf/year, and a pumping capacity of 203 taf/year. Kern groundwater recharge costs $14/af, and pumping costs $103/af. There is no charge for storage or minimum storage level. It starts from empty and has no storage losses or natural inflows.

To regulate State Water Project (SWP) inflows to Region 5, a large virtual reservoir was created just north of the Tehachapis. This reservoir allows flexible allocation of water throughout the year. It has a maximum capacity of 2.5 maf from October through August and a capacity of zero in September, allowing no over-year storage except through separate groundwater banking. This virtual reservoir has no evaporation, no minimum storage constraint, and no required end-of-period storage. It starts from an initial storage of zero each year.

According to DWR, the average annual flow over the Tehachapis is 2.5 maf/year (DWR 1995). The present study consists of five cases, delivering 100% (full availability), 50%, 25%, 10%, and 0% (none) of this average annual SWP inflow. Each case’s annual water allocation is delivered to the virtual reservoir every October, the first month of the water year, with no additional deliveries that year. Demands can then draw that water as needed, with the constraint that the reservoir must be empty by the end of September. This fixed annual delivery neglects the significant inter-annual variability in water availability from northern California due to droughts, environmental restrictions, water rights and contracts and water market conditions.

Calibration

To make the lower availability runs feasible, five small calibration losses were removed from the California Aqueduct. These losses combined average 3.4 taf/year, trivial compared to regional demand. For consistency, these losses were removed in all cases. In the no northern California imports case, evaporative losses had to be removed from all of the reservoirs supplied solely by SWP water, Pyramid Lake, Castaic Lake, Silverwood Lake and Lake Perris, as no inflow was available to offset these losses and keep the run feasible. The reservoirs are constrained to an ending storage nearly equal to the initial storage in all cases.

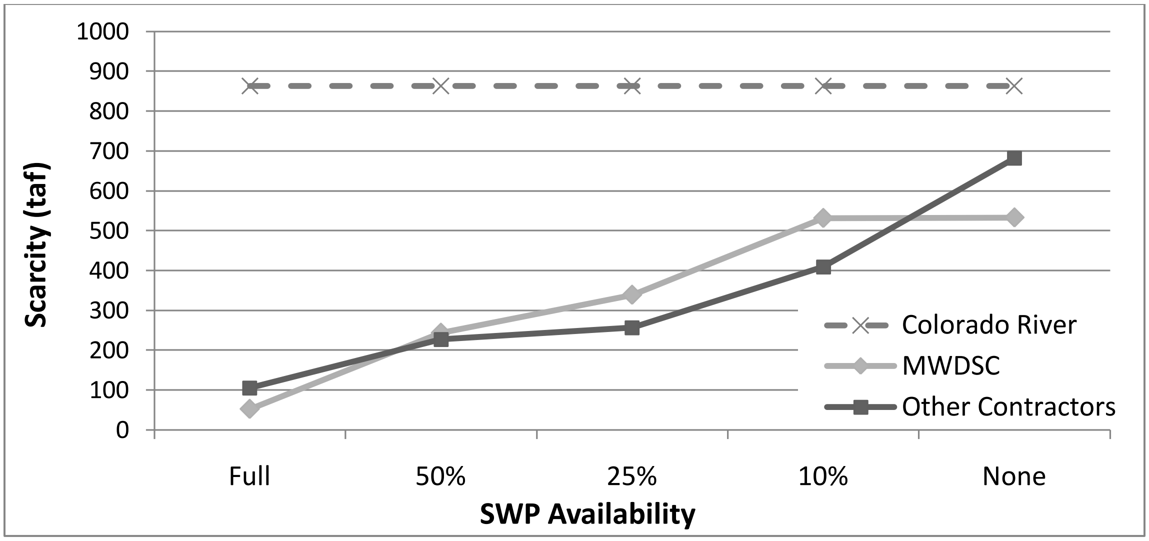
Results

Water Scarcity

As supply availability from north of the Tehachapi Mountains decreases, scarcity increases, and it is interesting to see where the model economically allocates this scarcity. Figure 6.1 shows combined residential, commercial, industrial and agricultural scarcity by region for each level of northern California (SWP) water availability.

The Colorado River region in 2050 is unaffected by reduced State Water Project inflows since east-west conveyance is already limited by Colorado River Aqueduct capacity, even with full SWP availability. The Colorado River region cannot transfer more water west regardless of scarcity on the South Coast. Since the Colorado River region is unaffected by changes in SWP inflows, all scarcity levels and costs there remain unchanged. This region includes Coachella, Blythe, Palo Verde, Imperial, and El Centro.

Figure 6.1: Average Annual Scarcity by Demand Area (taf/yr)

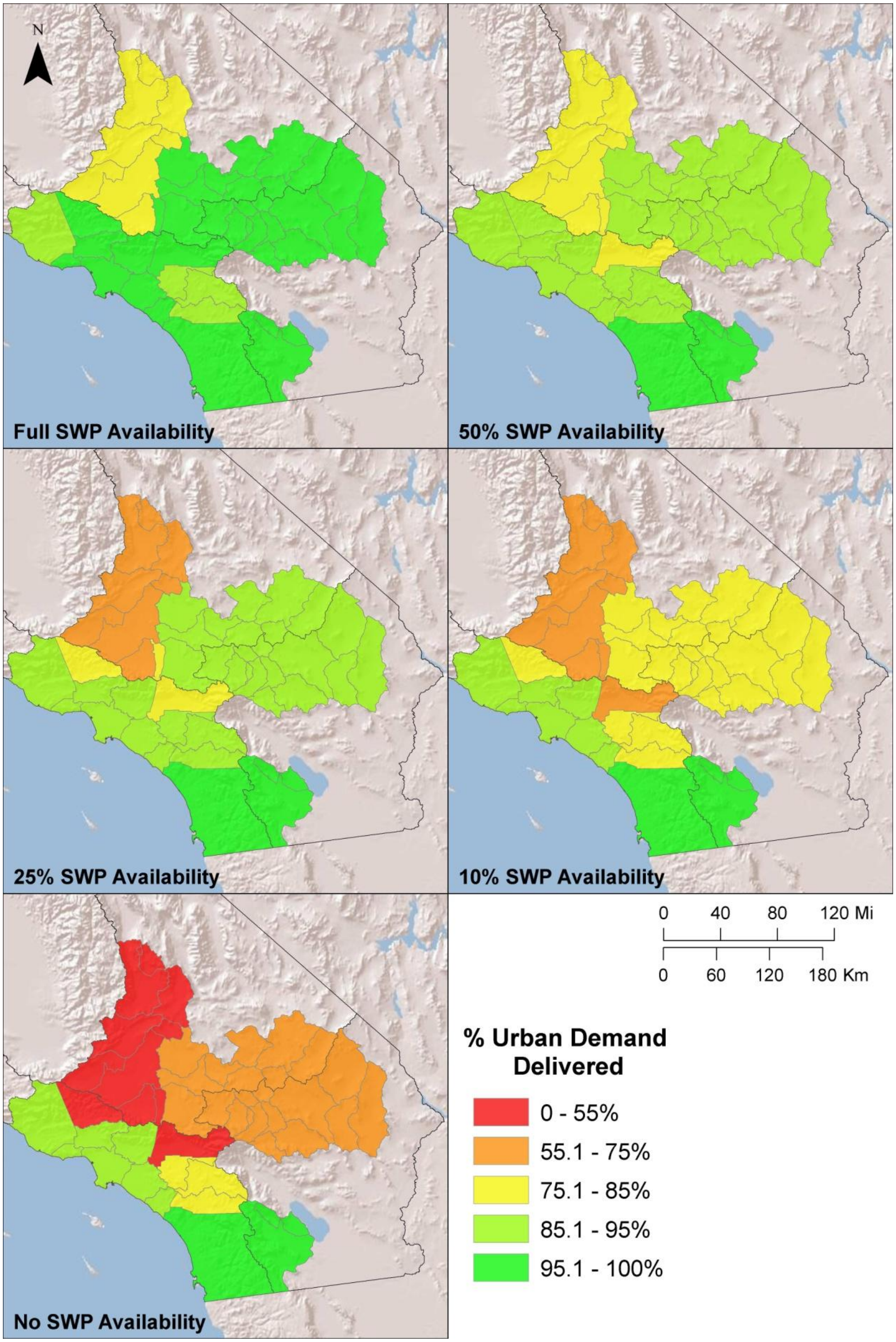


MWDSC member agencies (Central MWD, E&W MWD, and San Diego) receive water from the Colorado River Aqueduct (CRA), the Mono Lake and Owens Valley system via the Los Angeles Aqueduct (LAA), the State Water Project (SWP), and local supplies. Water scarcity for MWDSC increases as northern California imports decrease, up until the 10% SWP availability case. By the 10% case, the MWDSC member agencies have already sold nearly all SWP supplies to higher value demands among the other SWP contractors and rely on other water sources.

The combined target delivery for the MWDSC member agencies is almost four times the combined target demand of the other SWP contractors. Looking at the 50% SWP availability case, MWDSC and the other SWP contractors have comparable amounts of scarcity. However willingness-to-pay is relative to the percentage of demand remaining unmet, not just the amount of scarcity. While MWDSC has the higher amount of scarcity in the 50%, 25%, and 10% SWP availability cases, the other SWP contractors have a much higher percentage of unsupplied demand, thus the higher willingness-to-pay.

The other SWP contractors (Mojave, Antelope, Castaic, Ventura, and San Bernardino) depend on SWP water and local supplies, so they are the most affected by reduced SWP availability. Figure 6.2 and Table 6.1 show urban scarcity by demand area for MWDSC and the other SWP contractors.

Figure 6.2: Average Urban Water Scarcity for SWP Contractors



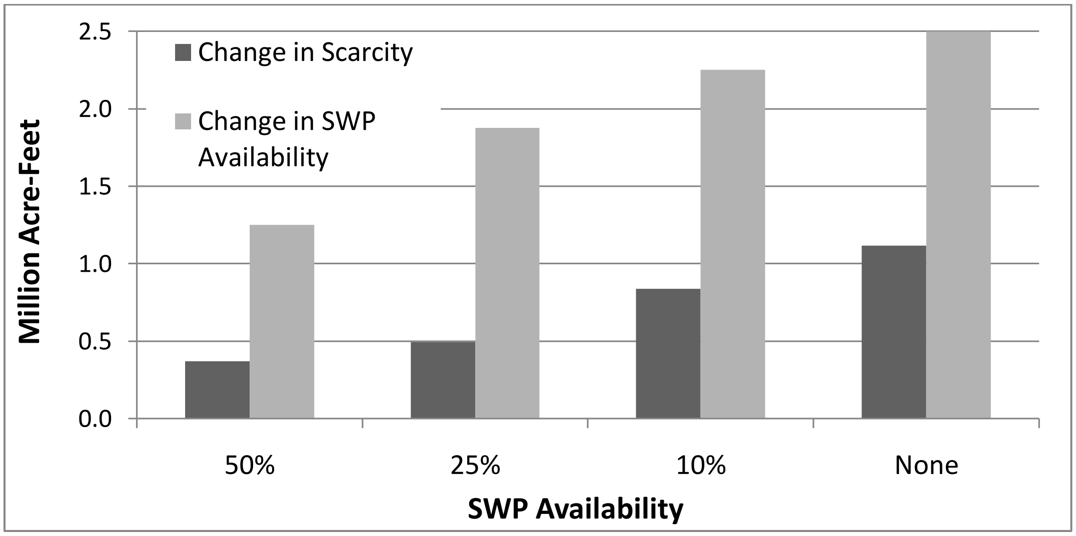
Agricultural scarcity among the non-MWDSC SWP contractors is unaffected by reductions in SWP availability. Antelope Valley and Ventura County are the two agricultural areas in this region. Antelope Valley agriculture receives no water in any case by year 2050 while Ventura County agriculture, dependent entirely on groundwater, receives full supply in all cases.

Table 6.1: Average Annual Water Scarcity (taf/yr)

		SWP Availability					**Target Demand**
		Full	**50%**	**25%**	**10%**	**None**	
Other SWP Contractors	Mojave	0	18	31	53	96	221
	Antelope	58	84	88	139	231	350
	Castaic	0	21	28	35	81	159
	Ventura	20	20	20	20	20	153
	SBV	27	83	88	154	250	547
MWDSC	Central MWD	0	173	210	353	355	3,280
	E&W MWD	0	71	127	140	140	886
	San Diego	0	0	3	38	38	837
CR	CR Region Urban	0	0	0	0	0	407
Agriculture	Antelope Ag	80	80	80	80	80	80
	Ventura Ag	0	0	0	0	0	175
	E&W MWD Ag	23	27	27	28	28	92
	San Diego Ag	0	0	0	7	7	172
	CR Region Ag	863	863	863	863	863	2928
	Total	**1,071**	**1,440**	**1,565**	**1,910**	**2,189**	**10,287**

In Table 6.1, Ventura County urban appears self-sufficient on local supplies and unaffected by reductions in SWP water. Ventura has a small SWP connection, only 32 taf/year. It uses this connection at capacity in the full SWP availability case, but replaces SWP water with recycling in all other cases.

