California Water Supply and Demand: Technical Report

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Copies of this report and two accompanying documents, *The Last Drop: Climate Change and the Southwest Water Crisis* and *The Water-Energy Nexus in the Western States: Projections to 2100*, may be downloaded at http://www.sei-us.org/publications/id/371.

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1. Overview

The *California Water Supply and Demand Model* (CWSD) examines the ways in which California's water supply and demand are likely to be affected by climate change; its purpose is to serve as a base for quantifying these impacts in economic terms. California's water future is modeled under conditions of no adaptation to climate change, and under several projected water use adaptation scenarios taken from the literature; climate change adaptation scenarios include water used for energy, the urban or residential sector, and agriculture.

The main CWSD compares key categories of water inputs and outputs on a month-by-month basis to capture seasonality in water availability. A supplementary model allows for the main model's beginning surface reservoir storage to result from water supply and demand interactions over a stylized previous 100 years. Three areas of water use are both especially critical and vulnerable to climatic change: the energy, agriculture, and urban sectors. In the energy module, water demand is a based on different scenarios of coal, nuclear and renewable power use, conservation technology, state population trends, and projected temperatures. In the agriculture module, crop and animal water use by county is a function of projected summer temperatures by county. In the urban module, residential, industrial/commercial, and public water use are based on projected levels of socio-economic growth.

At the foundation of the CWSD is the key simplifying assumption that water can be transported costlessly within California: If one district has a deficit in a given month, water can be supplied to it *without significant technical difficulty or economic cost* from any district with excess water supplies. Clearly, while California's water transference infrastructure is very well developed, this assertion is too strong. Making this assumption, however, allows the model user to abstract from questions of water conveyance within California to focus on changes in water supply and demand with climate change.

The energy, urban, and agriculture modules contain a second important simplifying assumption: The composition and scale of energy production and urban water use change only with increasing populations, and not with climate scenario, income, or conservation practices; the composition and scale of crops and livestock by county do not change with time or climate scenario. This "no adaptation" assumption provides a starting point for our analysis of energy adaptation strategies, which we base on a new model created for this study by Synapse Energy Economics,[1] and urban and agricultural adaptation strategies, which we base on the Pacific Institute adaptation projections for the California Department of Water Resources.[2]

The water and energy systems in California are inextricably linked: water is used in electricity production; electricity is used in water supply. Fossil fuels and nuclear power plants provide roughly 75 percent of the electricity used in this region; both of which rely on a constant flow of cooling water to prevent overheating. Hydroelectric power, which is wholly dependent on water flows, is also important, serving an additional 25 percent of the market. At the same time, energy is a key component of the water supply system. Nearly 20 percent of California's electricity is

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[1] For more information on the energy adaptation analysis see Fisher and Ackerman (2011).
[2] Gleick et al. (2005) and Groves et al. (2005).

used in water supply, wastewater treatment, and irrigation, or other water-related uses (Stokes and Horvath 2009). Southern California is particularly dependent on energy for its water supply – water from northern California must be pumped hundreds of miles, over mountains 2,000 feet high, in order to meet demand. Energy and water modeling for California, however, shows a surprising result: Electricity generation requires only 1 percent of California's total water supply and, even under the higher A2 climate assumptions, increases to this sector's water requirements would amount to a small fraction of 1 percent (Fisher and Ackerman 2011).

In California, water use is far higher in the summer, when there is very little precipitation, than in any other season. This means that storage capacity, and flows in and out of reservoirs (both built and snowpack), are central to a good understanding of water availability by season, and by climate scenario and year. At present there is barely enough water overall, and barely enough storage capacity to hold water from wet months to dry ones. The winter snowpack acts as an enormous, and vital, reservoir, storing winter precipitation until the summer high water usage season. Climate change may not reduce annual total precipitation in the U.S. West (and we model no change to average precipitation), but it is projected to lead to adverse changes in seasonal distribution that may render reservoir capacity inadequate (E. P. Maurer 2007; Purkey et al. 2007). If this occurs, an important share of winter rainfall would flow out to the ocean without being used (Barnett et al. 2005).

CWSD follows California's water inflows and outflows by month for a single year, based on the following inputs:

- Water-year type (Normal, Dry, Wet)
- Climate Scenario and Year (Baseline, B1-2030, B1-2050, B1-2100, A2-2030, A2-2050, A2-2100)
- Previous Year's Surface Storage Scenario (an average value for normal, dry or wet years based on data for the baseline climate scenario; the year-ending storage in the final iteration of a 100-iteration version of this model; a minimum total California reservoir storage of 7 MAF; or zero MAF)
- Adaptation Scenario: A separate choice of adaptation scenario for the Urban sector (No adaptation, Slow adaptation, Fast adaptation), the Agricultural sector (No adaptation, Slow adaptation, Fast adaptation), and the Energy sector (No adaptation, Energy efficiency (EE), EE and water conservation, EE and CO_2 reduction, All adaptation scenarios)

All values in the model are reported in million acre feet (MAF).

Figure 1: Water Flow Schematic
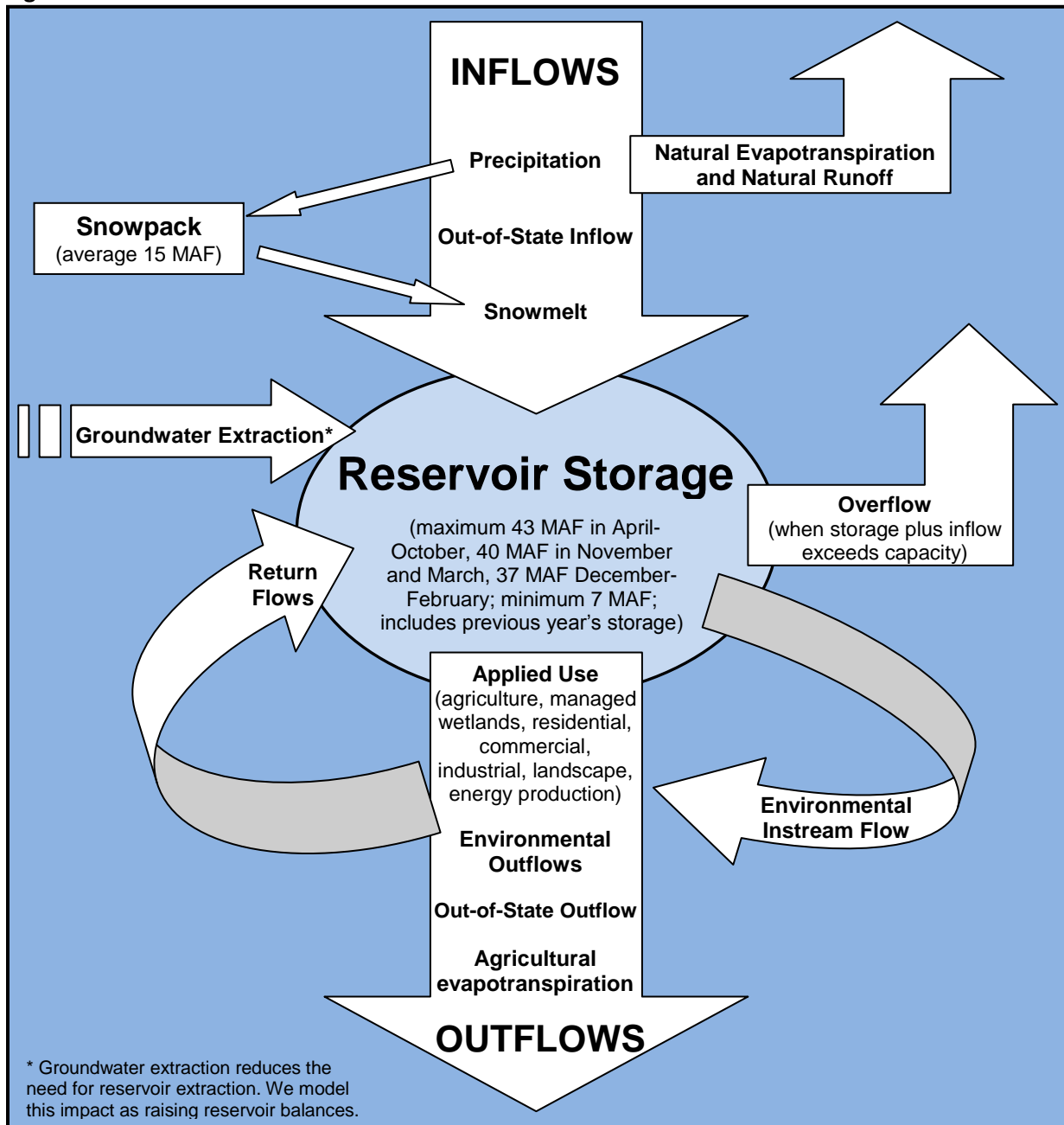
The quantity of water in reservoirs at the beginning of the year is a key variable, so the model offers a choice of approaches. The 100-year simulation is a useful way to address uncertainty in initial water storage: A year's beginning reservoir storage is a function not just of the previous year's water-year type and climate scenario, but of temperature and precipitation stretching back decades. (A period of drought provides an excellent example: In each succeeding drought year demand exceeds supply, and reservoir storage falls still lower.) The order of water years in the 100-iteration simulation is random; additional inputs are:

- 100-Year Distribution of Water Years (Evenly distributed, 10% more dry, 10% more wet years)
- 100-Year Distribution of Climate Scenarios (100 years of the same scenario selected for the main model; Gradual trend from baseline to the scenario selected for the main model)

The model includes both a ceiling (base capacity less storage reserved in winter months for flood control) on reservoir storage and a floor (the "deadpool" or inaccessible portion). If inflows net of outflows raise water available for reservoir storage beyond its capacity ceiling, water overflows to the ocean before it can be used. If inflows net of outflows are negative, and reservoir storage falls below its capacity floor, the model assumes that groundwater extraction will fill this gap up to a set annual limit. That is, in this model if reservoir storage falls below 7 MAF, first groundwater is extracted up to the annual limit; if the 7 MAF is still not reached, a demand shortfall is recorded for the year.

