The Last Drop:
Climate Change and the Southwest Water Crisis


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EXECUTIVE SUMMARY

At present, without climate change, the Southwest is relying on the unsustainable withdrawal of groundwater reserves to meet today's demand; those reserves will be drained over the next century as population and incomes grow. With climate change, the Southwest water crisis will grow far worse. Continuing the current trend in global greenhouse-gas emissions will make the cost of the next century's projected water shortage at least 25 percent higher. Adaptation (conservation and efficiency) measures, however, have the potential to greatly lower water use throughout the region. As climate change exacerbates water woes, some adaptation will be essential to stave off unplanned water shortages and restrictions. Bringing the Southwest's water use down to sustainable levels will necessitate either very strong residential adaptation measures, or a combination of strong agricultural adaptation measures (including the elimination of some low-value crops) and moderate residential measures.

Climate Change and the Southwest's Water Crisis

In the U.S. Southwest – Arizona, California, Nevada, New Mexico, and Utah – there is less rain and snowfall each year than the amount of water used in the region. Today that shortfall is made up for by pumping groundwater, well beyond the sustainable rate. Add the impacts of growing population and incomes, and the Southwest will face a major water crisis in the coming decades.

And that's the prediction before considering the effects of climate change. With rising temperatures, a bad situation will become still worse. All sectors increase their water use as temperatures climb, but none more than agriculture. Even with mild climate change – now considered a certainty by the scientific community – farmers will need more water to produce crops and livestock. With the more serious temperature increases likely to result from current trends in world greenhouse gas emissions, demand for agricultural water will clash with other uses.

This report offers an integrated picture of the effects of climate change on water supply, demand, and scarcity in the Southwest as a whole. For this analysis we developed three new intersecting models of water and climate change: a detailed depiction of California's supply and demand for water; a regional model of agricultural water use, and a regional model of water and electricity generation.

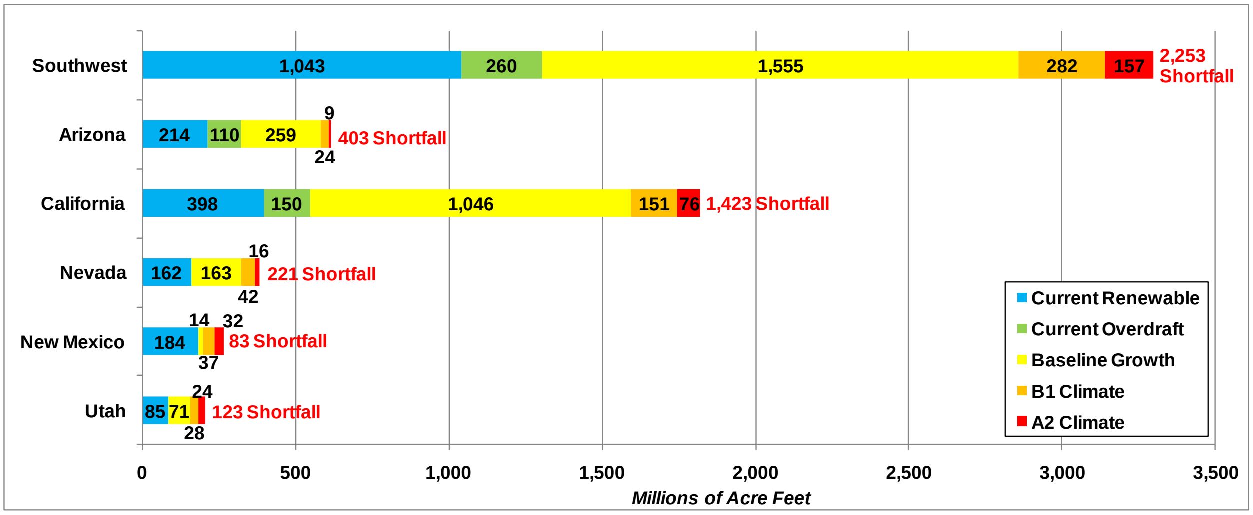
Our analysis differs from other studies in three fundamental respects. First, we focus on state-level interactions of water supply and demand, and, for water use and agriculture, on county-level data to provide a greater depth of insight than sweeping regional generalizations and a better overview than extremely detailed studies of local areas. Second, we make the (obviously overly optimistic) simplifying assumption that all water can be freely transported anywhere within a state; this allows for abstraction from questions of water conveyance and focuses our study on changes in water supply and demand with climate change. Third, we extend the analysis to cover a full century of climate change and water use in order to see the difference between a high-emission and a low-emission climate scenario – that is, to understand the difference that climate policy can make in the world that we will leave to our descendants.