Figure 6.3: Average Annual Change in Water Scarcity vs. Change in SWP Water Availability (maf/yr)



Decreased northern California water availability does not translate directly to an increase in total water scarcity in southern California, Figure 6.3. Changes are measured relative to the full SWP availability case (2.5 maf/year), a 2.5 maf/year reduction from full SWP availability to no SWP availability increases scarcity only a 1.1 maf/year. The remaining 1.4 maf is drawn from other supply sources. Overall SWP availability decreased more quickly than scarcity increased. Ratios range from an average of 0.26 acre-feet of scarcity for every acre-foot of SWP reduction in the full availability case to an average of 0.44 acre-feet of scarcity for every acre-foot of SWP reduction in the no availability case.

Table 6.2 shows the same scarcity information as Table 6.1, formatted as percent of combined residential, commercial, and industrial demands. This allows better visualization of scarcity in each area. Water scarcity is divided fairly evenly among non-MWDSC SWP contractors' urban uses in each case, excluding Ventura, though Antelope Valley has slightly higher urban scarcity in all cases. San Bernardino also has 0.8 taf of industrial scarcity in the no SWP availability case – the only industrial scarcity observed in this study.

Table 6.2: Average Annual Water Scarcity (% target delivery)

		SWP Availability				
		Full	**50%**	**25%**	**10%**	**None**
Other SWP Contractors	Mojave	0%	8%	14%	24%	44%
	Antelope	17%	24%	25%	40%	66%
	Castaic	0%	13%	17%	22%	51%
	Ventura	13%	13%	13%	13%	13%
	SBV	5%	15%	16%	28%	46%
MWDSC	Central MWD	0%	5%	6%	11%	11%
	E&W MWD	0%	8%	14%	16%	16%
	San Diego	0%	0%	0%	5%	5%
CR	CR Region Urban	0%	0%	0%	0%	0%
Agriculture	Antelope Ag	100%	100%	100%	100%	100%
	Ventura Ag	0%	0%	0%	0%	0%
	E&W MWD Ag	25%	30%	30%	30%	30%
	San Diego Ag	0%	0%	0%	4%	4%
	CR Region Ag	29%	29%	29%	29%	29%
	Total	**10%**	**14%**	**15%**	**19%**	**21%**

Examining scarcity for MWDSC member agencies, the average percent scarcity is significantly less than for the other SWP contractors. It is also less evenly distributed. E&W MWD has the highest percentage of scarcity in all cases, while San Diego has no scarcity until the 25% SWP availability case. San Diego has a significantly higher urban water rate, and thus WTP, than the other MWDSC demand areas. This means that among the MWDSC member agencies, in order to minimize total cost, San Diego's demands are filled first.

Agricultural demands in this region, San Diego and E&W MWD, only have a slight (12 taf/year), change in scarcity from full SWP availability to no SWP availability, a small scarcity compared to the rest of the region. All MWDSC areas have nearly constant scarcity between 10% SWP availability and no SWP availability.

Indoor-Outdoor Split

While water scarcity changes significantly between cases, the way scarcity is divided among indoor and outdoor urban uses does not. Table 6.3 shows the percent of each demand areas' total water scarcity allocated to indoor and outdoor uses. Cases without scarcity are blank. Indoor demands include residential uses inside of the home and commercial uses. In demand areas without a separate industrial demand area, indoor also includes industrial uses. Outdoor uses include residential uses outside of the home and large landscapes such as public parks and gardens.

Table 6.3: Average Annual Indoor-Outdoor Scarcity Split

(% combined indoor-outdoor target delivery)

		SWP Availability									
		Full		**50%**		**25%**		**10%**		**None**	
		In	Out	In	Out	In	Out	In	Out	In	Out
Other SWP Contractors	Mojave	0%	0%	2%	5%	4%	10%	8%	16%	12%	31%
	Antelope	2%	14%	3%	21%	4%	21%	4%	35%	7%	59%
	Castaic	0%	0%	3%	10%	3%	14%	6%	15%	16%	35%
	Ventura	3%	10%	3%	10%	3%	10%	3%	10%	3%	10%
	SBV	2%	6%	8%	19%	8%	20%	5%	23%	6%	39%
MWDSC	Central MWD	0%	0%	1%	4%	2%	5%	3%	7%	3%	8%
	E&W MWD	1%	5%	2%	6%	3%	12%	3%	13%	3%	13%
	San Diego	0%	0%	0%	0%	0%	0%	2%	3%	2%	3%

Each demand area has a unique ratio of indoor to outdoor water use, which remains relatively constant in all cases, except very low scarcity cases where all scarcity is assigned to either indoor or outdoor demands. Antelope and SBV allocate the highest fraction of scarcity to outdoor uses while Central MWD and San Diego allocate the lowest.

The ratio chosen by the model roughly correlates to each region's observed percentages of indoor and outdoor use. Antelope and the greater San Bernardino area (modeled here) are extensive suburban areas with large lawns and lots of golf courses. Central MWD and San Diego are denser urban areas. Since indoor-outdoor split is determined by matching indoor and outdoor willingness-to-pay, the slight shifts in allocation result from how that balance could best be achieved. This is discussed in more detail in the next section.

Marginal Willingness-To-Pay for Water

Each unit of water goes to the location with the highest marginal willingness-to-pay (WTP), if this is physically possible, guaranteeing that the highest value uses are supplied first when physically possible. The values in Table 6.4 are the maximum observed WTP over the 72-year period. All costs are in 2008 dollars, and maximum values for each case are highlighted for comparison.

The case with no SWP availability is omitted as the marginal willingness-to-pay estimates are not quantitatively reliable for the resulting extreme levels of scarcity. CALVIN uses piecewise linear approximations for the logarithmic penalty curves to calculate marginal WTP, and those approximations are only accurate up to approximately 30% scarcity, with accuracy decreasing beyond that point. Since urban scarcities among the non-MWDSC SWP contractors significantly exceed 30% without SWP deliveries, the scarcity costs and WTP generated for that case are significant misestimates.

Even if the linear approximation were not misestimating costs at high levels of scarcity, the penalty equations themselves are empirical and high scarcities are far outside of the range of most data studies. Low elasticity (below -0.5) employed in a constant elasticity of demand functional form, as is done here, makes response to price changes very small. Thus, when water is available, deliveries will stay almost constant regardless of the price of water. However, if there is little or no water available and deliveries fall well below the target, the penalty will be on the part of the penalty curve where the marginal price is in the vertical asymptotic zone of the constant elasticity of demand function. Small changes in the quantity delivered in this range cause large increases in the marginal price and shortage costs. The percentage shortage at which this erratic behavior occurs depends on the magnitude of the elasticity. Extremely low elasticities (< -0.15) make shortages extremely expensive, whereas higher elasticities add some flexibility.

Table 6.4: Avg. Annual Marginal WTP among SWP Contractors ($/af)

		SWP Availability							
		Full		**50%**		**25%**		**10%**	
		In	Out	In	Out	In	Out	In	Out
Other SWP Contractors	Mojave	0	68	1,179	1,149	1,549	1,356	1,549	2,031
	Antelope	1,036	980	1,186	1,353	1,652	1,353	1,652	2,677
	Castaic	0	0	1,676	1,601	1,676	2,157	1,676	2,204
	Ventura	1,226	1,155	1,226	1,155	1,226	1,155	1,226	1,155
	SBV	388	376	1,061	940	1,061	1,008	1,061	1,812
MWDSC	Central MWD	0	0	1,159	1,209	1,245	1,281	1,245	1,488
	E&W MWD	687	708	1,041	1,069	1,372	1,286	1,372	1,392
	San Diego	0	0	0	0	584	2	584	1,448
	MWDSC Ag	772		1,058		1,059		1,568	
	Maximum	**1,226**		**1,676**		**2,157**		**2,677**	

Although the magnitude of shortages in the no SWP availability case are this unrepresentative zone, since all demand areas are similarly misestimated, the model still allocates water reasonably because the relative costs between users remain valid. Results are shown separately for indoor and outdoor demands.

An area's overall marginal WTP is the maximum of the indoor and outdoor values for that area. Because the non-MWDSC SWP contractors have higher percentages of scarcity in all cases, they also have higher marginal WTP. WTP also increases more rapidly for non-MWDSC contractors than for MWDSC member agencies. Because MWDSC has alternative supply sources (the CRA and LAA), they sell their SWP water to higher value which lack alternative supplies. Areas with the highest WTP in the high scarcity cases have the least local inflows: Antelope, Mojave and Castaic Lake.

Water is allocated between indoor and outdoor uses to balance WTP within each demand area. In Table 6.4, this balancing seems to work better in cases and regions with lower scarcity.

For the non-MWDSC SWP contractors in the 25% and 10% SWP availability cases, the balancing of indoor and outdoor WTP within each demand area becomes very rough.

Indoor and outdoor demands have separate economic penalty functions, linear approximations of their estimated demand curves. In low scarcity situations, both the indoor and outdoor WTP are measured from the relatively flat portion of the curve where a small discrete change in delivery produces a small increase in WTP. Such small increments can be easily balanced to achieve comparable marginal WTP for indoor and outdoor uses.

However, when outdoor scarcity becomes three to four times indoor scarcity, the outdoor demand curve reaches its steeper portions first, where a small change in delivery has a large increment in marginal WTP. The optimization model cannot match coarse increments precisely on two different curves. The mismatches in indoor and outdoor WTP are the optimization engine’s best effort to achieve comparable marginal WTP for indoor and outdoor uses, not a different behavior pattern at high levels of scarcity.

MWDSC region agriculture has surprisingly high WTP, comparable to the less expensive urban uses in every case. The value in Table 6.4 is the maximum WTP of any agricultural area in the region. The maximum occurs at E&W for the 100% through 25% SWP availability cases (which explains why it matches so well with E&W MWD WTP in those cases) and at San Diego for the 10% SWP availability case.

Scarcity Cost

Table 6.5 shows annual urban scarcity costs. Ventura County was unaffected by reduction in SWP deliveries, and so has no additional water scarcity cost. Again, the no SWP availability case is excluded because of the unrepresentativeness of penalty quantities at these high scarcity levels.

Antelope Valley has the highest scarcity costs because it has few alternative water supplies. SBV has the lowest marginal WTP of the non-MWDSC SWP contractors, based on a low urban water rate. So the optimization engine assigns scarcity to SBV first, resulting in large scarcity and relatively high scarcity costs in SBVS. Total scarcity cost is calculated as the sum of the scarcity and operating penalties over all monthly timesteps.

Table 6.5: Average Annual Urban Scarcity Costs ($millions)

		SWP Availability			
		Full	50%	25%	10%
Other SWP Contractors	Mojave	0.06	19	39	89
	Antelope	47	83	90	225
	Castaic	0	29	45	62
	Ventura	20	20	20	20
	SBV	21	70	74	217
MWDSC	Central MWD	0	201	248	480
	E&W MWD	51	70	144	164
	San Diego	0	0	4	57
	Total	**$139**	**$491**	**$665**	**$1,314**

Examining the trend in scarcity costs, Figure 6.4, the slope is relatively flat for full SWP availability through the 25% availability case, indicating that each additional unit of SWP reduction costs about the same amount. From the 25% availability case to the 10% availability case, each unit of scarcity becomes more expensive, with the costs rising more steeply for the other SWP contractors than for MWDSC. The no SWP availability case is shown only to give a sense of continuing trends. For MWDSC, the maximum scarcity cost has already been reached by the 10% SWP availability case and costs remain constant beyond that. For the other SWP contractors, scarcity costs continue to rise.