Three-quarters of California's applied use of water goes to agriculture, a sector that is expected to face grave impacts from climate change. Without adaptation – i.e. if the composition of crops and livestock, and the number of acres planted or animals raised are held constant over time – agricultural water demand is strongly correlated with summer temperature. The model estimates water usage by applying this relationship to county data for irrigated crop acreage for 27 crop categories, number of animals for five livestock categories, historical agricultural water use, and summer temperature.

2. CWSD Methodology

The main parameter controls for the CWSD model are water-year type, climate scenario-year, a scenario defining the previous year's year-ending surface water storage, an interval defining the lag between precipitation occurrence and availability for water supply, and separate scenarios defining the levels of urban, agriculture, and energy sector water use adaptation. The previous year's ending storage can be set equal to: an average value for normal, dry or wet years based on data for the baseline climate scenario; the year-ending storage in the final iteration of a 100-iteration version of this model (described below); a minimum total California reservoir storage of 7 MAF[3]; or zero MAF. The water supply lag can be set to values from 0 to 4.3 weeks; this captures uncertainty about the length of time it takes for precipitation (and in particular, snow) to enter the water supply system. Based on these parameter choices, CWSD calculates the following summary statistics: previous year's surface storage; year-ending surface storage (which allows negative values in order to calculate the storage deficit); allowable minimum reservoir storage; and total groundwater extraction (the amount of water necessary to bring deficit reserves up to the allowable minimum).

The 100-iteration simulation introduces uncertainty into the initial water storage to reflect the impact on water storage of past years' weather. The first iteration takes its previous year's ending surface water storage to be that of an average water year (set to normal, wet or dry by the model

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[3] Estimated total deadpool (inaccessible water storage) for California's surface reservoirs. Personal communication, August 2010, Maury Roos, Division of Flood Management, California Department of Water Resources.

user) from California Department of Water Resources (CADWR) Water Portfolio data (as described below) and each succeeding year takes the previous year's ending surface water storage as its beginning point. Reservoir storage is restricted to be equal to or greater than the minimum total California reservoir storage of 7 MAF in every month.

The distribution of water-years and climate scenario-years are the main inputs to the 100-iteration simulation. Water years can be evenly distributed (34 normal years, 33 dry, and 33 wet), have 10 percent more dry years than in an even distribution (34 normal years, 37 dry, and 29 wet), or 10 percent more wet years than in an even distribution (34 normal years, 29 dry, and 37 wet). The order of water years across iterations is chosen by random draw. When the main model is set to take its previous year's ending storage from the 100-iteration simulation, a change in the random draw will cause small variations in the main model's results.[4]

Climate scenario-years can either be fixed such that all one hundred iterations have the same climate scenario-year as that chosen for the main model, or set to an assumed gradual trend towards the climate scenario-year chosen for the main model. The assumed gradual trend for each climate scenario-year presented in Table 1:

Table 1: Gradual Trend for Each Climate Scenario-Year in 100 Iteration Model

Iterations	Baseline	B1-2030	B1-2050	B1-2100	A2-2030	A2-2050	A2-2100
1-9	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline
10-29	Baseline	Baseline	Baseline	B1-2030	Baseline	Baseline	A2-2030
30-44	Baseline	Baseline	Baseline	B1-2050	Baseline	Baseline	A2-2050
45-64	Baseline	Baseline	B1-2030	B1-2050	Baseline	A2-2030	A2-2050
65-100	Baseline	B1-2030	B1-2050	B1-2100	A2-2030	A2-2050	A2-2100

CWSD calculates the following cumulative results of the 100-iteration simulation for reference: the iteration 100-year-ending reservoir storage; cumulative groundwater extraction necessary to meet demand for the 100 iterations while keeping reservoir storage at or above 7 MAF; cumulative groundwater extraction; cumulative demand shortfall (supply less demand); number of years in which a demand shortfall occurs; and the number of months in which required total applied use for environmental purposes is less than stored surface waters, taking into consideration previous year's ending storage and a baseline extraction of groundwater by water-year type (which would reduce the necessity for surface reservoir withdrawals).

Basic model functions

The model compares a year's water supply to its water demand. Annual values for each supply or demand data point are multiplied by a vector of month-specific shares to estimate monthly flows. Annual values and monthly shares are specific to water-year and climate scenario-year.

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[4] This is to say that California's water supply and demand in a given future year is partially dependent on the order of water-year types over the previous century. An interesting further development of this model would be to run it in a "Monte Carlo" mode to observe the distribution of model results across random draws of water-year orderings in the 100-iteration simulation.

Potential reservoir storage, assuming zero storage carried over from the previous year, is the cumulative sum of flows to reservoirs net of use.

Reservoir storage capacity is capped at the current California total surface water storage capacity, 43 MAF, in April through October. In CWSD, reserved flood control space reduces reservoir capacity by 3 MAF in November and March, and 6 MAF in December, January, and February.[5]

CWSD also estimates the previous year's ending storage based on model parameter selections described above. Reservoir storage is calculated twice – first, accounting for both monthly capacity and the previous year's ending storage; and second, accounting for monthly capacity, the previous year's ending storage, and the monthly groundwater extraction necessary to prevent total reservoir storage from falling below their 7 MAF minimum; groundwater extraction is assumed to reduce the need for surface water withdrawals. Groundwater extraction is estimated monthly and annually, and is limited at 9.7 MAF per year, the average CADWR value for a dry year.

CWSD also estimates the required applied use of environmental water (which includes instream flow). Total environmental required applied use is not directly relevant to supply and demand calculations, but is relevant to California's ability to meet its environmental water requirements. As a simple gauge of whether environmental water requirements *can* be met in any given month (but not whether they *would* be met – an administrative choice), CWSD compares total environmental required applied use to reservoir storage adjusted for the previous year's ending storage and groundwater extractions. "True" indicates that storage exceeds environmental required applied use; "False" indicates that environmental required applied use exceeds storage.

Agriculture water use module

An agriculture module estimates California's irrigation and livestock water use by county, and climate scenario-year. Final results for each scenario-year serve as inputs to the CWSD model.

Crop irrigation

The agriculture module estimates crop irrigation for 27 crop types: almonds, avocados, berries (other), broccoli, carrots, cauliflower, celery, corn (field), cotton, field crops (other), grapes, greenhouse/nursery, hay, lemons, lettuce, oats, oranges, orchards (other), peaches, pistachios, potatoes, rice, strawberries, tomatoes, vegetables (other), walnuts, and wheat.

To determine the amount of water used for crop irrigation, the agriculture module first estimates the annual applied water rate (in cubic meters/acre) for each crop. The water applied annually to

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[5] Personal communication, August 2010, Maury Roos, Division of Flood Management, California Department of Water Resources. For California surface storage capacity and September 30, 2002, and 2003 storage, see "2003 Water Portfolio, Reservoir Storage," May 3, 2006, provided to us in an email from the California Department of Water Resources, July 2010.

each crop type is a function of average summer temperature, where summer is defined as May to September, and average summer temperatures vary by county and climate scenario-year. The relationship between water use and temperature is based on a regression of the county-level historical applied water rate[6] on the county-level historical summer temperature[7] for each crop category. The regression uses data for 1999, 2002, and 2005 as these represent "normal" water years for California; precipitation during these years was similar to the historical average for the period 1961-1990. Water applied annually to crops is calculated by crop category, county, and climate scenario-year as:

$$APR_{tcs} = CoefA_t * Temp_{cs} + Constant_t$$

Where:

APR_{tcs} = Applied water rate (APR) by crop category, county, and climate scenario-year

$CoefA_t$ = Coefficient from regression of historical APR on historical summer temperature by crop category

$Temp_{cs}$ = Summer temperature by county and climate scenario-year

$Constant_t$ = Constant from regression of historical APR on historical summer temperature by crop category

t = Crop category

c = California county

s = Climate scenario-year

To determine the total annual water use for crops, the annual applied water rate is multiplied by the irrigated acreage for each crop category by county. Irrigated acreage by crop category and county is primarily based on U.S. Agricultural Census data for 2007.[8] Due to under-reporting for many crop categories at the county level, California totals by crop category are often greater than the sum of county-level estimates. A few adjustments were made to the Census data to fill in these gaps, specifically:

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[6] Historical applied water rates were provided by Frank Anderson at the CADWR for the years 1998 to 2005 by county and crop category. Note that applied water rates are only provided for 17 crop categories. These categories are: Almond/Pistachio, Subtropical, Other tropical, Corn, Cotton, Other Field, Vine, Alfalfa, Pasture, Grain, Other Deciduous, Potato, Rice, Fresh Tomatoes, Processed Tomatoes, Cucumber, Onion/Garlic. Each of the 27 crop types in the agriculture module is mapped to one of these crop categories.

[7] Historical temperature by county is based on average projections of six GCMs for the B1 scenario for 1998 to 2005. Projections provided by Mary Tyree and Dr. Dan Cayan, director of the California Nevada Applications Program and California Climate Change Center at Scripps Institution of Oceanography. Also see Cayan et al. (2009).