To the Last Drop: Unsustainable Water Mining

Water demand in the Southwest will outstrip water supply in the near future. Throughout the region, groundwater supplies 35 percent of water use, and the Colorado River supplies another 18 percent; in Arizona, groundwater plus the Colorado River amount to 90 percent of water use. Both sources are being used at a rate that cannot be sustained.

Figure ES-1 forecasts the Southwest's future water use under a "baseline" scenario of current climate conditions combined with expected population and income growth; and under two climate-change scenarios, comparing a mild (B1) and more severe (A2) climate forecast.

Figure ES-1: Southwestern States' Projected Groundwater Extraction, 2010 to 2110



Note: Shortfall = sum of all groundwater use, beyond the renewable (blue) level, under A2 climate assumptions.

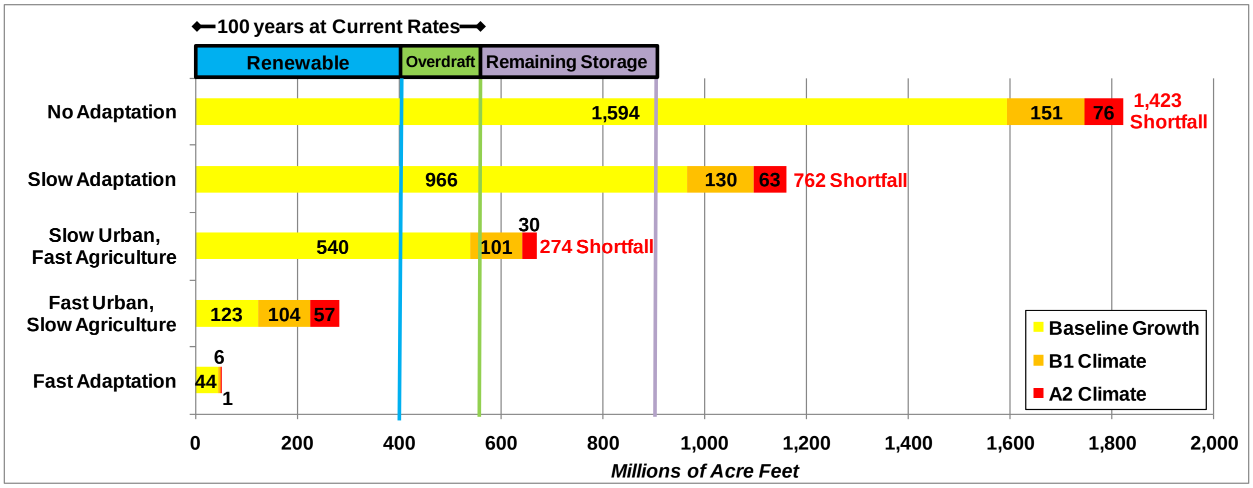
At today's rates of water use, the Southwest is projected to use 1,303 million acre feet of groundwater in the 100 years starting in 2010 (the blue plus green segments of the top bar in Figure ES-1); of this a conservatively estimated 260 million acre feet would be overdraft (shown in green). Adding only baseline growth of population and income, the Southwest's shortfall of water (green plus yellow in Figure ES-1) reaches 1,815 million acre feet. Using B1 climate assumptions, the Southwest's shortfall grows to 2,096 million acre feet (green, yellow, and orange). Under A2 climate assumptions – which are likely if current trends in global greenhouse gas emissions continue – the shortfall reaches 2,253 million acre feet (adding the red segment).