Figure 6.4: Average Annual Scarcity Cost Trends ($millions)

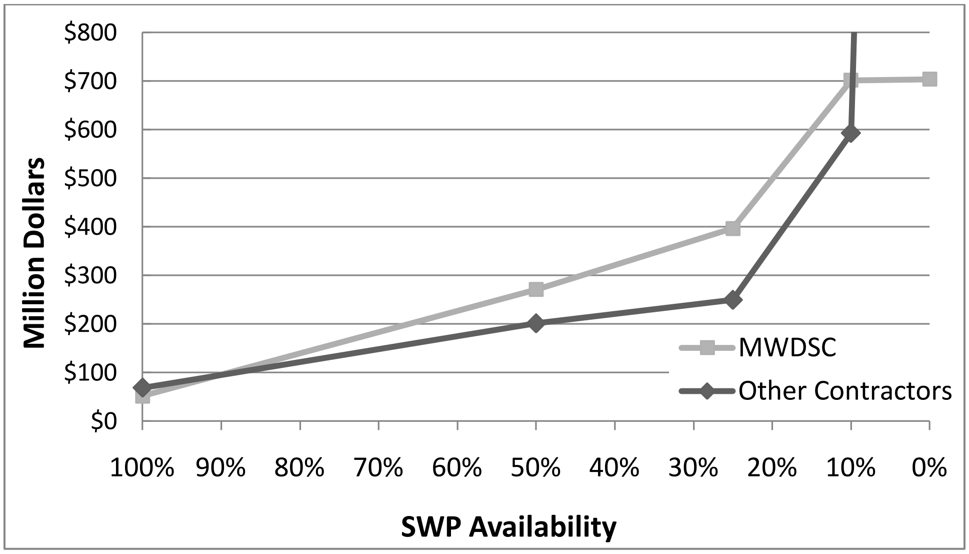
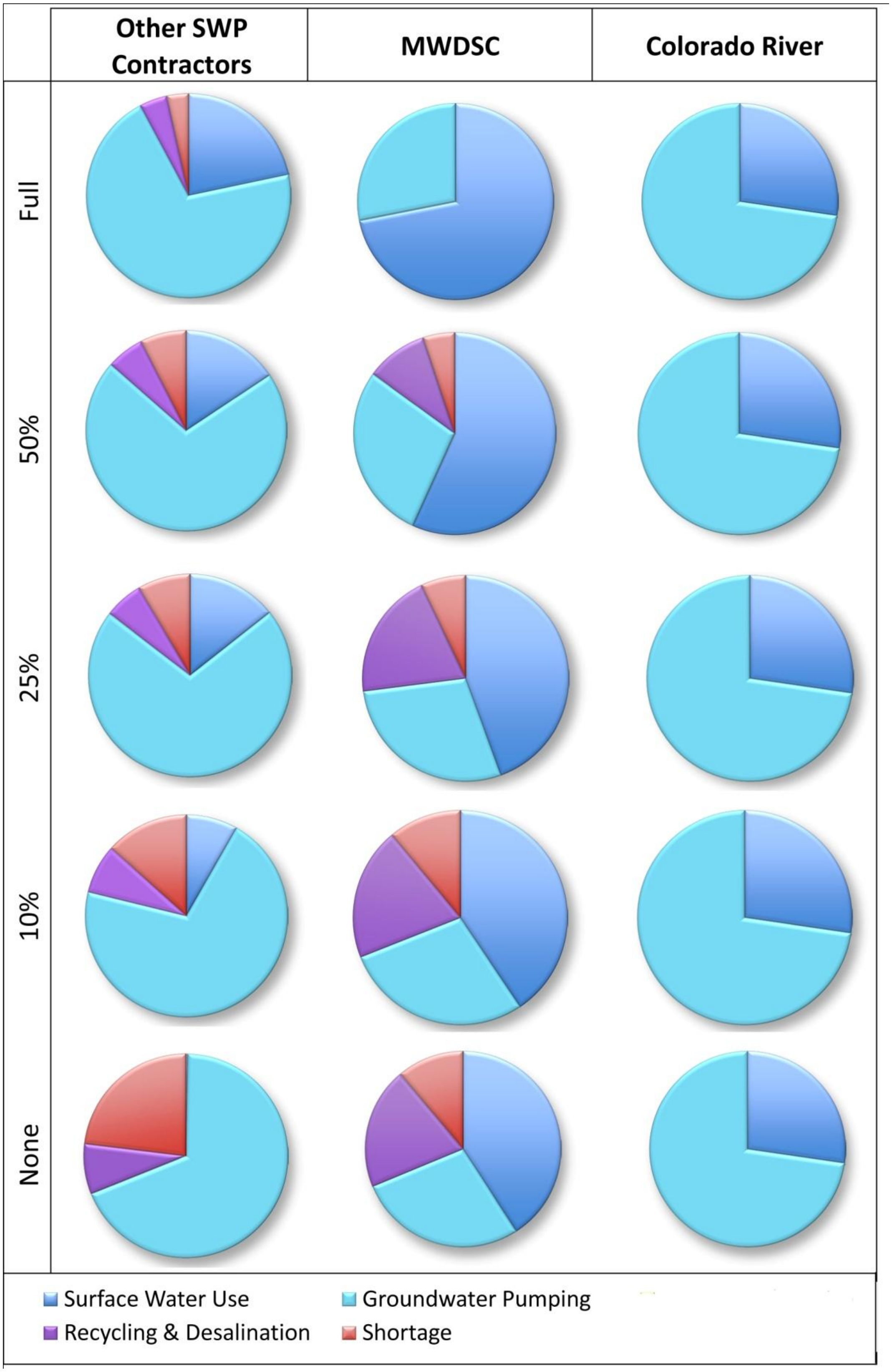


Figure 6.5: Average Annual Urban Water Supply Portfolios



Supply Portfolios

As imported surface water availability decreases, other supply options such as recycling, desalination, and groundwater pumping increase as shown in Figure 6.5 and Table 6.6. The Colorado River region is included in Figure 6.5 to show that scarcity and supply sources for this area are unaffected by reduced SWP imports.

Agricultural supply portfolios are not shown. Because southern California agriculture depends primarily on groundwater or the Colorado River, changes in SWP availability produce no significant shifts in agricultural supply portfolios. Agricultural supplies and scarcity remain unchanged for the non-MWDSC SWP contractors and the Colorado River region. In the MWDSC agricultural demand areas 11 taf of groundwater supply and 1 taf of surface water supply (100% of the surface water used by MWDSC agriculture) are replaced by scarcity as that water is transferred to urban uses.

The non-MWDSC SWP contractors supply most urban demands with groundwater, and overall groundwater pumping does not change significantly across the five cases. Groundwater pumping is limited by the available supply and does not provide a replacement for unavailable surface water. Groundwater pumping increases slightly from the full SWP availability case to the 25% SWP availability case, then decreases without SWP deliveries as decreased urban return flows reduce the available groundwater.

Table 6.6: Urban Supply Portfolios

(% of group's total water deliveries)

		SWP Availability				
		Full	**50%**	**25%**	**10%**	**None**
Other SWP Contractors	Surface Water	22%	16%	14%	8%	0.3%
	Groundwater	71%	71%	71%	71%	69%
	Recycling / Desal	4%	6%	6%	8%	8%
	Scarcity	3%	7%	8%	13%	23%
MWDSC	Surface Water	72%	57%	44%	41%	41%
	Groundwater	28%	28%	29%	28%	28%
	Recycling / Desal	0%	10%	20%	20%	20%
	Scarcity	0%	5%	7%	11%	11%

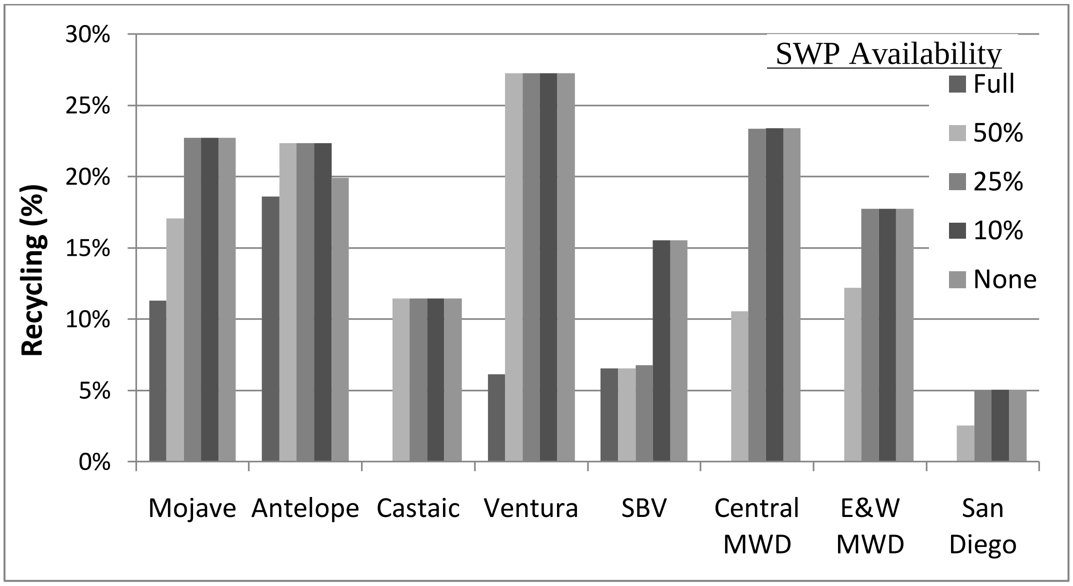
Recycling and seawater desalination remain nearly constant for non-MWDSC SWP contractors, and increase to about 20% of supplies for MWDSC member agencies as a whole. Most new technology supplies in southern California are recycling not seawater desalination, and when less supply is available, there is also less to recycle. The only non-MWDSC SWP contractor with potential access to seawater desalination is Ventura County, which is not greatly affected by reduced imports. Recycling and seawater desalination are discussed more in the next section. Overall, among the non-MWDSC SWP contractors, surface water imports are replaced by scarcity with little compensating mechanisms from other supply sources.

For the MWDSC member agencies, groundwater pumping also stays constant. However, recycling and seawater desalination increase dramatically from no use with full SWP availability to nearly 20% of total supply with no SWP availability. This helps to alleviate scarcity in that region and enable the transfer of SWP water to the other SWP contractors.

Recycling and Seawater Desalination

Use of new technologies increases dramatically for the MWDSC member agencies while remaining constant for the other SWP contractors. Surprisingly, there is no seawater desalination in any case. (CALVIN does not include brackish desalination due to a lack of characterization of brackish groundwater availability.) Areas with potential access to seawater desalination are Ventura, E&W MWD, San Diego, and Central MWD. In these areas, the maximum marginal WTP never exceeds $1,650/af while ocean desalination costs $2050/af in CALVIN (an optimistic cost estimate given the awkward representation of capital costs). This cost is based on data from DWR and represents a lower end estimate of the actual cost of desalination (DWR, 2005). Seawater desalination is not economically viable in the areas with the ability to implement it.

Figure 6.6: Avg. Annual Urban Water Recycling (% of total supply)



Water recycling is economically viable and heavily used, Figure 6.6. CALVIN includes two types of recycling. Existing recycling models the recycling capacity currently available in each area and costs $445 - $1200/af, based on the actual cost in that area. Expanded recycling represents recycling capacity that each area could choose to build. It has an upper limit of fifty percent of the area’s 2050 projected wastewater flows, minus existing recycling capacity, and costs $1480/af.

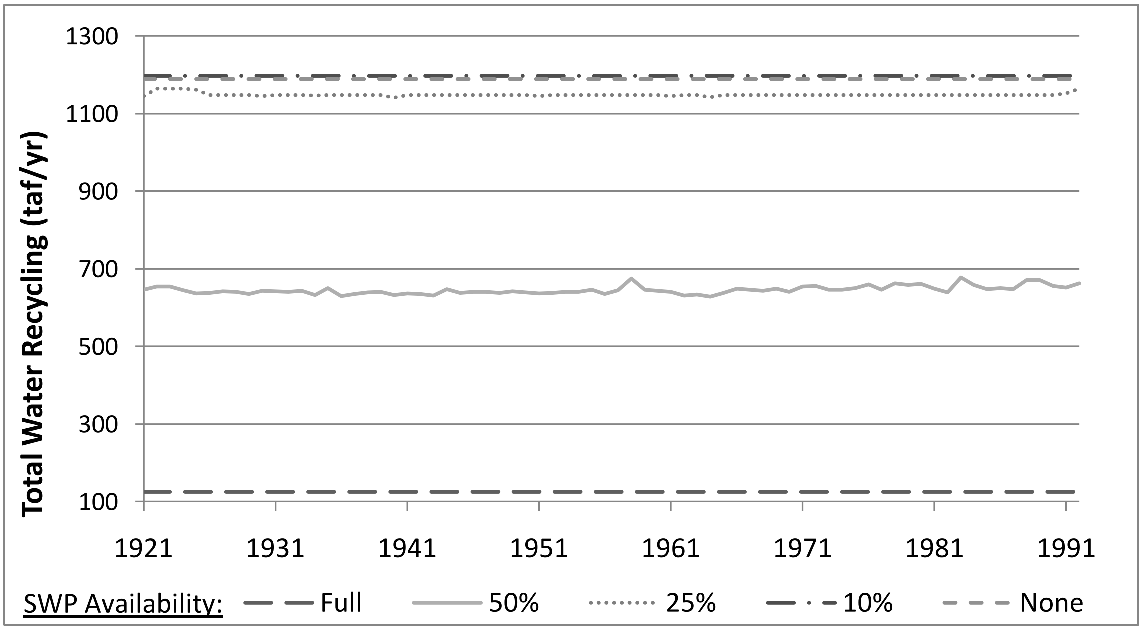
Table 6.7: Average Annual Urban Water Recycling (taf/yr)

		SWP Availability					Capacity	
		Full	50%	25%	10%	None	Existing	Expanded
Other SWP Contractors	Mojave	25	38	50	50	50	25	25
	Antelope	65	78	78	78	70	65	13
	Castaic	0	18	18	18	18	0	18
	Ventura	9	42	42	42	42	0.2	42
	SBV	36	36	37	85	85	36	49
MWDSC	Central MWD	0	346	766	767	767	344	422
	E&W MWD	0	108	157	157	157	43	114
	San Diego	0	21	42	42	42	18	24
	Total	**135**	**687**	**1,191**	**1,239**	**1,231**	**531**	**793**

Among the non-MWDSC SWP contractors, all demand areas except Castaic fully use their existing recycling capacity with full SWP availability and expand recycling capacity from the 50% SWP availability case onwards. Castaic has no existing recycling capacity and uses its full expanded recycling capacity in all cases. Capacities are listed in Table 6.7.

The MWDSC member agencies use no recycling with full SWP availability, their existing recycling with 50% SWP availability, and all allowed recycling beyond that. In the 10% and 0% SWP availability cases, all demand areas use their full existing and expanded recycling capacities. The exceptions are Antelope Valley which lacks enough supply to fill its recycling capacity without SWP deliveries and the Colorado River region, which does not use recycling.