[8] U.S. Department of Agriculture's Agricultural Census for 2007. County-level information for the California retrieved using the Quick Stats tool: http://quickstats.nass.usda.gov/.

- For almonds, the residual between the California total and the sum of counties is divided between Colusa county and Kings county based on California Almond Board data.[9]
- For walnuts, the residual between the California total and the sum of counties is divided between Colusa, Kern, Napa, San Benito, Santa Clara, and Solano counties based on approximate relative production for 2005 from California Walnut Board data.[10]
- For fresh market and processing tomatoes, the residual between the California total and the sum of counties is divided between those counties in which the U.S. Agricultural Census for 2007 provides a positive value for "total tomatoes in the open" acreage and both fresh market and processing tomato-acreage are suppressed, in proportion to each county's share of the state total of missing tomatoes (i.e., the difference between total tomatoes reported and fresh market plus processing reported).

As a result of these adjustments, California state acreage summed from county data rises from 96 to 98 percent of California state total as reported in the Agricultural Census.

Water for livestock

Water used for animals is determined by animal category, county, and climate scenario-year. The agriculture module estimates monthly water intake for calves, milk cows, other cattle, chickens, and turkeys. Water intake per animal is a function of monthly temperature, which varies by county and climate scenario-year. Monthly water intakes are then aggregated to determine annual water intake per animal by animal category, county, and climate scenario-year. The relationship between animal water intake per animal and temperature is based on a regression of observed water intake per animal on observed temperature. Animal water intake per animal is then estimated by animal category, month, county, and climate scenario-year as:

Turkeys and Chickens:
$$AWI_{tmcs} = CoefA_t * Temp_{mcs}^3 + CoefB_t * Temp_{mcs}^2 + CoefC_t * Temp_{mcs} + Constant_t$$

Calves, Milk Cows, and Other Cattle:
$$AWI_{tmcs} = CoefB_t * Temp_{mcs}^2 + CoefC_t * Temp_{mcs} + Constant_t$$

Where:

AWI_{tmcs} = Animal water intake (AWI) by animal category, month, county, and climate scenario-year

$CoefA_t$ = Coefficient on $Temp_{mcs}^3$ from regression of observed AWI on observed temperature by animal category

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[9] California Almond Board 2009 Almond Almanac:
http://www.almondboard.com/AboutTheAlmondBoard/Documents/2009-Almond-Board-Almanac.pdf.
[10] California Walnut Board 2010 Inventory:
http://www.walnuts.org/tasks/sites/walnuts/assets/File/January_10_Inventory_-_REVISED.pdf.

$CoefB_t$ = Coefficient on $Temp_{mcs}^2$ from regression of observed AWI on observed temperature by animal category

$CoefC_t$ = Coefficient on $Temp_{mcs}$ from regression of observed AWI on observed temperature by animal category

$Temp_{mcs}$ = Temperature by month, county, and climate scenario-year

$Constant_t$ = Constant from regression of observed AWI on observed temperature by animal category

t = Animal category; either Turkeys, Chickens, Calves, Milk Cows, or Other Cattle

m = Calendar month

c = California county

s = Climate scenario-year

To determine total annual animal water intake, the annual water intake per animal is multiplied by the inventory of each animal category by county, primarily based on the U.S. Agricultural Census for 2007[11] but, again, adjustments are made due to county-level underreporting. In particular, data on milk cows and other cattle is augmented using data reported by the California Department of Food and Agriculture, Resource Directories for 2008-2009 and 2009-2010.[12] For turkeys and chickens, state rank orderings for inventories are used to distribute the residual across the highest ranking counties for which no county-level data were available.[13]

Southwest states agriculture model

We have in addition constructed a parallel agriculture water use model that uses data for western states in place of California counties. The states modeled are Arizona, Colorado, Idaho, Montana, Nevada, New Mexico, Utah and Wyoming. These results do not impact on CWSD analysis. Temperatures by state and climate scenario-year are based on regional temperature projections for the Pacific Northwest[14] and the Colorado River Basin[15]. Monthly average projected temperature increases in the Pacific Northwest for 2010-2039, 2030-2059, 2070-2099

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[11] U.S. Department of Agriculture Agricultural Census for 2007. County-level information for the California retrieved using the Quick Stats tool: http://quickstats.nass.usda.gov/.

[12] California Department of Food and Agriculture, Resource Directory for 2008-2009: http://www.cdfa.ca.gov/statistics/PDFs/ResourceDirectory_2008-2009.pdf and Resource Directory for 2009-2010: http://www.cdfa.ca.gov/statistics/.

[13] Based on state rank ordering from U.S. Agricultural Census Highlights for California in 2007; http://www.agcensus.usda.gov/Publications/2007/Online_Highlights/County_Profiles/California/index.asp.

[14] See Mote et al. (2008); scenario summaries are available at http://www.atmos.washington.edu/~salathe/AR4_Climate_Models/Summaries.html.

[15] See Christensen and Lettenmaier (2007).

are applied to baseline[16] temperatures in Idaho and Montana. Annual projected temperature increases in the Colorado River Basin for 2010-2039, 2040-2069, and 2070-2099 are applied to baseline temperatures in Arizona, Colorado, New Mexico, Nevada, Utah and Wyoming and are distributed monthly in proportion to an index of California's monthly temperature change relative to the baseline.

Urban water use module

In the baseline scenario, urban water use is based on CADWR 2009 water portfolio state totals for 2000 distributed to counties as described below. Note that in this model, urban water use does not vary by climate scenario.

Baseline total residential water use is the sum of single-family and multi-family interior and exterior use. Counties are assigned a value for total residential water use that is the state total multiplied by each county's share of total state domestic water use (in million gallons per person per day multiplied by the county population).[17] Each county's total residential water use is then sub-divided into single-family and multi-family interior and exterior use according to the share of these uses in its district, where district shares are taken from CADWR 2009 water portfolio data. Baseline total industrial/commercial and public water use by district are distributed among counties based on each county's share of district employees and population, respectively. Public water use includes only the CADWR 2009 water portfolio category "landscape" and not "energy," which is instead addressed in a separate energy module.[18]

In years 2030, 2050, and 2100, single-family water use is the ratio of baseline single-family water use to the number of single-family residences in the baseline multiplied by the number of single-family residences projected for each of the future years. Multi-family water use is the ratio of baseline multi-family water use to the number of multi-family residences in the baseline multiplied by the number of multi-family residences projected for each of the future years. Industrial/commercial water use is the ratio of baseline industrial/commercial water use to the number of employees in the baseline multiplied by the number of employees projected for each of the future years. Public water use is the ratio of baseline public water use to the population in the baseline multiplied by the population projected for each of the future years. Baseline and projected residences, employees and population are based on 2000 U.S. Census data,[19] California Department of Finance population projections,[20] and projections regarding changes in the share of single-family households and size of single and multi-family households from Gleick et al. (2005) and Groves et al. (2005).

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[16] Baseline temperature for all states are based on historical data monthly temperature data for 1971-2000. See: http://www.esrl.noaa.gov/psd/data/usclimate/pcp.state.19712000.climo.

[17] County-level domestic water use is the sum of "domestic self-supply water" and "domestic public supply water" from the 2005 USGS Water Use Survey, Estimated Use of Water in the United States County-Level Data: http://water.usgs.gov/watuse/data/2005/index.html; County-level population data is based on 2000 US Census: http://quickfacts.census.gov/qfd/

[18] See Fisher and Ackerman (2011) for energy model description.

[19] 2000 U.S. Census: http://quickfacts.census.gov/qfd/.

[20] State of California, Department of Finance (2007); Groves et al.(2005). We assume a constant population after 2050.

Water use adaptation

Agriculture adaptation

CWSD models two agricultural adaptation scenarios – slow adaptation[21] and fast adaptation[22] – which are based closely on the work of the Pacific Institute. Future water use estimates are based on projected price changes; price elasticities; land use and crop acreage changes; and efficiency practices.

By 2030 in the slow adaptation scenario, agricultural water prices increase 10 percent,[23] and efficiency improvements result in a 3 percent decrease in water use. By 2030 in the fast adaptation scenario, agricultural water prices increase 68 percent, and efficiency improvements result in a 0.4 to 22 percent decrease in water use, depending on crop.

Urban adaptation

Adaptation modeling for urban water use is very similar to that for agriculture water use. Again, CWSD models two scenarios – a "slow adaptation" scenario and a "fast adaptation" scenario. By 2030 in the slow adaptation scenario, urban water prices increase 20 percent,[24] and urban conservation and efficiency improvements result in a 15 percent decrease in water use. By 2030 in the fast adaptation scenario, urban water prices increase 41 percent, and conservation and efficiency improvements result in a 39 percent decrease for residential interior and commercial/industrial and public use, and a 33 percent decrease for residential exterior use.

Energy sector adaptation

CWSD allows for the selection of four energy adaptation scenarios in addition to the no adaptation scenario: energy efficiency; energy efficiency and water conservation; energy efficiency and CO_2 reduction; and all adaptation measures combined (energy efficiency, water conservation, and CO_2 reduction). These scenarios are described in detail in a separate methodology (see Fisher and Ackerman 2011).