California: A Case Study of Unsustainable Water Use

More than half of the region's current and projected groundwater withdrawals take place in California. There are no up-to-date studies, and two very different estimates, of the state's groundwater reserves. Even on the more optimistic estimate, California would need three times the available groundwater to get through the next century. Unless adaptation measures are taken to reduce California's water use, 7 out of 10 years will require water restrictions or additional (above current levels) overdraft by 2030, and every year will have a water shortfall by 2050.

We modeled the Pacific Institute's adaptation scenarios for California's urban and agricultural water use. Their slow urban adaptation scenario involves a 15 percent reduction from conservation and efficiency, and a 20 percent price increase by 2030; slow agricultural adaptation means 5 percent reduction in water use plus a 10 percent price increase by 2030. The savings from slow urban and agricultural adaptation, combined, are not enough to reduce California's water use to the sustainable level, even without the impacts of climate change.

Figure ES-2: California's Projected Groundwater Extraction plus Shortfall, 2010 to 2110



Note: Baseline growth (yellow) now includes renewable and overdraft (shown as blue and green in earlier figures). Shortfall is total water use, under A2 climate assumptions, minus renewable (blue line).

Fast adaptation includes reductions in water use of up to 41 percent, and price increases of 41 percent for urban and 68 percent for agricultural users by 2030. Fast adaptation in one or both sectors is required to bring California's water use in line with available supplies. Fast urban adaptation, which has a bigger effect, is necessary to bring water use down to a renewable level.