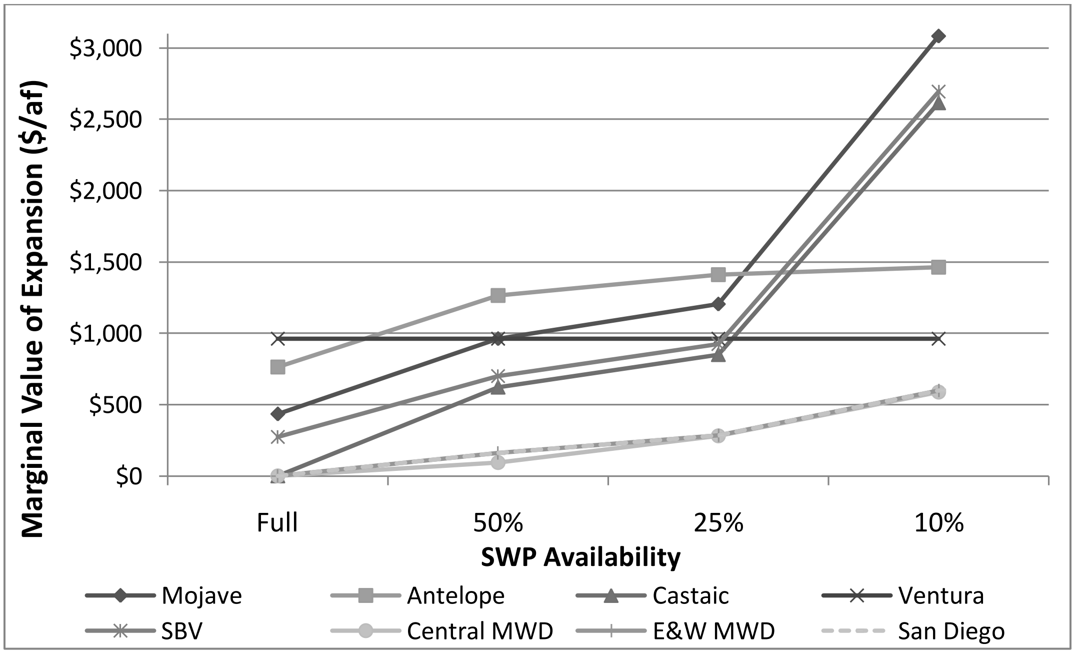
Figure 6.7: Annual Water Recycling (taf/yr)



Although this modeling set did not include inter-annual variability in imported water supplies from northern California, local supplies and groundwater inflows still varied with hydrology. Figure 6.7 shows the inter-annual variations in total southern California recycling. In the full, 10% and no SWP availability cases, the amount of recycling does not vary with hydrology. In the full SWP availability case, the areas using recycling use it as a constant part of their supply, and in the low SWP availability cases, all recycling is being used to capacity even in the wettest years. The 50% and 25% SWP availability cases have inter-annual variation in the amount of water recycling with more use in drier years and less in wet years.

Figure 6.8 shows the change in the marginal value of expanding water recycling capacity among the SWP contractors with the change in SWP availability. The marginal value of expanding water recycling capacity for the MWDSC member agencies stays relatively low. All three urban demand areas within MWDSC also have nearly identical values of expansion at every SWP availability level, demonstrating the interconnectivity of MWDSC.

Figure 6.8: Marginal Value of Expanding Recycling Capacity ($/af)



The non-MWDSC SWP contractors do not have the same similarly in the marginal value of expansion as MWDSC. Mojave, Castaic and SBV all have steadily rising values for expanding recycling capacity. In the 10% SWP availability case, the marginal value for expanding recycling in those areas far exceeds the marginal value of expanding any other piece of infrastructure examined (Figure 6.10). Ventura has a constant marginal value of expansion for recycling because it has a constant amount of scarcity. Antelope Valley has an interesting pattern of marginal expansion values. In the full SWP availability case through the 25% SWP availability case it follows the same pattern of rising marginal value of expansion as the other non-MWDSC SWP contractors. However, in the 10% SWP availability case, when the marginal value of expanding recycling for the other non-MWDSC SWP contractors spikes, Antelope Valley, with the highest level of scarcity in southern California, runs out of water to recycle. This significantly reduces the marginal value of expanding water recycling capacity in Antelope Valley in the 10% SWP availability case as compared to the marginal value of expanding recycling among the other non-MWDSC SWP contractors.

Given the value of expanded water recycling with little northern California water availability, it might be worthwhile to examine the upper limit of regional and local water recycling expansion more thoroughly. This might include recycling configurations that involve more indirect potable reuse.

Operating Costs

As SWP imports decrease, surface pumping, water treatment, and hydropower generation also decrease. Recycling costs increase as areas turn to alternative supplies, while groundwater pumping costs remain roughly constant.

In Table 6.8, operating costs increase from the full availability case until the 25% availability case, then decrease again in the 10% and no availability cases. By the 25% availability case, most recycling is already being used to capacity (SBV is still expanding their use), but surface pumping and treatment costs continue to decline, as do hydropower benefits due to a lack of imported water to pump and treat.

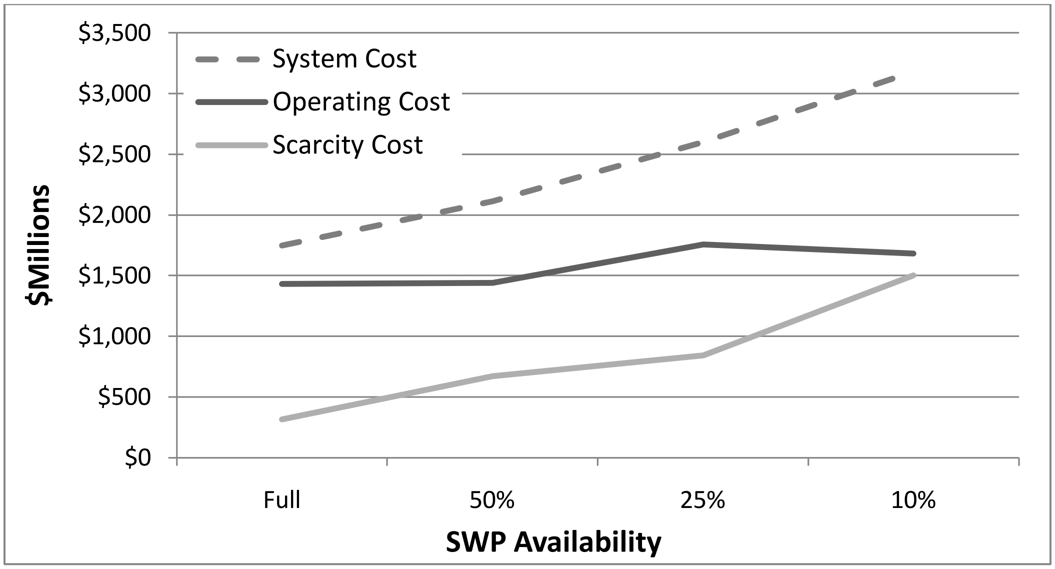
Table 6.8: Average Annual Operating and System Costs ($millions/yr)

	SWP Availability				
	Full	50%	25%	10%	None
Groundwater Pumping	98	97	96	94	91
Surface Pumping	712	428	232	115	35
Water Treatment	812	509	456	418	375
Recycled Water	103	607	1,104	1,150	1,140
Seawater Desalination	0	0	0	0	0
Hydropower Benefits*	-291	-199	-131	-96	-80
Total Operating Costs	**$1,433**	**$1,442**	**$1,757**	**$1,681**	**$1,561**
Scarcity Costs	315	669	844	1,502	
Total System Costs	**$1,748**	**$2,112**	**$2,601**	**$3,183**	

*Hydropower benefits are negative costs

Examining total system cost (operating costs plus scarcity costs), including the Colorado River region, system costs increase as SWP availability decreases. This is shown graphically in Figure 6.9. Scarcity costs are not shown for the no SWP availability case. Total system costs are almost linear, balancing out changes in the slopes of the operating and scarcity costs.

Figure 6.9: Average Total System Costs ($millions/yr)



Overall, system costs nearly double as SWP deliveries are reduced from full availability to 10% availability. Since scarcity cost represents what an area would be willing to pay for full supply, southern California, particularly MWDSC and the other SWP contractors, would be willing to pay almost twice as much in 2050 to have access to full SWP supply. At 10% availability, system costs are $3.1 billion/year, split fairly equally between scarcity and operating costs.

Expanded Conveyance

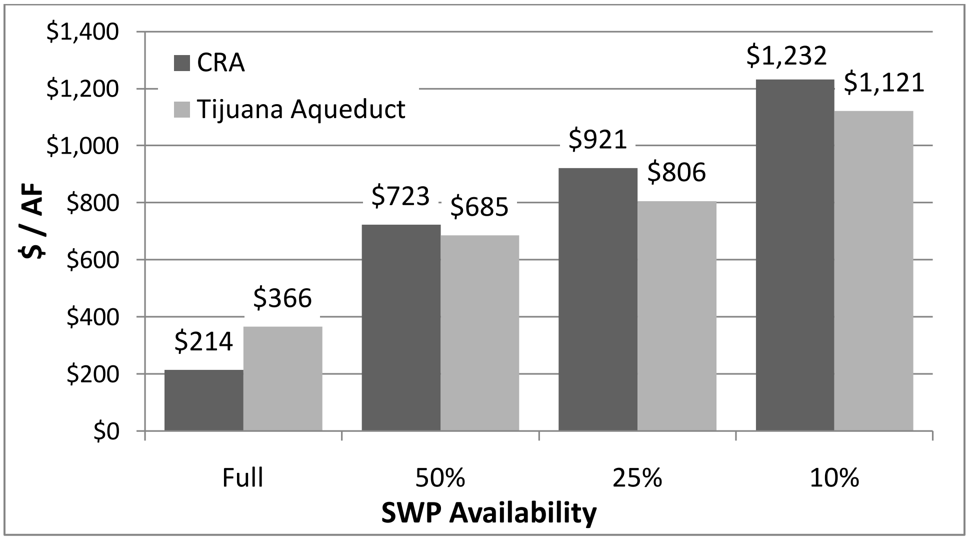
In this model, no additional water could be transferred from Colorado River region agricultural users to the thirsty South Coast because of limited capacity of the Colorado River Aqueduct. Figure 6.10 shows the marginal value of expanding the Colorado River Aqueduct (CRA) or a potential Tijuana Aqueduct. The no SWP availability case is omitted.

The CRA runs from the Colorado River to Lake Matthews of MWDSC, with side branches supplying San Diego and E&W MWD. It has a capacity of 1.3 maf/year. The marginal value of expanding the CRA increases as SWP availability decreases, up to $1,232/af.

The Tijuana Aqueduct (TA) is a potential intertie connecting Imperial Valley with San Diego. The existing aqueduct has a capacity of 135 taf/year and runs east-west just south of the California-Mexico border to serve the cities east of Mexicali in Baja California including Tijuana, Rosarito and Tecate. A proposed addition would then turn and run north along the coast to San Diego.

The existing facility originates in the Mexicali Valley and climbs roughly 3500 ft (nearly double the pumping lift over the Tehachapis) through La Rumorosa Range of the San Pedro Martír Mountains, running more than 70 miles in pipelines, tunnels, and lined canals. Actual operating costs associated with the TA include treatment and pumping costs. Medellín-Azuara et al. (2009) estimated combined costs of roughly $985/af for his study of future water management alternatives for Baja California. Energy requirements in the TA average 4900 kW-hour/af, for an annual average cost of $495/af. Despite the drop elevation from the top of the mountains to the coast, there is no hydropower generation to defray some of the pumping costs. Current treatment costs for the Mexican cities range from $425-$495/af (CESPM 2005). More recent estimates of energy and other fixed costs, not including treatment, are roughly $575/af ($2010) (CEA 2010). These costs do not include additional pumping that might be necessary for the proposed extension north to San Diego.

Figure 6.10:Avg. Marginal Annual Value of Expanded Conveyance ($/af)



In CALVIN, the TA currently has no conveyance capacity. The link exists only to examine the marginal benefit such a connection. Operating costs for the TA currently in CALVIN are a conveyance cost of $380/af which includes salinity damage but not pumping costs. While in Figure 6.10 constructing the Tijuana Aqueduct appears only slightly less valuable than expanding the CRA in all except the 100% SWP availability case, $450 - $600/af in unaccounted for pumping costs plus an extra $40 - $115/af in treatment costs rapidly erode the value of the connection.

Storage

Less inflow to the region means less water to store and reservoirs filling less frequently. However less overall water availability also means more value for any additional water captured. Reservoirs on the SWP have increasing but trivial (less than $1/af) marginal values of expansion. Additional storage on the CRA has decreasing marginal values of expansion, and storage on the LAA has increasing marginal value.

Lake Skinner fills every year in all cases, though the marginal value of expansion decreases dramatically from $368/af to $9/af. It is a small reservoir, 44 taf, and connected to the CRA. Despite being connected to the CRA, Lake Matthews fills infrequently, and Diamond Valley Lake never fills. On the California Aqueduct, Castaic Lake and Silverwood Lake have initial storage values near the maximum storage, and so fill in the first year or two of all except the no SWP deliveries case, before that storage is depleted. Pyramid Lake fills only with full SWP availability, and Lake Perris never fills. Grant Lake and the Los Angeles Reservoir on the Mono Lake /Owens Valley system preserve the same filling patterns presented in Chapter 5, but the marginal value of expanding Grant Lake increases from $59/af to $111/af. The Los Angeles Reservoir never fills. Overall, there is little additional value to expanding surface storage in southern California to help avert shortages from reductions in SWP deliveries. For these model runs, there is a shortage of water, not a shortage of storage.