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[21] This follows the "Current Trends" scenario as described by the Pacific Institute. See Gleick et al. (2005) and Groves et al. (2005).
[22] This follows the "High Efficiency" scenario as described by the Pacific Institute. See Gleick et al. (2005) and Groves et al. (2005).
[23] CWSD extends the Pacific Institute's water price projections by assuming the same annual growth trend through 2050 and constant prices thereafter.
[24] CWSD extends the Pacific Institute's water price projections by assuming the same annual growth trend through 2050 and constant prices thereafter.

3. Data

Annual data in baseline scenario

Baseline annual values by water-year type are derived from the CADWR's Water Portfolios for 1998 through 2005.[25] CADWR's Water Portfolios contain information on various sources of inflows and outflows. Based on these data, CWSD calculates values for three different water-year types; normal, dry, and wet. Values by water-year type are simple averages of given sets of years as follows – normal: 1999, 2000, 2003, and 2004; dry: 2001 and 2002; and wet: 1998 and 2005. (CWSD assigns water-year types based on CADWR portfolio data on precipitation.) In reorganizing these data, water balance tables in the California Water Plan Update 2009 regional reports were followed and verified wherever possible.[26] In doing so, the following assumptions were made:

- We define the annual flow into reservoirs as precipitation plus inflow from out of state (the Klamath and Colorado Rivers) less evapotranspiration from natural areas and runoff that flows directly from precipitation or snowmelt without being diverted for use. The CADWR Water Portfolio does not estimate natural evapotranspiration; we instead calculate this value as the portfolio's, or total inflow plus total return flows less total outflow, storage change, measured evaporation and evapotranspiration, sewage, agriculture-effective precipitation, and natural runoff to salt sink. In CADWR terminology:
  - Total inflow equals precipitation plus inflows from Oregon, Mexico, and the Colorado River.
  - Total return flows equal recycled water-urban waste water, recycled water-urban desalination, return flow to developed supply-agriculture, return flow to developed supply-wetlands, return flow to developed supply-urban, return flows to salt sink-agriculture, return flows to salt sink-wetlands, return flows to salt sink-urban, reuse of return flows within region-agriculture, reuse of return flows within region-wetlands-instream-wild and scenic, and reuse of return flows with region-urban.
  - Total outflow equals agricultural applied water use, managed wetlands applied water use, urban residential use-single family-interior, urban residential use-single family-exterior, urban residential use-multi-family-interior, urban residential use-multi-family-exterior, urban commercial use, urban industrial use, urban large landscape, urban energy production, instream flow net use, required delta outflow net use, excess delta outflow, wild and scenic rivers net use, and outflows to Nevada, Oregon, and Mexico.
  - Total storage change equals groundwater net change in storage plus surface water net change in storage.
  - Sewage equals urban waste water produced.

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[25] "California Water Portfolio 1998 to 2005," provided in an email from the California Department of Water Resources, July 2010.

[26] California Department of Water Resources, March 2010, California Water Plan Update 2009, http://www.waterplan.water.ca.gov/cwpu2009/index.cfm, Volume 3.

- ▪ Agriculture-effective precipitation equals agriculture effective precipitation on irrigated lands.
- ▪ Natural runoff to salt sink equals remaining natural runoff-flows to salt sink.
- Normal-year Sierra snowpack is 15-million acre feet based on CADWR estimates;[27] we assume that each year's snowmelt is equal to its snowpack (i.e., no snow survives the summer). Dry and wet-year snow pack is calculated as this average multiplied by an index derived from CADWR California Cooperative Snow Surveys data for April through July unimpaired runoff summed across the Sacramento and San Joaquin Valley river basins.[28] We assume that total snowpack is proportional to Sacramento and San Joaquin Valley river basin snowpack . Small adjustment are then made to dry and wet-year snow pack such that January snowpack is always less than or equal to January precipitation.
- Total water use is the sum of total applied use, total environmental outflows, total return flows, outflows to Nevada, Oregon, and Mexico, agriculture-effective precipitation on irrigated lands, and sewage as reported in the CADWR Water Portfolios. In CADWR terminology:
  - ▪ Total applied use is the sum of agricultural, managed wetlands, urban residential, urban commercial, urban industrial, urban large landscape, and urban energy production applied uses.
  - ▪ Total environmental outflows are the sum required Delta outflow net use, excess Delta outflow, Instream flow net use, and Wild and Scenic rivers nets use. Note that these are outflows, not the total required use. (This distinction is more readily viewed in the CADWR's Water Balances[29] than in its Water Portfolio.)
  - ▪ Total return flows are the sum of recycled water from urban wastewater and desalination; return flows from developed supply from agriculture, wetlands and urban uses; return flows to the salt sink from agriculture, wetlands and urban uses; and reuse of return flows within the region from agriculture, wetlands, Instream, Wild and Scenic Rivers, and urban uses.
  - ▪ Total sewage and agricultural effective precipitation is the sum of urban waste water produced and agricultural effective precipitation on irrigated lands.
- Maximum reservoir capacity, 43 MAF, is based on CADWR data.[30]

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[27] California Water Plan Update 2009, Volume 1, Chapter 4, http://www.waterplan.water.ca.gov/docs/cwpu2009/0310final/v1c4_califtoday_cwp2009.pdf; and State of California, "Managing an Uncertain Future", October 2008, http://www.waterplan.water.ca.gov/docs/cwpu2009/0310final/v4c02a09_cwp2009.pdf.

[28] California Department of Water Resources, California Cooperative Snow Surveys, November 2009, "Chronological Reconstructed Sacramento and San Joaquin Valley Water Year Hydrologic Classification Indices," http://cdec.water.ca.gov/cgi-progs/iodir/wsihist.

[29] California Water Balances 1998 to 2005, provided in an email from the California Department of Water Resources, July 2010.

[30] Personal communication, August 2010, Maury Roos, Division of Flood Management, California Department of Water Resources. For California surface storage capacity and September 30, 2002 and 2003 storage, see "2003 Water Portfolio, Reservoir Storage," May 3, 2006, provided to us in an email from the California Department of Water Resources, July 2010.

- Previous year surface water storage is based on user parameter selections (see description above). If "Previous Year Normal," "Previous Year Dry," or "Previous Year Wet" are selected, the annual value is the CADWR Water Portfolio average for the given water-year type for surface storage-end of year.
- Groundwater extraction is groundwater net change in storage from the CADWR Water Portfolio.
- Delta minimum required is taken directly from the CADWR Water Portfolio. Instream Flow total required applied use is derived from California Water Plan Update 2003 data.[31] Wild and Scenic Rivers total required applied use is derived from CADWR Bulletin 160-93 data.[32]

Table 2: Baseline Annual Values by Water Year Type and Climate-Scenario (MAF)

	Baseline		
	Normal	Dry	Wet
Precipitation	185.0	149.6	290.8
Inflow from Klamath and Colorado Rivers	6.5	6.5	6.3
Natural ET	-106.6	-99.5	-186.4
Natural runoff	-23.1	-13.4	-25.4
Snowpack	-15.0	-7.5	-26.0
Snowmelt	15.0	7.5	26.0
Agricultural	31.9	32.6	26.8
Managed wetlands	1.5	1.4	1.3
Urban residential	5.8	5.8	5.5
Urban commercial/industrial/large landscape	2.5	2.5	2.2
Urban energy production	0.1	0.1	0.1
Required Delta outflow	6.9	4.7	8.3
Excess Delta outflow	10.6	3.4	21.0
Instream Flow outflow	2.8	2.4	2.8
Wild and Scenic Rivers outflow	21.4	12.2	25.4
Return flows from agriculture	-5.5	-5.3	-4.6
Return flows other	-14.8	-12.5	-17.4
Outflow to Nevada/Oregon/Mexico	1.1	0.7	1.5
Agricultural effective precipitation on irrigated lands	2.8	3.0	3.7
Urban wastewater	3.9	4.0	3.7
With previous year surface water storage	24.6	21.1	29.9
Groundwater extraction	7.8	9.7	2.9
Delta minimum required	6.9	4.7	8.3
Instream Flow total required applied use	7.8	6.6	8.3
Wild and Scenic Rivers total required applied use	23.1	9.8	41.6

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[31] "Table 1 – California Water Plan Update 2003: Instream flow requirements (cfs) for 2001)", June 2002, provided in an email from the California Department of Water Resources, July 2010.
[32] "WildandScenic.98.00.01," provided in an email from the California Department of Water Resources, July 2010.

Monthly share data in baseline scenario

Data sources for baseline monthly shares are as follows:

- Precipitation, natural evapotranspiration, natural runoff, instream flow outflow, wild and scenic rivers outflow, return flows other, and agricultural effective precipitation on irrigated lands monthly shares, averaged across years, based on historical data, 1961 to 1990, from the California Climate Tracker[33] and our own water-year definitions such that normal years' precipitation falls within one standard deviation of the average across this period, dry years' precipitation is less than 1 standard deviation, and wet years' precipitation is greater than 1 standard deviation.

Table 3: Precipitation, Natural Evapotranspiration, Natural Runoff, Instream Flow Outflow, Wild and Scenic Rivers Outflow, Return Flows Other, and Agricultural Effective Precipitation on Irrigated Lands

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Normal	0.02	0.06	0.15	0.17	0.18	0.15	0.14	0.07	0.03	0.01	0.01	0.01
Dry	0.07	0.06	0.13	0.09	0.12	0.16	0.18	0.06	0.06	0.02	0.01	0.03
Wet	0.02	0.05	0.12	0.16	0.20	0.16	0.15	0.08	0.01	0.01	0.01	0.02

- Inflow from Klamath and Colorado Rivers monthly shares based on 2009-2012 total releases from Lakes Powell, Mead, and Mohave, average across years;[34] an assumed monthly flow from the Klamath Reservoir;[35] and the following weights: 4.4/6.5 for Colorado and 2.1/6.5 for Oregon.[36] These shares do not vary by water-year type.