However, the value of surface storage and storage generally is perhaps greatly underestimated in this modeling set because the SWP supplies are modeled as constant amounts, without inter-annual variability. This makes droughts in the model less severe and wet years less bountiful. In reality there are often large swings in SWP availability between years, which is the main reason for using groundwater and surface water storage.

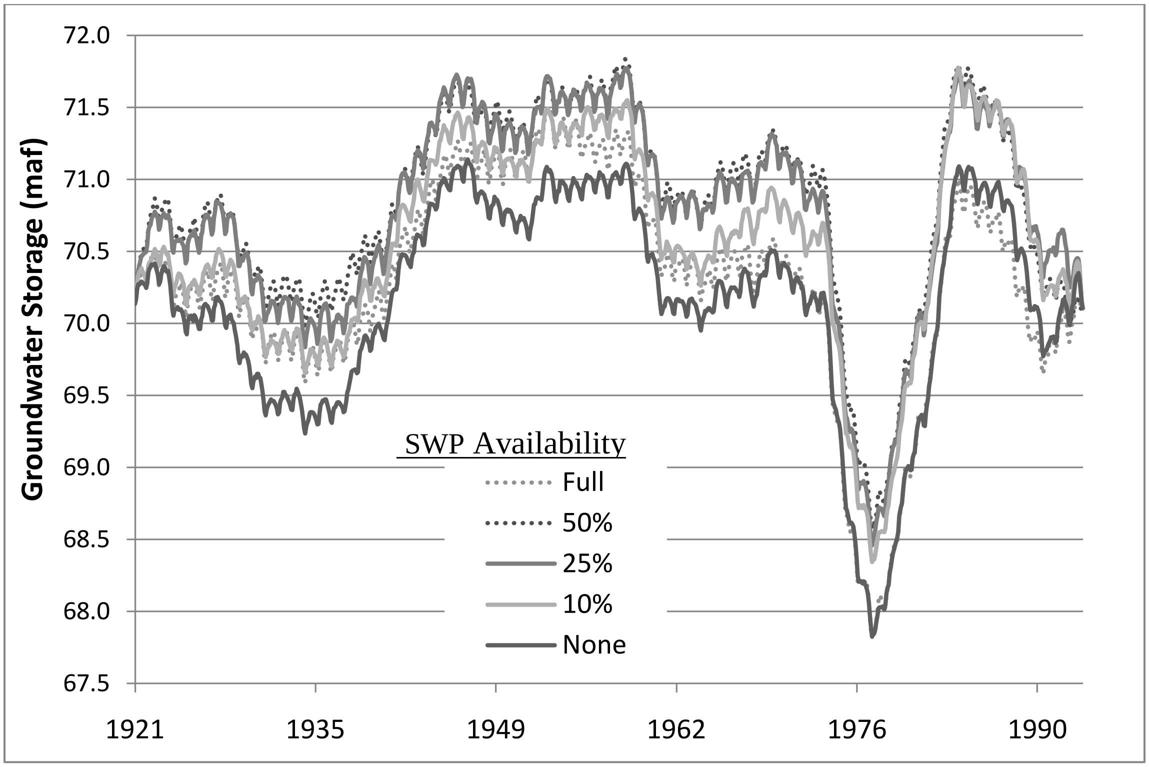
Groundwater Storage

Figure 6.11 shows monthly groundwater storage for all five cases. All basins are constrained to begin and end at the same storage level for all cases, but there is a lot of variability in how they behave in between. The supply portfolios have relatively constant overall levels of total groundwater pumping in all cases, so the differences below are largely from reduced groundwater recharge with imported water and reduced urban and agricultural return flows.

Groundwater levels in Imperial Valley and Coachella not affected by reduced SWP inflows and aren’t included in Figure 6.11. Groundwater levels in Owens Valley and Ventura County do change with reduced SWP inflows, despite the effect not being visible in the shortage levels. Owens Valley is on the LAA and serves as a remote groundwater storage basin for Central MWD.

As imported water availability decreases, groundwater basins have less flexibility in their operations. Since ending storage is constrained to a level close to initial storage, every unit of water withdrawn must be replaced by inflows, recharge, or return flows. Groundwater inflows remained unchanged, but with reductions in imported water, return flows and the potential for recharge decrease, causing groundwater basins to hedge their operations. The standard deviation among monthly storage levels over the 72-year period for each basin decreases with decreasing SWP inflows, reflecting reduced operational flexibility. Antelope, Mojave, and Central MWD all recharge their groundwater basins with imported water. As imported water becomes less available, storage levels in these basins decrease.

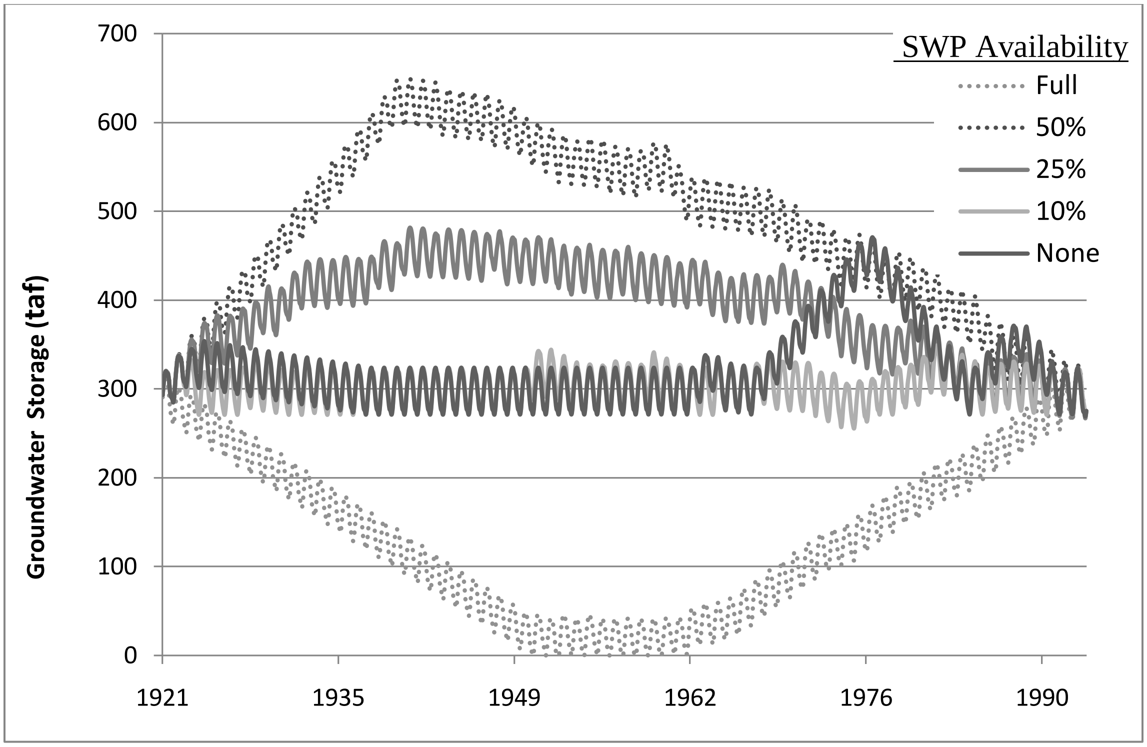
Figure 6.11: Southern California Groundwater Storage (maf)



In Figure 6.11, without SWP deliveries, groundwater is drawn down lower and does not rebound as high as in the other cases. Since imported water is unavailable to half of the demand areas in southern California, groundwater is drawn down with no opportunity to replenish it. Oddly, the case that most closely parallels the use pattern of the no SWP availability case is the full SWP availability case. Because the full SWP availability case has ample water for recharge and a reliable imported supply, there is no reason not to draw the basin down and less need to stockpile water against the next drought. Groundwater storage for the 50% and 25% SWP availability cases are almost identical, with the 50% case maintaining higher storages in the beginning part of the run and 25% case having higher storages near the end of the run. These cases stockpile larger amounts of groundwater to meet drought demands, and have enough imports to do so. The 10% SWP availability case also follows a similar pattern, but lack of imports restricts ability to stockpile water for droughts.

Examining Ventura County's groundwater storage cautions against concluding too much from Figure 6.11. Ventura County replaces all of its SWP water with recycled water from the 50% SWP availability case onwards. Inflows and return flows to groundwater are identical in pattern and quantity in all cases, and the total groundwater pumping remains constant though all cases, though the pumping patterns differ from case to case. Scarcity, WTP and scarcity cost remain constant in all cases, and operating costs and the total amount of recycling remain constant from the 50% SWP availability case onwards. Since water recycling has a constant capacity and a constant cost, Ventura's groundwater use is unaffected by changes in SWP inflows, indicating that the varied groundwater storage patterns shown below in Figure 6.12 are economically and practically identical from the perspective of the CALVIN optimization engine.

Figure 6.12: Ventura County Groundwater Storage (taf)



The Hayfield and Kern groundwater banks are not used in any of the cases. This implies no benefit for expanding groundwater storage in this situation. This is not surprising since the surface reservoirs are not being filled, and it is less expensive to keep water in surface reservoirs than to recharge it to groundwater. The advantage of groundwater storage is that there are no evaporative losses, but the water lost to evaporation must not be worth the recharge and pumping costs in this situation. However these results are likely to be considerably affected by the lack of inter-annual variability in modeled SWP water availability, which in reality is highly variable.

Conclusions

Extended failure or significant reduction of State Water Project and other northern California water supplies would have significant economic effects on southern California even if inter-annual variability in these supplies is eliminated. Effects are particularly severe for non-MWDSC SWP contractors. By the 10% SWP availability case, the SWP contractors, including MWDSC, have a combined average water scarcity cost of $1.3 billion annually. After a few years, that could be enough money to build peripheral conveyance around the Delta and expand the CRA without government assistance. (Both projects seem unlikely now, but could take on new urgency if the SWP was to fail.)

Despite the high levels and costs of scarcity, seawater desalination was not economically justified in any locations in southern California. CALVIN models seawater desalination from an optimistic perspective. It does not directly represent the initial costs of building desalination capacity, instead including them in variable costs. It does not include the maintenance costs for keeping the plant in working condition even when it is not being used or require the plant to operate at some minimum level even when less expensive options are available. The cost per unit of desalinated water, $2050/af is in the middle of the $1000-$2500 range estimated by DWR (2009), and near the lower end of estimates produced by Gleick (2003) of $997-$3250 and Fryer (2009) of $2000-$3000. In this model, desalination isn't economically justified even with no SWP deliveries and CALVIN's optimistic representation of the costs involved. Without significant advancement in the technology, seawater desalination is unlikely to provide a major replacement water source for California.

Wastewater recycling, however, appears to be viable and promising. Recycling has the capacity to provide additional supplies at reasonable cost, particularly in southern California where return flows are not generally utilized by other municipalities downstream. All South Coast urban areas use their recycling to their full allowed capacity. However, expanded water recycling costs are represented in the same optimistic manner as ocean desalination, with capacity costs included in variable unit costs.

Additional storage, either surface storage or groundwater banking, seems unhelpful in the event of long-term failure of the State Water Project, particularly given the lack of inter-annual variation in modeled SWP supplies. There is already substantial storage in southern California – enough that most of it fills only in the wettest few years of historical record with full SWP availability. When SWP availability is reduced (and its inter-annual variability is eliminated), those existing reservoirs do not fill. Southern California lacks large local supplies of surface water. Without major imports, there is no water to put into storage. Building storage does not create water. It provides a place to put existing water.

Additional east-west conveyance from the Colorado River would be useful with decreases availability of SWP supplies. Both the CRA and the Tijuana Aqueduct have high marginal values for expansion. Agriculture in the Colorado River region produces largely relatively low-valued crops. Ignoring established water rights, or assuming that farmers would be willing to sell those rights, if more water could be sent east to west it would significantly reduce overall system costs in southern California. This would be particularly true if that water could somehow be delivered to the SWP contractors currently lack access to Colorado River Water.

Overall, the economic effects of reducing SWP deliveries to 10% of their current availability, while significant, would not be disastrous. All SWP contractors except Antelope Valley still receive more than 70% of their projected 2050 water demand, and the remaining 30% could be saved through urban water conservation. Such urban conservation is not only possible, but appears to be cost effective (Ragatz 2011).

With no SWP availability, urban areas reliant solely on SWP and local supplies receive only 30% to 50% of their projected target demand, which is likely more than conservation can easily save. While this modeling set does not show this level of scarcity affecting industry, it would cause major shifts in lifestyle and negatively affect the social and economic wellbeing of these areas.

Chapter 7

Conclusions

Integrated hydro-economic, modeling, like CALVIN, provides a versatile way to explore the advantages and drawbacks of various components of potential statewide and regional policies and plans. When trying to predict the outcomes of changes to a large network such as California's water supply system, modeling provides better, more defensible results than unaided intuition and provided a potential framework for policy discussions.

Nevertheless, no model can perfectly reflect a complex reality due to inevitable imperfections in data and mathematical representations. It is important to periodically revisit any model to make sure it continues to operate with the best data available. This project updated and improved several aspects of the CALVIN model, particularly in southern California. These improvements significantly change scarcity costs and operating costs for the system, but cause little change in the overall water allocation. Improvements to the model are listed below.

Improvements

A range of improvements were made to the CALVIN model. These include updating and improving the model's representation of southern California (south of the Tehachapi Mountains), improving the accuracy of the urban scarcity cost equations, updating scarcity costs calculations with the most recent urban water rates, bringing all operating and scarcity costs into 2008 dollars, and dividing urban residential and commercial uses into indoor and outdoor demands with separate economic demand functions. These changes are summarized in Table 7.1.

Table 7.1: Improvements to CALVIN

Southern California
Updated year 2050 projected urban and agricultural water demands to match current estimates.
Added four new agricultural demand areas representing 207,500 cultivated acres and 520 taf/year of agricultural water demand in southern California.
Updated conveyance and recycling infrastructure to match 2050 operating capabilities.
Expanded modeled local supplies with four new groundwater basins.
Revised local surface water and groundwater inflows to better reflect historical hydrology.
Scarcity Costs (Statewide)
Improved urban scarcity cost calculations through adjustments to the penalty equations.
Recalculated the urban scarcity cost functions with the latest urban water rate data.
Brought all operating and scarcity costs into 2008 dollars, improving internal consistency.
Indoor-Outdoor Demand Split (Statewide)
Divided urban scarcity reporting into separate indoor and outdoor components with independent economic demand functions.

Southern California

Changes in southern California 2050 projected urban and agricultural demands reduced projected urban demands by 1.5 maf/year and increased projected 2050 agricultural demands by nearly 1 maf/year. Half of the increase in agricultural demand is due to expanded model coverage, and the other half is due to recalculation of cropping areas.

With the addition of 0.5 maf/year of agricultural demand in the South Coast and a shift in the region of highest urban demand from the Colorado River region to the South Coast, scarcity patterns shifted. In the revised model, Colorado River region urban demands receive full delivery in every case examined, and the CRA always runs to capacity to supply MWDSC member agencies. Because limited east-west CRA conveyance capacity prevents additional agriculture to urban water transfers, Colorado River region agricultural users receive a higher percentage of their target demand in the revised model.

Because almost all of southern California agricultural water demand is supplied by the Colorado River or by groundwater, the rest of the state feels almost all of 1.5 maf/year reduction in southern California urban demands. This reduction reduces pumping through the Sacramento-San Joaquin Delta and frees up capacity in the State Water Project for other users. This additional conveyance availability reduces the need for storage in the San Joaquin and Tulare Basins. Overall, annual average statewide scarcity costs decreased by $20 million and annual average statewide operating costs decrease by $700 million with the update.

Scarcity Costs

Part of the reduction in scarcity costs may be due to improvements in the equations that calculate urban scarcity costs. These improvements corrected overestimates scarcity cost in most urban demand areas. Changing the scaling factor in the equations from the population ratio to a ratio of the target deliveries preserves the slope of the empirical demand function as it is scaled up from the observed target demand (year 1995 in the initial model; year 2006 in the revised model) to the desired target demand (year 2050). This corrected overestimates of scarcity cost in 36 out of the 41 urban demand areas and underestimates in the rest.

The empirical demand functions are calculated based on an observed target delivery and a corresponding water price. The most recent Black & Veatch *California Water Rate Survey* (2006) was used to update the observed water prices to better reflect current pricing practices, as 2050 pricing practices remain unknown. This changed the relative marginal WTP between demand areas and shifted scarcity from demand areas which had increased their effective water rate to demand areas where the water rate did not keep up with inflation.

The initial model calculated operating and urban scarcity costs in 1995 dollars, but agricultural scarcity costs within the model were converted to 2008 dollars as part of an earlier update (Howitt et al. 2010). For internal consistency, urban scarcity costs and operating costs within the model were also converted to 2008 dollars. No obvious shifts in scarcity or scarcity cost resulted from this change, but it eliminates the need to manually convert model outputs to 2008 dollars and improves comparison of costs during the optimization process.

Indoor-Outdoor Demand Split

Urban demand areas statewide were divided into indoor and outdoor components with separate elasticities of demand and economic demand functions. This division did not affect each urban area’s target demand, total cost of scarcity, or connectivity to the network. Dividing urban areas into indoor and outdoor components allows examination of the economically optimized division of water between indoor and outdoor uses. Each area uses water differently with high density urban areas like Central MWD having relatively little outdoor water use and sprawling suburban areas with low precipitation such as Antelope Valley having a high percentage of outdoor water use.

Indoor-outdoor water scarcity is balanced to achieve comparable marginal WTP between indoor and outdoor demands within each demand area. This assigns a larger fraction of scarcity to outdoor water uses. The ratio of outdoor to indoor scarcity for demand areas with scarcity in the base case ranges from 1.6 in Mojave to 6 in Antelope Valley and averages 3.3. Most, but not all, low value urban uses of water are outside the home.

Conclusions from CALVIN Modeling

The revised model was used to study how reduced water supply imports from northern California would affect southern California and its water management. Five cases were modeled in which imports over the Tehachapi Mountains were limited to: full availability (2,500 taf/year), 50% availability (1,250 taf/year), 25% availability (625 taf/year), 10% availability (250 taf/year), and no availability. These amounts were delivered every year without the normal inter-annual variation in supply.

Urban and agricultural demand areas in the Colorado River region are likely to be unaffected by changes in SWP availability. Under economically optimal conditions, agricultural water users in the South Coast may sell 3% of their supply to South Coast urban users but for the most part rely on groundwater and may not be significantly affected. MWDSC member agencies, Central MWD, E&W MWD, and San Diego, have access to imported supplies from the Colorado River via the CRA in addition to imports from northern California and local supplies. Consequently, they are likely to be less affected than the non-MWDSC SWP contractors, Mojave, Antelope, Castaic, Ventura, and SBV.

In this modeling set, urban scarcity for the MWDSC member agencies increases from 0% to 11% of target water delivery with the reduction in SWP availability while urban scarcity for non-MWDSC SWP contractors increases from 7% to 47% of target water delivery. Groundwater pumping stays almost constant for all urban demands with imported surface water being replaced mainly by recycling for the MWDSC member agencies and mainly with scarcity for the non-MWDSC member agencies.

Water recycling increases from 0% to 20% of total urban water supply for MWDSC member agencies and from 4% to 8% of total urban water supply for non-MWDSC SWP contractors with decreasing SWP availability. With no SWP availability, all existing and potential South Coast urban water recycling capacity used. Seawater desalination, however, is not used in any case.

Both operating and scarcity costs increased with reductions in SWP availability. Decreases in surface water pumping and treatment costs were more than offset by the cost of recycling water and the loss of hydropower benefits. Average annual southern California scarcity costs increased from $1.7 million/year in the full SWP availability case to $3.2 million/year in the 10% SWP availability case. Scarcity costs are not given for the no SWP availability case as the level of scarcity among the non-MWDSC SWP contractors exceeds the range of validity for the CALVIN empirical economic water demand functions.

Urban water conservation has the potential to alleviate scarcity in the reduced SWP delivery cases. The state is calling for 20% urban conservation by the year 2020, and conservation levels up to 30% are still reasonable (Gleick et al. 2003). In the 10% SWP availability case, 30% urban water conservation could completely alleviate scarcity in every urban demand area except Antelope Valley.

Urban demand areas in southern California could probably adapt to much less than current imports from northern California through urban water conservation, expanded wastewater recycling, and some transfers from local agriculture., all incurring costs. However, scarcity levels among non-MWDSC SWP contractors in the no SWP availability case exceed what could be easily conserved or recycled. With the current infrastructure, at least some imported water appears to be necessary to support the projected 2050 population of southern California.

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Appendix 1
CALVIN Demand Areas by DAU

DAUs or Detailed Analysis Units are the smallest units or area at which DWR processes statewide data. A list of DAUs corresponding to each urban demand center may be found in Appendix B1, Tables B1-2 and B1-3. Table A1.1 contains an updated statewide list including changes and additions to the demands and the percentage splits between DAUs.

Table A1.1: CALVIN Demand Areas and Corresponding DAUs

Demand Area:	DAUs
URBAN	
Redding	141, 143
Yuba City	159, 168
Sacramento	172, 173, 158, 161,186
Napa-Solano	191, 40, 41
EBMUD	70% of 47, 30% of 46
Contra Costa	192, 70% of 46
San Francisco	43
SCV	44, 45, 62, 30% of 47
Stockton	182
City of Fresno	233
Bakersfield	254
SB-SLO	67, 68, 71, 74, 75
Mojave	309-314, 316-332
Antelope Valley	299-307
Castaic Lake	83
Ventura	81
SBV	44% of 100, 308
Central MWD	87, 89, 90, 92, 96, 114, 56% of 100
E&W MWD	98, 104, 110
San Diego	120, 350,351,352
Coachella	348, 349
Blythe	333-347
El Centro	353-356
URBAN and AGRICULTURE	
CVPM 2	142, 144
CVPM 3	163
CVPM 4	164, 165, 167
CVPM 5	166, 170, 171
CVPM 6	162
CVPM 8	180,181, 184

CVPM 9	185
CVPM 10	216
CVPM 11	205, 206, 207
CVPM 12	208, 209
CVPM 13	210-215
CVPM 14	244, 245
CVPM 15	235, 237, 238, 241, 246
CVPM 17	236, 239, 240
CVPM 18	242, 243
CVPM 19	255, 259 260
CVPM 20	256, 257
CVPM 21	258, 261
AGRICULTURE	
Ag: Antelope Valley	303-307
Ag: Ventura	81
Ag: E&W MWD	96, 98, 100, 104
Ag: San Diego	110, 114, 120
Ag: Coachella	348
Ag : Imperial Valley	353
Ag: Palo Verde	345

The CVPM areas include both an urban and an agricultural demand area defined by the same DAUs. Other agricultural demand areas are listed at the end of the table, separate from their urban component.

In the original tables in Appendix B1 (Jenkins et al. 2001), there are references to “CR1” and “SL4” in the list of DAUs, which may be hard to track down. These letter-number codes refer to DWR’s old planning sub-areas. DWR has since changed the nomenclature, referring to them as planning areas with a new number-number code that does not necessarily correspond, making the old nomenclature difficult to correlate to the DAUs and locate on a map. A map of the former planning sub-areas and associated DAUs is available in Appendix I of the original CALVIN report (Jenkins et al. 2001). In this thesis, all labeling is by DAU numbers to avoid confusion.

Appendix 2
Major Changes to the Network

Table A2.1: Added Nodes

Name	Type	Notes
N1	Junction	SBMWD foothill pipeline intertie
N2	Junction	SBMWD foothill pipeline intertie
N3	Junction	Lake Perris Bypass
N4	Junction	Eastside Reservoir connection
N5	Junction	Eastside Reservoir connection
N6	Junction	Eastside Reservoir connection
N7	Junction	SWP diversion to Antelope
Wadsworth Power Plant	Power Plant	Bidirectional PMP / PWP
Ventura Ag	Agricultural Demand	
E&W MWD Ag	Agricultural Demand	
San Diego Ag	Agricultural Demand	
Antelope Valley Ag	Agricultural Demand	
GW-VC	Groundwater Storage	
GW-EW	Groundwater Storage	
GW-SBV	Groundwater Storage	
GW-SD	Groundwater Storage	

Table A2.2: Deleted Nodes

Name	Description	Notes
GW-CDZ	Cadiz Conjunctive use	Never constructed
GW-UCK	Upper Chuckwalla Conjunctive use	Never constructed
C319	Recharge to Cadiz	Never constructed
C320	Recharge to Upper Chuckwalla	Never constructed
C312	Diversion to El Centro	Moved El Centro
C140	Junction near Diamond Valley Lake	Rerouted the area
C14	Junction near Owens Lake	Unnecessary
C17	Junction near Owens Lake	Unnecessary
C19	Junction near Owens Lake	Unnecessary
C161	Junction near Central MWD	Unnecessary

Table A2.3: Added Pipelines

Name	Description	Notes
D881_N3	Lake Perris Bypass Pipeline	Routes water from SWP to Diamond Valley Lake around Lake Perris
N1_N2	SBVMWD Foothill Intertie	Inland Feeder to SBV intertie (bi-directional)
GW-OW_OW Ag	Agricultural Deliveries	Changed connectivity, Agriculture supplied by groundwater not surface.