Table 4: Inflow from Klamath and Colorado Rivers

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
All years	0.04	0.05	0.05	0.05	0.05	0.06	0.07	0.07	0.17	0.18	0.13	0.08

- Snowpack and snowmelt monthly shares derived from CCCC data for 1996 snow water equivalent centroid date and snow-water equivalent values for the Sierra Nevadas.[37] These shares do not vary by water-year type.

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[33] California Climate Tracker, http://www.wrcc.dri.edu/monitor/cal-mon/frames_data.html. See Abatzoglou et al. (2009).

[34] U.S. Bureau of Reclamations, Lower Colorado Region, August 2010, "Operation Plan for Colorado River System Reservoirs," http://www.usbr.gov/lc/region/g4000/24mo.pdf.

[35] U.S. Bureau of Reclamations, Klamath Project, May 2010, "Klamath Project 2010 Operation Plan," http://www.klamathbasincrisis.org/BOR/2010_OP_PLAN_050610.pdf.

[36] U.S. Bureau of Reclamations, "The Law of the River – The Boulder Canyon Project Act of 1928," http://www.usbr.gov/lc/region/g1000/lawofrvr.html, states that California receives 4.4 MAF from the Colorado River annually. 6.5 MAF approximates inflows from the Klamath and Colorado Rivers for 1998 through 2005, according to the CADWR Water Portfolio.

[37] See Kapnick and Hall (2009) and Maurer (2007).

Table 5: Snowpack

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
All years	0.00	0.00	0.00	0.13	0.58	0.21	0.08	0.00	0.00	0.00	0.00	0.00

Table 6: Snowmelt

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
All years	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.55	0.45	0.00	0.00	0.00

- Agriculture, return flows from agriculture, and groundwater extraction monthly shares based on historical irrigation water use estimates for a normal (1996), dry (1997) and wet (1983) year.[38] (Return flows from urban and wetlands are more likely to be reused and groundwater is more likely to be extracted during times of high water demand. For this reason, these flows are here assumed proportional to the use of irrigation water.)

Table 7: Agriculture, Return Flows from Agriculture and Groundwater Extraction

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Normal	0.04	0.00	0.00	0.00	0.00	0.01	0.05	0.15	0.24	0.27	0.15	0.07
Dry	0.03	0.01	0.00	0.00	0.00	0.03	0.08	0.22	0.23	0.21	0.12	0.07
Wet	0.04	0.01	0.00	0.00	0.00	0.00	0.03	0.12	0.26	0.28	0.17	0.09

- Managed wetlands, urban residential, urban commercial/industrial/large landscape, and urban wastewater assumed to have equal shares for all twelve months.
- Urban energy production assumed to have equal shares for all twelve months pending completion of the energy production module of this model.
- Required delta outflow, excess delta outflow, and delta minimum required monthly shares based on CADWR Water Portfolio data, average across years for each water-year type.[39]

Table 8: Required Delta Outflow, Delta Minimum Required

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Normal	0.04	0.04	0.04	0.05	0.13	0.21	0.17	0.12	0.09	0.07	0.04	0.03
Dry	0.05	0.06	0.06	0.06	0.12	0.15	0.14	0.12	0.09	0.07	0.05	0.04
Wet	0.03	0.03	0.03	0.04	0.13	0.15	0.17	0.13	0.17	0.05	0.03	0.02

Table 9: Excess Delta Outflow

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Normal	0.02	0.04	0.14	0.18	0.30	0.18	0.04	0.06	0.00	0.01	0.02	0.01
Dry	0.02	0.03	0.20	0.41	0.09	0.16	0.02	0.05	0.00	0.00	0.00	0.02
Wet	0.01	0.01	0.03	0.14	0.28	0.15	0.10	0.12	0.08	0.04	0.03	0.03

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[38] Data for 41 counties provided in an email from William Salas, Applied Geosolutions, LLC, June 2010. See Salas et al. (2006).
[39] "DeltaOutflow(18Jul2007)" provided in an email from the California Department of Water Resources, July 2010.

- Outflow to Nevada/Oregon/Mexico monthly shares assumed proportional to monthly values for precipitation less snowpack plus snowmelt; these shares are calculated within the model itself.

- Instream Flow total required applied use monthly shares derived from California Water Plan Update 2003 data.[40]

Table 10: Instream Flow Total Required Applied Use

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Normal	0.08	0.07	0.08	0.07	0.09	0.10	0.12	0.14	0.09	0.06	0.05	0.06
Dry	0.08	0.08	0.08	0.07	0.09	0.10	0.12	0.13	0.09	0.06	0.06	0.06
Wet	0.08	0.07	0.07	0.07	0.08	0.10	0.13	0.15	0.10	0.05	0.05	0.05

- Wild and Scenic Rivers total required applied use monthly shares derived from CADWR Bulletin 160-93 data.[41]

Table 11: Wild and Scenic Rivers Total Required Applied Use

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Normal	0.01	0.04	0.06	0.20	0.24	0.16	0.10	0.11	0.06	0.02	0.01	0.01
Dry	0.03	0.04	0.08	0.08	0.16	0.21	0.14	0.17	0.05	0.03	0.01	0.01
Wet	0.01	0.03	0.05	0.21	0.21	0.16	0.09	0.08	0.09	0.05	0.01	0.01

Climate projections

The California temperature projections used in the CWSD model vary by county, month, and climate scenario-year; climate change-induced differences in precipitation are not modeled. The raw data used to determine temperature by county, month, climate scenario-year, and climate variable were developed by the CCCC.[42] The data are monthly Bias Corrected and Spacially Downscaled climate data for 1950-2099 for 58 California counties, six Global Climate Models (GCMs),[43] two climate change scenarios (B1 and A2), and 13 climate variables including average monthly temperature and total monthly precipitation.[44]

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[40] "Table 1 – California Water Plan Update 2003: Instream flow requirements (cfs) for 2001)," June 2002, provided in an email from the California Department of Water Resources, July 2010.

[41] "WildandScenic.98.00.01," provided in an email from the California Department of Water Resources, July 2010.

[42] Projections provided by Mary Tyree and Dr. Dan Cayan, director of the California Nevada Applications Program and California Climate Change Center at Scripps Institution of Oceanography. Also see Cayan et al. (2009).

[43] The six GCMs used referred to throughout our analysis are the National Center for Atmospheric Research (NCAR) Parallel Climate Model (PCM); the National Oceanic and Atmospheric Administration (NOAA) Geophysical Fluids Dynamics Laboratory (GFDL) model, version 2.1; the NCAR Community Climate System Model (CCSM); the Max Plank Institute ECHAM5/MPI-OM; the MIROC 3.2 medium-resolution model from the Center for Climate System Research of the University of Tokyo and collaborators; and the French Centre National de Recherches Météorologiques (CNRM) models.

[44] See http://www.hydro.washington.edu/SurfaceWaterGroup/Data/vic_global.html for a complete listing of variables with definitions and references.

In order to work with the data in Excel, the individual county files were aggregated into a single file for each GCM and scenario using STATA, reorganized, and then averaged across GCMs. Averages for 1961-1990, 2021-2040, 2041-2060, and 2090-2099 by scenario, county and month constitute our baseline, 2030, 2050, and 2100 projections, respectively. Note that for the baseline, climate data for the B1 scenario are used.

Annual data for climate change scenarios

Data sources for annual values by climate scenario-year, where variations from baseline occur, are as follows:

- Snowpack and snowmelt annual values by climate scenario-year are proportional to baseline snowpack and snowmelt based on an index derived from CCCC snow-water equivalent projections.[45]
- Agriculture annual values by climate scenario-years are based on the results of the irrigation water use module of this model. Annual values for return flows from agriculture by climate scenario-year are proportional to those from agriculture. Annual values for return flows other by climate scenario-year are proportional to non-agricultural applied water use as calculated within the model.
- Urban residential annual values by climate scenario-years are assumed proportional to our projections of residential water use for future years. Per capita residential water use for 2005 is the sum of self-supplied domestic withdrawals and publicly supplied domestic deliveries by total population based on U.S. Geological Survey data; county water use per capita is assumed to remain constant over time and climate scenario.[46] Population data and projections taken from State of California, Department of Finance data;[47] each county's population is assumed to stay constant after 2050. Annual values for urban wastewater by climate scenario-year are proportional to projected population.

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[45] Snow water equivalent estimates averaged across six general circulation models. Baseline data based on the B1 scenario average for 1961 through 1990; 2030 and 2050 estimates based on 20-year averages around these dates; and 2010 estimates based on average for the 2090s. Projections provided by Mary Tyree and Dr. Dan Cayan, director of the California Nevada Applications Program and California Climate Change Center at Scripps Institution of Oceanography. Also see Cayan et al. (2009).

[46] U.S. Geological Survey, Water Use Survey, Estimated Use of Water in the United States County-Level Data for 2005, http://water.usgs.gov/watuse/data/2005/index.html. See "Guidelines for preparation of State water-use estimates for 2005," http://pubs.usgs.gov/tm/2007/tm4e1/.

[47] Projections for 2000-2050 based on State of California, Department of Finance, July 2007, "Population Projections for California and Its Counties 2000-2050," http://www.dof.ca.gov/research/demographic/reports/projections/p-1/. Projection for 2100 set equal to 2050 projection.