Table A2.4: Renamed Nodes

Initial	Revised
Eastside Reservoir (SR-ER)	Diamond Valley Lake (SR-DV)
Eastside Pumping Plant	Wadsworth Pumping Plant

Table A2.5: Reservoir Lower Bounds (taf)

Reservoir	Initial	Revised
Lake Perris	31	4.1
Castaic Lake	294	18.6
Diamond Valley Lake	400	230.4
Silverwood Lake	44	20
Pyramid Lake	95	4.8
Grant Lake	4.75	11.5

Table A2.6: Groundwater Basin Capacities (taf)

Basin	Initial	Revised
Owens Valley	100000	30000
Antelope Valley	100000	68000
Imperial Valley	100000	1000

Table A2.7: Major Capacity Changes (Upper Bounds) (taf)

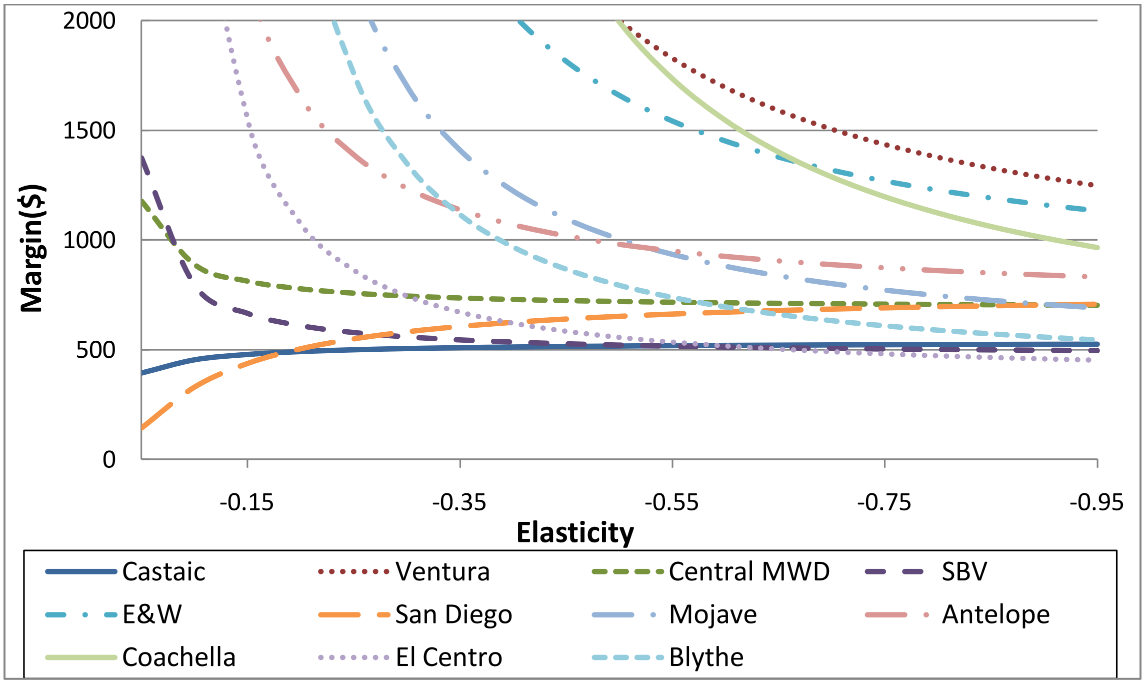
Link Name	Description	Initial	Revised	Notes
C136_C145	CRA diversion to Coachella	∞	12.1	Whitewater River capacity
D876_C161	Rialto Pipeline	65.2	37.1	Removed Box Springs Feeder, never built
GW-CH_C147	GW-CH Ag Pumping	5	65.6	
GW-CH_T31	GW-CH Urban Pumping	15	287.4	
GW-MWD_T5	GW-MWD Pumping	146	98.9	
T56_T55	Existing recycling for Ventura	4.1	0.02	
C153_C154	SD Pipeline 1,2,4 & 6 (treated)	20.9	67.6	SD Pipelines regrouped from 1,2,3,4 / 5,6 to 1,2,4,6 / 3,5 with adjustments in capacity
C153_C156	SD Pipelines No. 5 & 3 (untreated)	37.8	40.1	
Alamo Power Plant_D868	SWP East Branch Plant	190	105	
C131_N1	East Branch SWP Diversion to SBV	14.4	22.5	

Appendix 3

Penalty Graphs for Southern California Urban Demands

Figure A3.1 is the graph that initially alerted us to the problem with the penalties. On the Y-axis is the marginal cost of water at a 95% delivery level. On the X-axis is price elasticity of demand (the percent change in demand for a 1% change in price). The legend applies for all figures in this appendix.

Figure A3.1: Initial Margin vs. Elasticity for Urban Demands



As elasticity increases, marginal cost should decrease. With the original penalties, for the San Diego and Castaic demand areas, it does not. This runs contrary to both the laws of economics and to common sense. Figure A3.2 shows the corrected penalties.

Figure A3.2: Revised Margin vs. Elasticity for Urban Demands

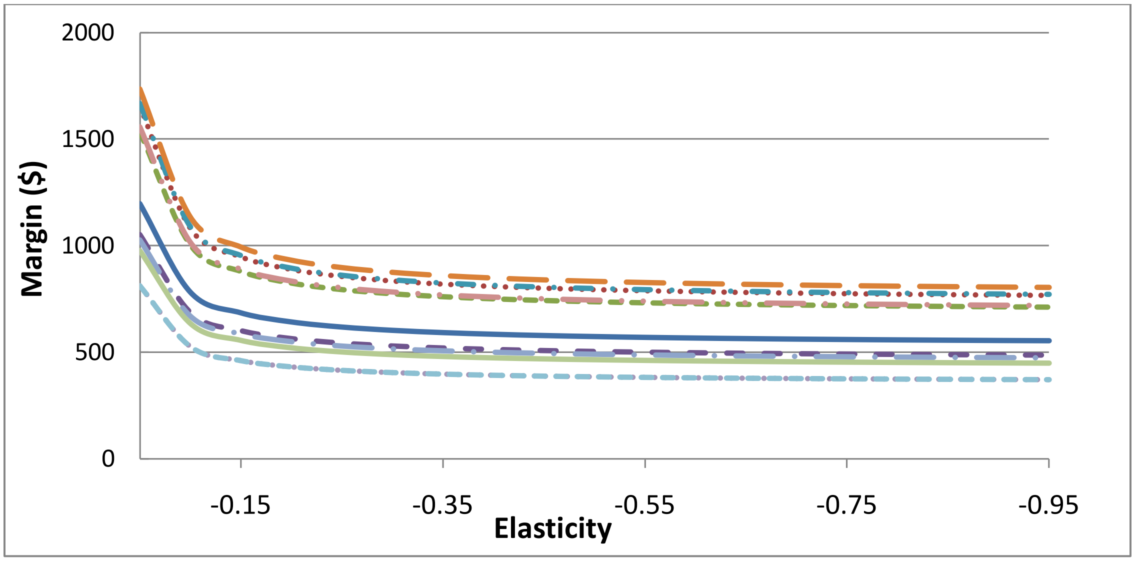


Figure A3.3 shows the original marginal price of water across a range of delivery levels. While nothing in this graph explicitly violates the laws of economics, some of the lines, particularly Blythe, are unusually steep and the spread is wider than would be expected for such a geographically similar region. Figure A3.4 shows the corrected graph.

Figure A3.3: Initial Margin vs. Delivery for Urban Demands

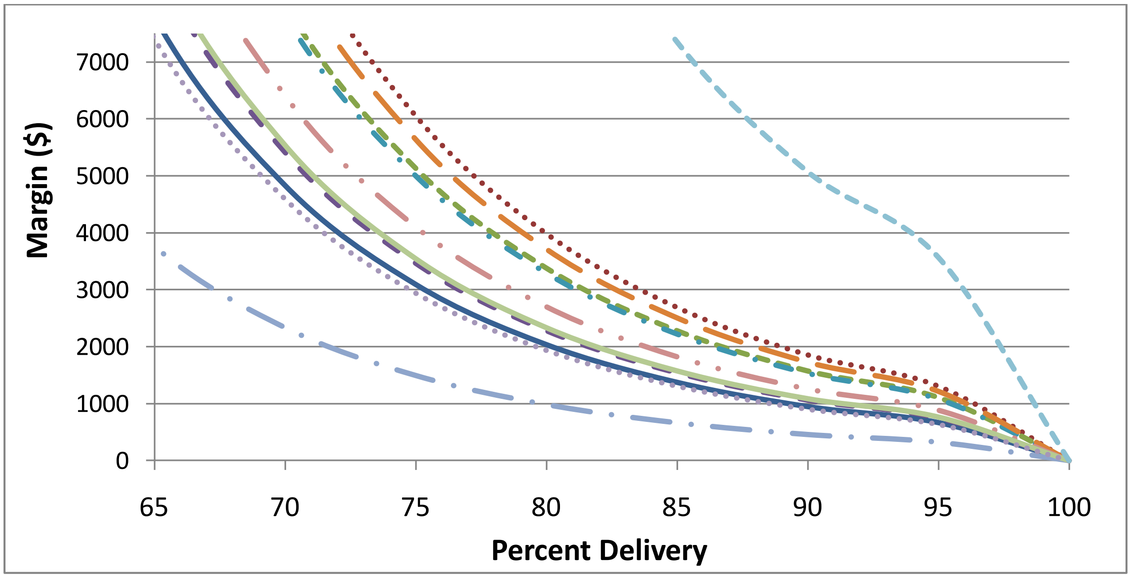
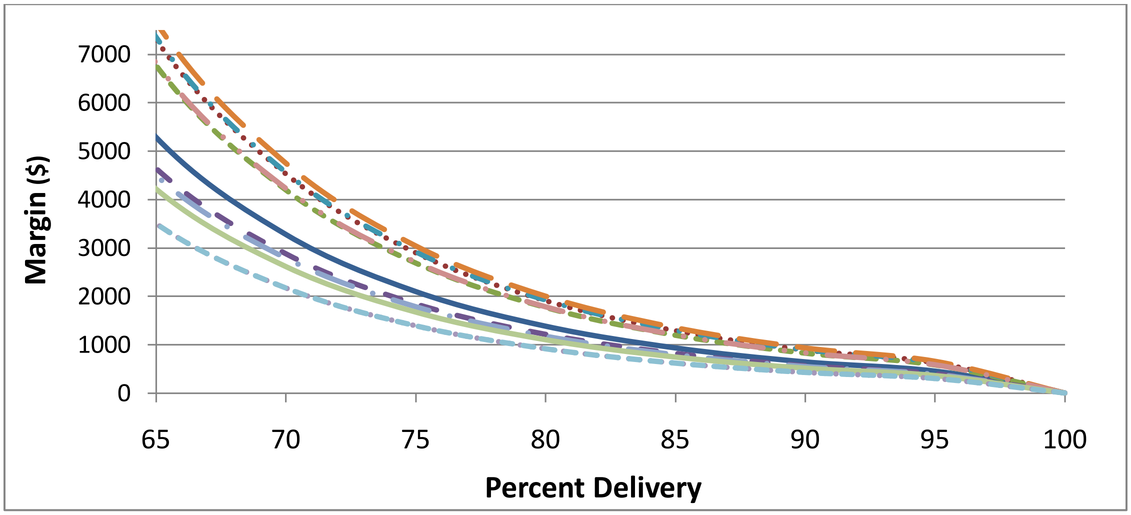


Figure A3.4: Revised Margin vs. Delivery for Urban Demands



After the update both the elasticities and the marginal prices are in a much tighter band, and demand areas are ordered logically from top to bottom by water rate.

Appendix 4

Naming Conventions

Agriculture

Agricultural demand areas are divided into surface and groundwater demands based of the source of supply. The areas are named Ag-S DemandName and Ag-G DemandName, respectively. For example Ventura County agricultural areas are named Ag-S Ventura and Ag-G Ventura. This naming convention was applied to all agricultural demand areas outside of the Central Valley. Central Valley agricultural areas retained their original naming convention: CVPM 3S and CVPM 3G for example. Palo Verde and Imperial Irrigation District both irrigate exclusively with surface water, so there are no Ag-G demands in those locations.

All agricultural demand areas are connected to the network via a hidden node. This hidden node separates the shadow value of the diversion from the shadow value of the delivery. The hidden nodes are named HUD plus a two letter demand area abbreviation such as HUDAV in Antelope Valley.

Indoor-Outdoor Split

For areas without a separate industrial component, the split demands (combined residential, commercial and industrial) were named Int: DemandName and Ext: DemandName. Previously, these demand areas had no prefix. For areas with a separate industrial component, split demands (residential and commercial) were named IRes: DemandName and ERes: DemandName, for interior (indoor) and exterior (outdoor) residential, commercial demands, in addition to the preexisting Ind: DemandName. Previously, these areas had the Res: prefix.

During this renaming process, some compatibility issues were also addressed. Recent versions of DSS Admin, an Excel tool used in post-processing results, and some of the macros had been producing errors associated with failure to store long location names. Consequently, demand names were simplified where doing so would not cause confusion. Table A4.1 lists former and current demand area names. These name simplifications were applied to industrial and agricultural demand areas as well.

Table A4.1: Changes in Demand Area Names

Original	**Simplified**
Redding Area	Redding
Yuba City et al	Yuba
Greater Sacramento	Sacramento
Napa-Solano Co Urban	Napa-Solano
Contra Costa WD	Contra Costa
San Francisco PUC	San Francisco
CVPM# Urban	CVPM#
Mojave Urban	Mojave
Antelope Valley Urban	Antelope
Castaic Lake WA	Castaic
Ventura Co Urban	Ventura
Coachella Urban	Coachella
El Centro et al	El Centro

Junctions

Several new junction nodes were added to while reconfiguring the network. Appendix 1 lists these nodes and their locations. New junction nodes were named N1 through N7 to distinguish them from existing nodes.

Appendix 5
Urban Water Rates

The CALVIN urban water rates were taken from the Black & Veatch 1995 and 2006 California Water Rate Surveys. These surveys give the water rate in \$/1500 ft^3. Table A4.1 displays municipalities' 1995 and 2006 water rates, converted into \$/af, and the population weighted averages, converted into 2008 dollars for ease of comparison. Municipalities are grouped by CALVIN demand area. Cities not included in one of the surveys are left blank for that year.

Table A5.1: Urban Water Rates

City/Agency	**1995 \$/af**	**1995 Population**	**2006 \$/af**	**2006 Population**	**2008 \$/af (1995)**	**2008 \$/af (2006)**
REDDING						
Redding, City	334	76800	564			
Population Weighted Average					**494**	**615**
YUBA						
Gridley	431	4910	842	5702		
Paradise	935	26950	1055	26500		
Marysville	196	12800	915	12628		
Oroville	436	9620	1234	13369		
City of Yuba	-	-	895	103211		
Population Weighted Average					**478**	**468**
SACRAMENTO						
Auburn	568	116000	1118	12849		
Roseville	454	56000	864	102191		
Rio Linda	290	14000	534	13200		
Florin CWD	397	9750	-	-		
Northridge	-	-	912	85000		
Population Weighted Average					**751**	**561**
NAPA-SOLANO						
American Canyon	1188	8875	1089	14306		
Napa	781	66300	1222	76346		
St. Helena	691	5600	1137	6006		
Benicia	706	27150	1156	27323		
Fairfield	871	86500	1241	105026		
Vallejo	808	116100	1203	121222		
Vacaville	524	82500		96735		
Population Weighted Average					**1121**	**1165**
CVPM2						
Butte Co.	415	113250	-	-		

Tehema Co.	403	76860	-	-		
Chico	-	-	789	73558		
Paradise	-	-	978	26500		
Population Weighted Average					**596**	**915**
CVPM3						
Glenn Co.	403	-	-	-		
Hamilton City	-	-	789	1900		
Willows	-	-	877	6438		
Population Weighted Average					**596**	**934**
CVPM4						
Colusa city	239	5275	514	5582		
Population Weighted Average					**354**	**560**
CVPM5						
Sutter Yuba City	290	33600	895	58368		
Population Weighted Average					**429**	**975**
CVPM6						
Vacaville	524	82500	560	96735		
Davis	398	51400	587	64401		
Woodland	413	42450	690	53382		
Population Weighted Average					**611**	**752**
CVPM8						
Galt	269	13900	557	22955		
Population Weighted Average					**398**	**607**
CVPM9 and 10						
Los Banos	195	18750	427	32380		
Gustine	339	4140	-	-		
Unincorporated	252	3000	575	73610		
Population Weighted Average					**373**	**627**
CVPM11						
Tracy	576	42100	-	78307		
Modesto	630	180300	-	207634		
Turlock	580	48100	966	67009		
Population Weighted Average					**858**	**1053**
CVPM12						
Manteca	218	44250	945	61.97		
Population Weighted Average					**322**	**1030**
CVPM13						
Merced	-	60800	640	73610		
Madera	-	33900	-	-		
Chowchilla	-	6700	552	16065		
Atwater	431	23650	-	-		
Population Weighted Average					**638**	**681**
CVPM14 and 15						

Coalinga	711	9575	-	-		
Readley	298	18900	373	22599		
Sanger	337	18550	-	-		
Fowler	336	3830	-	-		
Hanford	256	35850	457	48070		
Lenmore	331	15300	434	22508		
Clovis	-	-	426	86015		
Population Weighted Average					**490**	**467**
CVPM17						
Orange Cove	441	6125	-	-		
Kerman	446	6525	-	-		
Kingsburg	588	8325	-	-		
Firebaugh	519	5375	704	11237		
Population Weighted Average					**768**	**768**
CVPM 18						
Visalia	336	89400	469	107550		
Tulare	386	39300	280	94477		
Portersville	374	34050	469	44496		
Population Weighted Average					**554**	**511**
CVPM 19, 20 and 21						
Arvin	430	10550	-	-		
Buttonwillow	377	20000	-	-		
Delano	430	29950	558	53972		
Taft	331	6650	-	-		
Wasco	406	17800	558	24228		
Population Weighted Average					**601**	**558**
SCV						
San Jose W.Com.	741	1 M+	917	944857		
Population Weighted Average					**1097**	**1000**
EBMUD						
East Bay MUD	705	1.2 M	1048			
Population Weighted Average					**1043**	**1143**
CCWD						
Contra Costa WD	1168		1463			
Population Weighted Average					**1729**	**1594**
SFPUC						
San Francisco	602	751700	1012			
Population Weighted Average					**892**	**1103**
STOCKTON						
Stockton	420	228700	792	279513		
Population Weighted Average					**622**	**863**
BAKERSFIELD						

Bakersfield	471	201800	1346	295893		
Population Weighted Average					**697**	**1467**
FRESNO						
Clovis	310	61500	426	86015		
Fresno	-	-	-	-		
Population Weighted Average					**458**	**464**
SB-SLO						
Morro Bay	1804	10000	-	-		
San Luis Obispo	1321	43700	1545	44519		
Lompoc	1107	40850	1266	42320		
Santa Barbara	1504	89200	1998	90518		
Sant Maria	787	67800	1655	88793		
Solvang	874	5050	1061	5429		
Population Weighted Average					**1805**	**1830**
VENTURA						
Camarillo	758	56500	822	62739		
Ojai	829	7925	1359	8153		
Oxnard	618	151900	1011	188849		
Port Hueneme	-	-	1022	22445		
Moorpark	703	27150	-	-		
San Beuna Ventura	765	97000	943	106096		
Santa Paula	1009	26850	1146	29281		
Simi Valley	833	103700	1139	121427		
Thousand Oaks	873	110300	1200	127112		
Population Weighted Average					**1136**	**730**
CASTAIC						
Oak View	668	4700	850	4700		
Santa Clarita	529	128800	930	167945		
Population Weighted Average					**790**	**1011**
CENTRAL MWD						
So. Cal. Water Co	793	1655000	1160	590761		
Azusa VWC	463	238000	694	48520		
Beverly Hills	891	32600	1210	35969		
Burbank	693	98700	792	106739		
El Monte	637	111000	1160	125832		
Glendale	360	190200	1047	207007		
Inglewood	1180	113600	1374	118164		
La Crescenta	907	31000	1476	32000		
Las Virgenes	1060	60000	804	65000		
City of LA	777	3620500	805	3957875		
So. Cal Water Co	637	225350	1369	1831142		
Pasadena	357	134800	672	146166		
Pomona	475	138600	1160	160815		

Torrance	764	136700	949	147405		
Whittier	646	80600	778	87250		
Anaheim	390	290700	714	345317		
Costa Mesa	713	102400	1016	113440		
Fullerton	502	121500	949	135672		
Garden Grove	386	151800	678	172042		
Huntington Bch	472	189200	1017	200763		
Irvine	384	121200	595	180803		
Orange	398	118000	846	137751		
Santa Ana	407	310400	970	351697		
So Cal Water Co.	511	232800	1160	245065		
Chino	859	62800	776	76070		
Fontana	691	103200	1108	160015		
Ontario	463	143900	848	170373		
Rialto	428	80000	682	99242		
Rancho Cucamonga	669	115000	839	161830		
Montclair	820	30150	1160	35530		
Upland	820	67500	1093	73697		
Population Weighted Average					**1012**	**1059**
SBV						
Rialto	498	80000	682	99242		
San Bernardino	401	184400	489	199803		
Colton	540	45100	563	51627		
Loma Linda	519	21300	732	21952		
East Valley/Highland	552	39500	658	50860		
Redlands	556	66300	593	70324		
Yucaipa	383	37050	657	49388		
Population Weighted Average					**694**	**639**
E&W MWD						
Hemet	838	52800	961	66455		
Riverside	284	244200	423	285537		
Jurupa	539	45000	552	45000		
Elsinore	551	24150	932	38045		
Temescal	-	-	681	81397		
Moreno	811	134700	961	165328		
San Jacinto	838	24000	961	28438		
Corona	759	94500	1098	144070		
Murrieta	930	31400	1256	85102		
Perris	794	30200	961	44594		
Temecula	499	36450	-	-		
Unicorp	647	25000	-	-		
Population Weighted Average					**1099**	**880**
ANTELOPE						
Ridgecrest	692	29900	568	29000		

Population Weighted Average					**1024**	**619**
MOJAVE						
Hesperia	555	59200	777	76114		
Victorville	331	57200	662	43236.5		
Victorville	555	13000	1179	43236.5		
Population Weighted Average					**675**	**931**
COACHELLA						
Palm Springs	412	42450	481	45731		
Banning	607	23850	-	-		
Coachella	465	19950	476	30764		
Coachella VWD	393	107050	446	157254		
Population Weighted Average					**638**	**498**
SAN DIEGO						
City of San Diego	674	1184800	1329	1305736		
Helix Water Co	827	174000	1134	365217		
Sweetwater Auth.	947	204900	1403	281316		
Padre Dam MWD	1302	61000	1429	61000		
Santa Fe Irr. Dist.	836	32950	1053	20130		
Oceanside	866	145400	1157	175085		
Carlsbad	987	67900	1300	95146		
Cal Amer. W Co	752	54300	1154	272226		
Encinitas	903	58000	1215	62774		
Escondido	571	116900	1434	70675		
Escondido	859	27000	1177	70675		
Fallbrook PUD	1044	29000	1270	30000		
San Marcos	829	46000	1114	73054		
Vista	976	79500	1330	94109		
Population Weighted Average					**1145**	**1391**
EL CENTRO						
Brawley	-	21750	-	-		
Calexico	-	23700	1985	36274		
El Centro	358	36700	600	41030		
Imperial	-	-	995	9567		
Population Weighted Average					**530**	**1332**

Out of the 125 municipalities in the CALVIN coverage area that were included in both the 1995 and the 2006 *Water Rate Survey* (Black & Veatch 1995 and 2006), 40% had an increase in their effective water rate, while 60% had a decrease. Municipalities in southern California were more likely to increase their rates then municipalities in northern California. Forty-three percent of southern California municipalities increased their rates as opposed to only thirty-five percent of northern California municipalities. The population weighted average water rate for the modeled portion of the state as a whole increased from $989/af to $1064/af, driven by increases in the large southern California urban areas.

Appendix 6
Potential Issues with CALVIN Groundwater

The first version of the revised model to be postprocessed contained a significant bug. When the penalties were updated for the Split model, the time series of deliveries to the new outdoor portions of the non-economically modeled urban demands was forgotten. This resulted in those links being blank and able to serve as sinks for the groundwater basins. Water could be sent to them at no cost and no benefit and, since the return flow links for the outdoor portions of urban demands have amplitude 0.1, 90% of the water sent over those links would vanish, with the remaining 10% being returned to groundwater.

The final version discussed in Chapter 5 was repaired, but the results from the bug give interesting insights into groundwater operations of the system. The bug had increased pumping through the Delta, 6.6 maf/year from 5.7 maf/year in the initial model. Table A5.1 shows how much each of the affected nodes pumped and used in the initial model, and how much they pumped and used and how much they sent to sink in the model with the bug. Note that the columns in Table A5.1 don't need to have the same total, as supplies were supplemented by surface water in both cases.

Table A6.1: Groundwater Pumping and Disposal (taf/yr)

	Initial	**With Bug**	
	Pumped	Pumped	To Sink
GW-2	460	278	380
GW-3	453	476	0
GW-4	285	234	103
GW-5	410	243	351
GW-6	412	292	276
GW-9	71	25	97
GW-10	329	329	0
GW-15	1,286	492	0
GW-19	291	0	694
GW-21	589	538	161
Total	**4,587**	**2,908**	**2,063**

With the error, there was 1.2 maf/year less groundwater pumping in the Tulare Basin. The primary shifts were for agricultural users in CVPM 15 and CVPM 19. CVPM 15 is located just south of Fresno and includes the towns of Reedley and Sanger. CVPM 19 is located northeast of Bakersfield and includes the towns of Taft and Buttonwillow. Both are major agricultural producers.

CVPM 15 pumped an average of 794 taf/year less groundwater in the model with the bug and CVPM 19 pumped 291 taf/year less. To replace this water, CVPM 15 drew an additional 600 taf annually from just above the Mendota Pool and 200 taf annually from the Kings River. CVPM1 9 drew an additional 320 taf annually from the California Aqueduct. These demands continued to draw from groundwater in drought years, when surface water was not available. Both areas have relatively high costs to pump groundwater ($80 to $100 per acre-foot) due to draw-down in the Tulare Basin.

Examining the supply portfolios, in northern California, including North-of-Delta and the San Joaquin Valley, 8% of urban supply shifted from groundwater to surface water. In the Tulare Basin, 11% agricultural supply and 4% of urban supply shifted from groundwater. Shifts in southern California supply portfolios were caused by other factors, discussed in Chapter 5.

The fact that areas in the San Joaquin and Tulare Basins have groundwater that they wish to dispose of confirms that there is too much groundwater in that portion of the model, which has been suspected for some time. There should be no excess groundwater in that part of the state (USGS 2009). This is being addressed in the upcoming groundwater update.