Table 12: Annual Values by Water Year Type and Climate-Scenario (where variations from baseline occur)

	Baseline			B1-2030			A2-2030					
	Normal	Dry	Wet	Normal	Dry	Wet	Normal	Dry	Wet			
Snowpack	-15.0	-7.5	-26.0	-11.5	-5.7	-19.9	-10.4	-5.2	-18.0			
Snowmelt	15.0	7.5	26.0	11.5	5.7	19.9	10.4	5.2	18.0			
Agricultural	31.9	32.6	26.8	33.2	33.9	27.9	33.3	34.0	28.0			
Urban residential	5.8	5.8	5.5	9.1	9.1	8.6	9.1	9.1	8.6			
Return flows from agriculture	-5.5	-5.3	-4.6	-5.7	-5.6	-4.8	-5.7	-5.6	-4.8			
Return flows other	-14.8	-12.5	-17.4	-14.8	-12.5	-17.4	-14.8	-12.5	-17.4			
Urban wastewater	3.9	4.0	3.7	4.1	4.1	4.4	4.1	4.1	4.4			
	B1-2050			A2-2050			B1-2100			A2-2100		
	Normal	Dry	Wet	Normal	Dry	Wet	Normal	Dry	Wet	Normal	Dry	Wet
Snowpack	-10.0	-5.0	-17.4	-9.3	-4.7	-16.2	-8.4	-4.2	-14.6	-4.5	-2.2	-7.8
Snowmelt	10.0	5.0	17.4	9.3	4.7	16.2	8.4	4.2	14.6	4.5	2.2	7.8
Agricultural	33.6	34.3	28.2	34.1	34.8	28.6	34.6	35.3	29.0	36.7	37.5	30.8
Urban residential	11.5	11.6	11.0	11.5	11.6	11.0	11.5	11.6	11.0	11.5	11.6	11.0
Return flows from agriculture	-5.8	-5.6	-4.8	-5.9	-5.7	-4.9	-6.0	-5.8	-5.0	-6.3	-6.1	-5.3
Return flows other	-14.8	-12.5	-17.4	-14.8	-12.5	-17.4	-14.8	-12.5	-17.4	-14.8	-12.5	-17.4
Urban wastewater	4.1	4.1	4.4	4.1	4.1	4.4	4.1	4.1	4.4	4.1	4.1	4.4

Monthly Share Data for Climate Change Scenarios

All monthly shares remain constant across climate scenario-years with the exception of snowpack and snowmelt.

- The timing of snowpack build up and snowmelt is projected to change over time with climate change. Monthly shares by climate scenario-year are derived from our application of snowmelt projections with climate change from the Scripps Institute of Oceanography and the U.S. Geological Survey[48] to baseline timing (derived from CCCC research, see description above).

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[48] Stewart et al. (2004) and Maurer (2007).

Table 13: Monthly Shares by Climate-Scenario (where variations from baseline occur)

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
						Snowpack						
Baseline	0.00	0.00	0.13	0.58	0.21	0.08	0.00	0.00	0.00	0.00	0.00	0.00
B1-2030	0.00	0.05	0.29	0.45	0.18	0.02	0.00	0.00	0.00	0.00	0.00	0.00
A2-2030	0.00	0.05	0.32	0.44	0.18	0.02	0.00	0.00	0.00	0.00	0.00	0.00
B1-2050	0.00	0.06	0.35	0.41	0.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00
A2-2050	0.00	0.09	0.43	0.35	0.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00
B1-2100	0.00	0.10	0.46	0.33	0.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00
A2-2100	0.00	0.13	0.58	0.24	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
						Snowmelt						
Baseline	0.00	0.00	0.00	0.00	0.00	0.00	0.55	0.45	0.00	0.00	0.00	0.00
B1-2030	0.00	0.00	0.00	0.00	0.00	0.21	0.70	0.09	0.00	0.00	0.00	0.00
A2-2030	0.00	0.00	0.00	0.00	0.00	0.23	0.73	0.04	0.00	0.00	0.00	0.00
B1-2050	0.00	0.00	0.00	0.00	0.00	0.28	0.72	0.00	0.00	0.00	0.00	0.00
A2-2050	0.00	0.00	0.00	0.00	0.00	0.38	0.62	0.00	0.00	0.00	0.00	0.00
B1-2100	0.00	0.00	0.00	0.00	0.00	0.41	0.59	0.00	0.00	0.00	0.00	0.00
A2-2100	0.00	0.00	0.00	0.00	0.00	0.57	0.43	0.00	0.00	0.00	0.00	0.00

4. Results

CWSD estimates the economic impacts of climate change on California's water supply and demand systems over the next 100 years. Results are modeled by county for three areas of water use that are vital to California's economy and at particular risk from climate change: the agriculture, urban, and energy sectors; a separate agriculture model follows the CWSD agricultural methodology for Western states. For the agricultural sector, CWSD estimates water use given varying assumptions about emissions, economic growth, and adaptation behavior. For the energy sector, water use is based on different scenarios of coal, nuclear and renewable power use, conservation technology, state population trends, and projected temperatures. Urban water use, on the other hand, does not vary with climate change and is based only on projected levels of socio-economic growth.

CWSD models three climate scenarios: a baseline scenario, B1, and A2; and three scenarios of adaptation: no adaptation; slow adaptation, and fast adaptation. Here we present results of the agriculture module for California (aggregated to eight districts[49]) and for the remaining Western

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[49] California's 58 counties are assigned to 8 water districts as follows: (i) Mohave: Inyo and San Bernardino; (ii) Northeast: Lassen and Modoc; (iii) Northwest: Colusa, Del Norte, Glenn, Humboldt, Lake, Mendocino, Napa, Shasta, Siskiyou, Sonoma, Tehama, and Trinity; (iv) Sacramento-Delta: Alameda, Contra Costa, Marin, Sacramento, San Francisco, San Joaquin, San Mateo, Santa Clara, Santa Cruz, Solano, Stanislaus, Sutter, Yolo, and Yuba; (v) San Joaquin Valley: Fresno, Kern, Kings, Merced, Monterey, San Benito, San Luis Obispo, and Tulare; (vi) Sierra: Alpine, Amador, Butte, Calaveras, El Dorado, Madera, Mariposa, Mono, Nevada, Placer, Plumas, Sierra, and Tuolumne; (vii) Sonaran: Imperial and Riverside; (viii) South Coast: Los Angeles, Orange, San Diego, Santa Barbara, and Ventura.

states. We also present estimates of groundwater extraction and demand shortfall for California through 2110 by climate scenario and adaptation scenario. Results from the urban water use and energy modules are incorporated into overall estimates of water supply and demand.
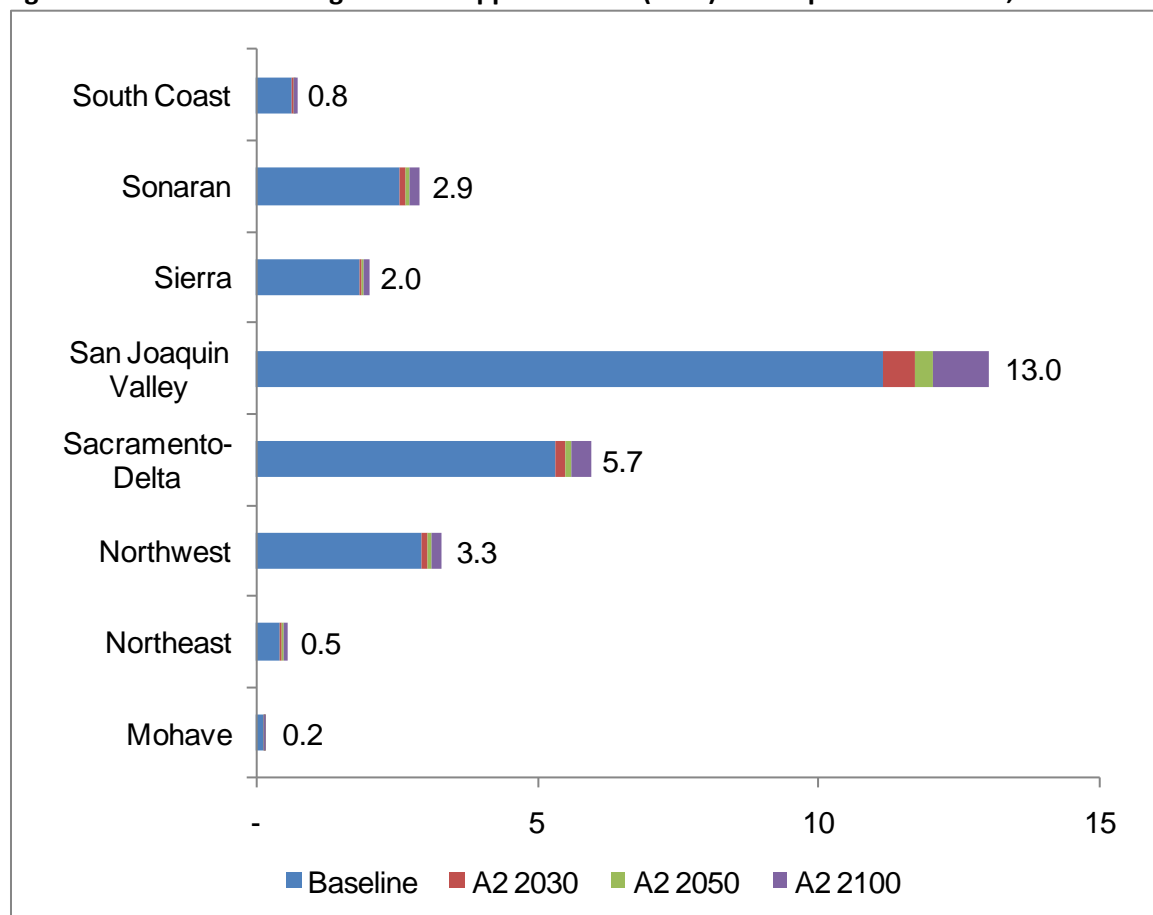
California Agriculture Water Use (No Adaptation)

Figure 2 and Figure 3 present district-level water use for crop irrigation and livestock in California by climate scenario-year. These results do not account for adaptation.

Figure 2: California's Average Annual Applied Water (MAF) for Crops and Livestock, B1 Climate
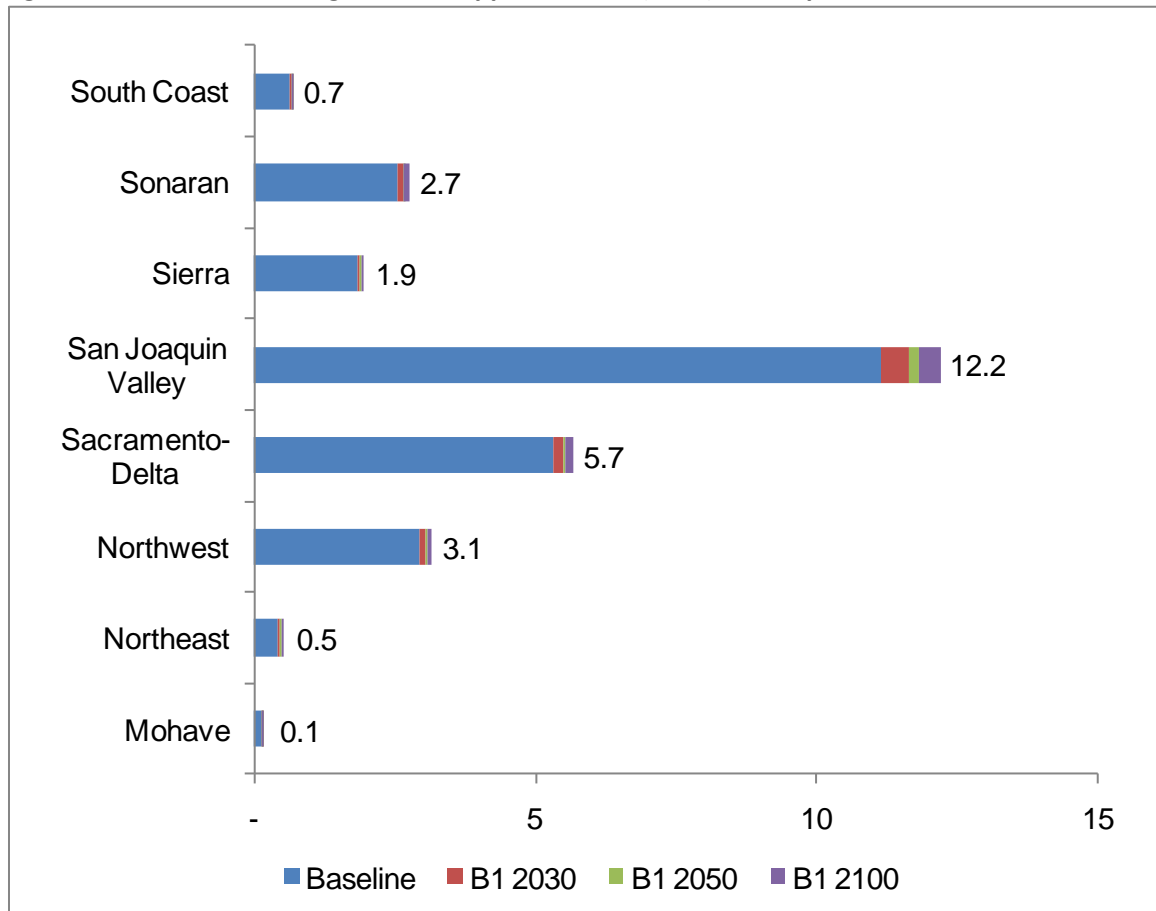
Source: Authors' calculations.

Figure 3: California's Average Annual Applied Water (MAF) for Crops and Livestock, A2 Climate

Source: Authors' calculations.

California's baseline annual agriculture water use is 24.9 MAF, more than 99 percent of which is used for crop irrigation. Nearly half of California's agricultural water use is driven by demand in the San Joaquin Valley water district, which includes important crop-producing counties, such as Fresno, Kern, Tulare, Merced, and Kings. In the absence of adaptation, annual demand for agricultural water increases over time for both climate scenarios, reaching 28.7 MAF (or 115 percent of the baseline) by 2100 for the A2 climate scenario as hotter temperatures place upward pressure on irrigation needs. In absolute terms, the greatest increase over the baseline water use occurs in the San Joaquin Valley; ranging from 1.1 MAF by 2100 for the B1 climate-scenario to 1.9 MAF by 2100 for the A2 climate scenario. In other districts, climate-induced increases in water use are smaller, ranging from 0.0 MAF in Mohave to 0.4 MAF in the Sacramento-Delta district by B1-2100; and from 0.0 MAF in Mohave and 0.7 MAF in the Sacramento-Delta district by A2-2100.

California Agriculture Water Use (with Adaptation)

Table 14 shows California's agricultural water use by climate scenario-year and by district with slow adaptation and fast adaptation. With slow adaptation, water use is always lower than without adaptation; but adaptation reductions are ultimately outstripped by climate-induced increases in demand for the A2 climate scenario. By 2050, slow adaptation leads to marginal reductions in agriculture water use, reducing agricultural water use to 23.2 to 23.5 MAF, depending on the climate scenario; nonetheless, water use rises to 101 percent of the baseline, or 25.3 MAF, by 2100. Fast adaptation leads to more significant decreases in demand over time for every climate scenario. The greatest reductions occur in 2050, by which point increasing water prices and technological advancement reduce demand to just 17.4 and 17.6 MAF for the B1 and A2 climate scenarios, respectively. By 2100, water use is still much lower than the baseline, with overall reduction of 24 to 26 percent, depending on the climate scenario.

Table 14: California's Average Annual Applied Water (MAF) for Crops and Livestock by District, Climate Scenario-Year and Adaptation Scenario

| No Adaptation	California	Mohave	Northeast	Northwest	Sacramento-Delta	San Joaquin Valley	Sierra	Sonaran	South Coast
Baseline	24.9	0.1	0.4	2.9	5.3	11.1	1.8	2.5	0.6
B1 2030	25.9	0.1	0.5	3.0	5.5	11.6	1.9	2.6	0.6
A2 2030	26.0	0.1	0.5	3.0	5.5	11.7	1.9	2.6	0.7
B1 2050	26.2	0.1	0.5	3.1	5.5	11.8	1.9	2.7	0.7
A2 2050	26.6	0.1	0.5	3.1	5.6	12.0	1.9	2.7	0.7
B1 2100	27.0	0.1	0.5	3.1	5.7	12.2	1.9	2.7	0.7
A2 2100	28.7	0.2	0.5	3.3	6.0	13.0	2.0	2.9	0.7
Slow Adaptation	California	Mohave	Northeast	Northwest	Sacramento-Delta	San Joaquin Valley	Sierra	Sonaran	South Coast
Baseline	24.9	0.1	0.4	2.9	5.3	11.1	1.8	2.5	0.6
B1 2030	23.8	0.1	0.6	2.9	5.4	10.4	1.8	2.1	0.5
A2 2030	23.9	0.1	0.6	2.9	5.4	10.4	1.8	2.1	0.5
B1 2050	23.2	0.1	0.7	2.9	5.6	9.8	1.7	2.0	0.4
A2 2050	23.5	0.1	0.7	2.9	5.7	9.9	1.7	2.0	0.4
B1 2100	23.8	0.1	0.7	3.0	5.8	10.1	1.7	2.0	0.4
A2 2100	25.3	0.1	0.8	3.1	6.1	10.7	1.8	2.1	0.5
Fast Adaptation	California	Mohave	Northeast	Northwest	Sacramento-Delta	San Joaquin Valley	Sierra	Sonaran	South Coast
Baseline	24.9	0.1	0.4	2.9	5.3	11.1	1.8	2.5	0.6
B1 2030	20.4	0.1	0.5	2.5	4.6	8.8	1.5	1.9	0.4
A2 2030	20.4	0.1	0.5	2.6	4.7	8.8	1.5	1.9	0.4
B1 2050	17.4	0.1	0.6	2.2	4.3	7.1	1.2	1.6	0.3
A2 2050	17.6	0.1	0.6	2.3	4.3	7.2	1.2	1.6	0.3
B1 2100	18.4	0.1	0.6	2.4	4.5	7.6	1.3	1.6	0.3
A2 2100	19.0	0.1	0.7	2.4	4.6	7.9	1.3	1.7	0.3

Source: Authors' calculations.

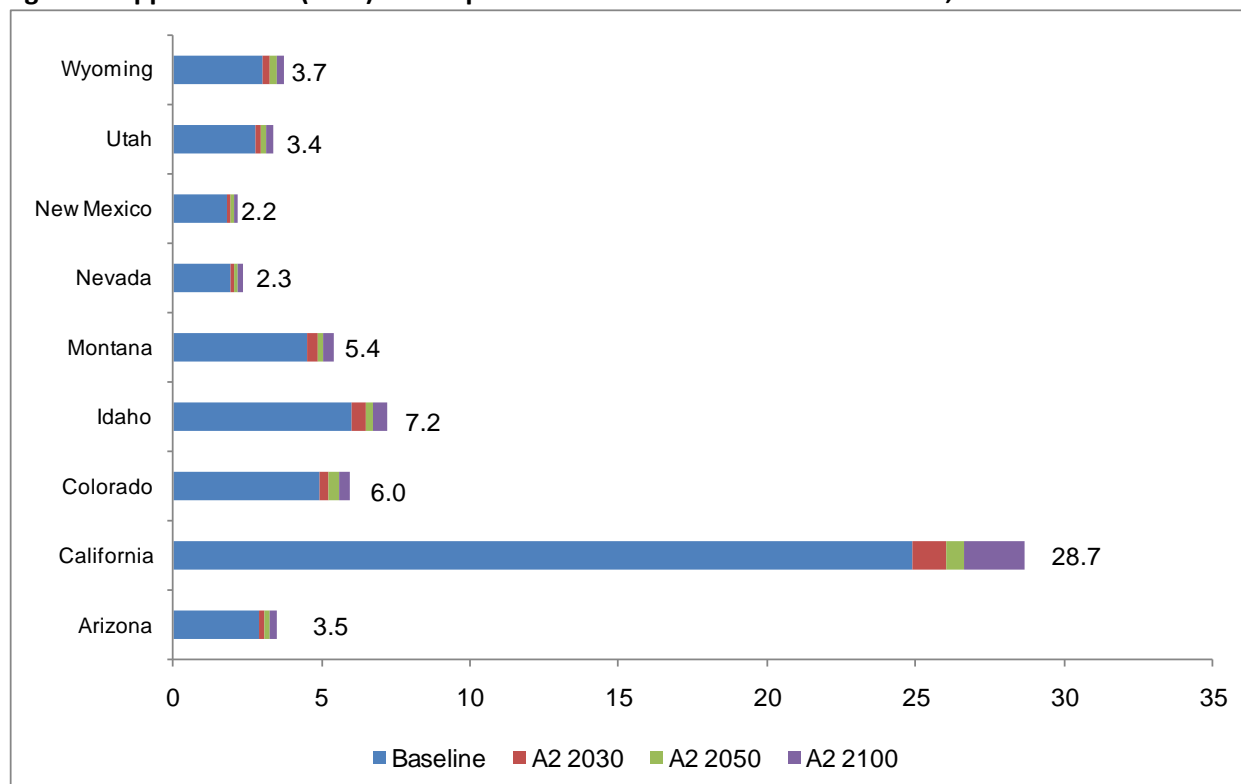## Southwest Agriculture Water Use

Figure 4 reports agriculture water use for each Western state for the B1 climate scenario; Figure 5 shows these results for the A2 climate scenario. The Western states include: Arizona, California, Colorado, Idaho, Montana, Nevada, New Mexico, Utah, and Wyoming. Note that we

do not model adaptation scenarios for the Western states and assume that irrigation acreage and livestock choices remain constant at 2007 levels.

Figure 4: Applied Water (MAF) for Crops and Livestock for the Western States, B1 Climate Scenario
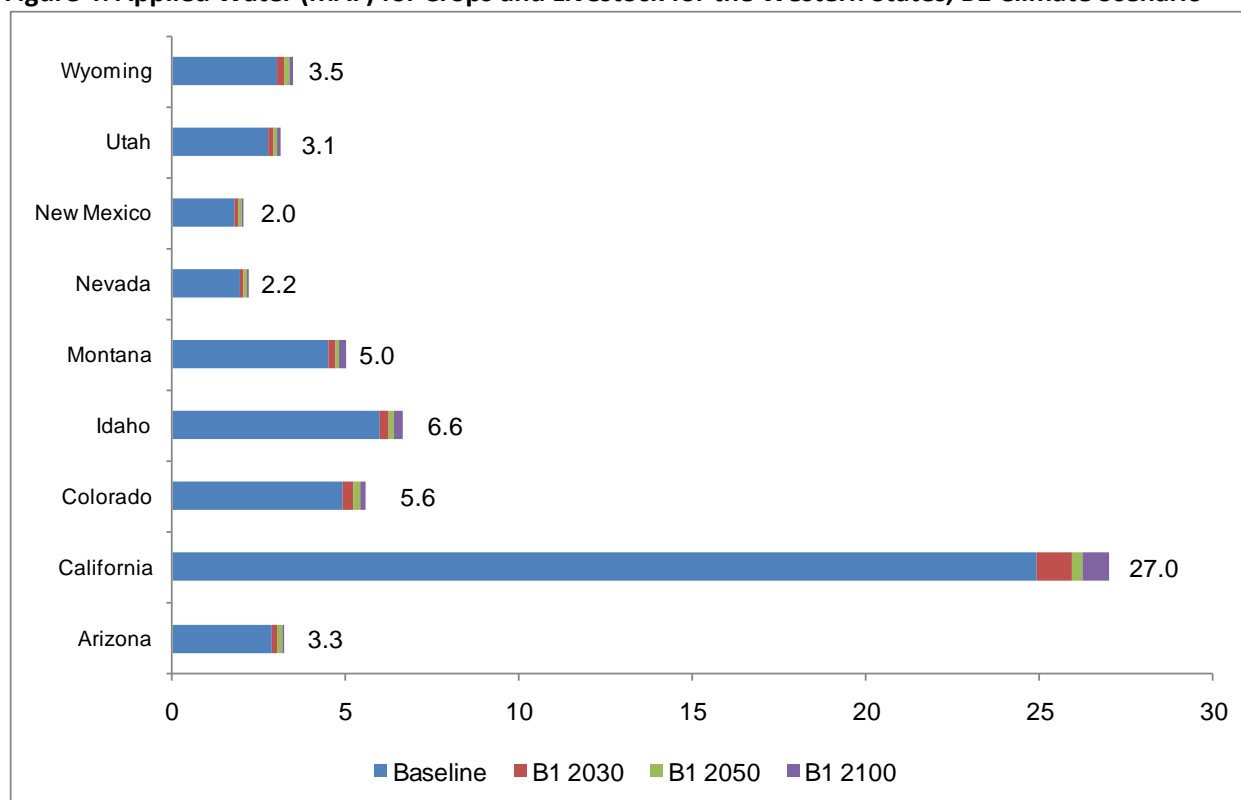
Source: Authors' calculations.

Figure 5: Applied Water (MAF) for Crops and Livestock for the Western States, A2 Climate Scenario

Source: Authors' calculations.

In the Western states, baseline annual agriculture water use is 52.8 MAF. This demand grows over time and is higher for the A2 climate scenario than the B1 climate scenario. By 2100, annual water use for the Western states reaches 58.3 and 62.4 MAF for the B1 and A2 climate scenarios, respectively. This translates to a 10 to 18 percent increase over the baseline. California comprises roughly 47 percent of this demand, with Idaho, Colorado, and Montana accounting for an additional 29 percent, combined. Aside from California, Idaho uses the most agriculture water among the Western states, reaching 7.2 MAF by 2100 for the A2 climate scenario; primarily driven by irrigation of hay, potatoes, and field crops. Colorado and Montana also use a significant amount of water for agriculture; with Colorado using 6.0 MAF and Montana using 5.4 MAF by 2100 for the A2 climate scenario. In both states, agricultural water is mainly used for hay irrigation. Table 15 presents these results by state and for the entire Western United States by climate scenario-year.

Table 15: Average Annual Applied Water (MAF) for Crops and Livestock by State and Climate Scenario-Year

Scenario-year	West Total	ARIZONA	CALIFORNIA	COLORADO	IDAHO
Baseline	52.8	2.9	24.9	4.9	6.0
B1 2030	55.3	3.1	25.9	5.2	6.3
A2 2030	55.9	3.1	26.0	5.2	6.5
B1 2050	56.6	3.2	26.2	5.4	6.4
A2 2050	58.1	3.3	26.6	5.6	6.7
B1 2100	58.3	3.3	27.0	5.6	6.6
A2 2100	62.4	3.5	28.7	6.0	7.2
Scenario-year	MONTANA	NEVADA	NEW MEXICO	UTAH	WYOMING
Baseline	4.5	1.9	1.8	2.8	3.0
B1 2030	4.7	2.1	1.9	2.9	3.3
A2 2030	4.9	2.1	1.9	2.9	3.3
B1 2050	4.8	2.1	2.0	3.0	3.4
A2 2050	5.1	2.2	2.0	3.1	3.5
B1 2100	5.0	2.2	2.0	3.1	3.5
A2 2100	5.4	2.3	2.2	3.4	3.7

Source: Authors' calculations.

Groundwater Extraction and Shortfall

CWSD models California's annual water supply and demand; estimating the cumulative groundwater extraction and demand shortfall over the next century as well as the number of years in which a shortfall will occur. To capture uncertainty about future precipitation, emissions, economic growth, and adaptation, we perform several different "runs" of the CWSD model based on different input parameters.

CWSD results are the average of 60 model runs for each climate year and scenario varying: the distribution of water years (even, 10% more wet years, and 10% more dry years); the supply lag (0 weeks, and 4.3 weeks); and, since the distribution of future water years is unknown, ten runs for each for each combination of these parameters, where each run randomly distributes water years over the course of the century. Detailed results are presented in an accompanying report (Ackerman and Stanton 2011).

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