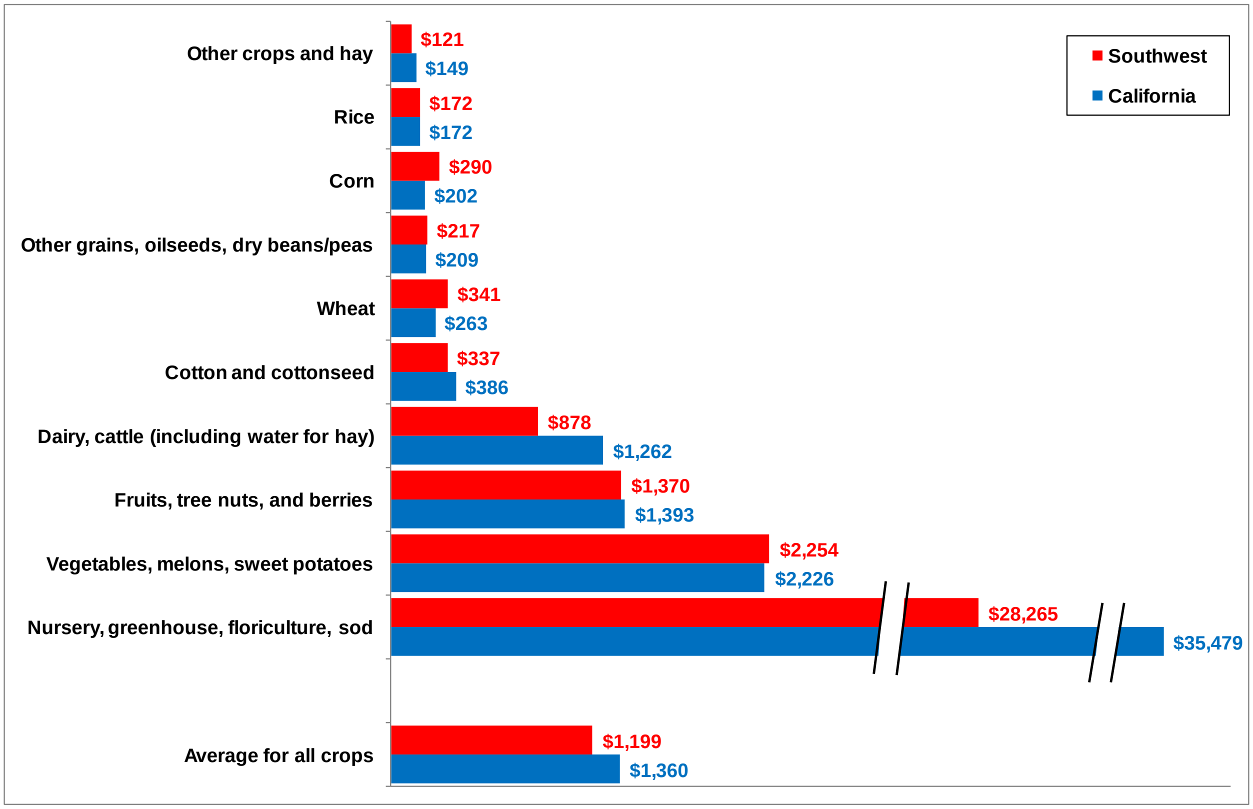
Southwest Water Use: Farms and Homes

California is by far the top agricultural state in the nation; 1 percent in the Southwest. Yet nearly four-fifths of the region's water is used for agriculture.

Southwest agricultural products vary greatly in profitability, and in the revenues they earn per unit of water. An astonishing 42 percent of the region's agricultural water (and more than 90 percent in Utah and Nevada) is used to grow hay, a low-value product; however, hay is an input to the dairy and cattle industry. We calculated the sales revenue per acre foot of water for crops in each state, including water for hay as part of the dairy and cattle industry's water use.

The top crops, in value per unit of water, are nursery and greenhouse products, earning $28,000 per acre foot for the region as a whole, and more than $35,000 in California. They are followed by vegetables, and then by fruits and nuts, with sales above $1,000 per acre foot in most cases. Dairy and cattle (including water for hay) brings in about $900 per acre foot for the region, more than $1,200 in California, but less than $250 in Utah and Nevada. Other crops – such as cotton, wheat, corn, rice, and other grains – have low values, under $500 per acre foot in most cases. The average for all crops is $1,200 for the region, and $1,360 for California.

Figure ES-3: Value of crops per acre foot of water, California and Southwest average



Urban use also varies widely; Nevada has the highest per capita domestic use in the nation, followed by Utah. Economic and population growth trends imply that urban water use will grow faster than agricultural water, making reductions in domestic water use of great importance.

Solutions: How to Make a Big Enough Difference

There are four possible solutions to the gap between water supply and demand. First, ***supply could be increased through imports or desalination.*** None of the neighboring states, however, are able to export significant amounts of water. Ocean desalination is potentially inexhaustible, but it is expensive and has been plagued with start-up problems. The true cost of the planned San Diego and San Francisco/Marin County plants may be $2,600 - $2,700 per acre foot.

Second, ***additional groundwater could be extracted.*** While the exact size of groundwater reserves is uncertain, the amounts that would be needed are far above the best estimates of available supply. The natural recharge rate is slow; planned recharge can increase reserves to some extent, especially in wet years, but climate change may make this option more difficult to pursue.

Third – and the only viable solution – there can be ***planned reductions in water use.*** In our energy modeling, we found that water constraints may shape the future energy system, but the amounts of water that can be saved in the energy sector are too small to contribute much to the solution to the regional water crisis. Water use will have to be reduced in the urban and agricultural sectors, the dominant users at present and in the future. The ambitious reductions called for in the fast adaptation scenarios are needed; slow adaptation would postpone but not solve the problem.

Among other areas for reduction, many farmers are growing crops worth less than $100 per acre foot of water use, and half of all agricultural water is used to grow crops worth less than $1,200 per acre foot. Some farmers, in other words, could make more selling water than using that same water to grow crops; water users in the Southwest, however, rarely have the right to sell their water. Eliminating the lowest value-per-unit-water crops (excluding hay) would lower agricultural water use by 24 percent, while reducing farm sales by less than 5 percent.

The final approach to water shortages is the least desirable: if nothing else happens, there will be ***unplanned shortages and draconian restrictions on water use***.

The Bottom Line: Failing to Act is the Most Expensive Option

The cumulative water shortfall for the Southwest for the next century, without adaptation, will be 1,815 million acre feet under current climate conditions, plus 282 million acre feet due to the B1 climate scenario or 439 million acre feet due to the A2 scenario. What would it cost to buy this much water, if it were for sale? We used a low price based on the cost of building new reservoirs and distribution systems in California, $1,252 per acre foot, and a high price based on a study of the average cost of water delivery in municipalities in the region, $2,211 per acre foot.

At these prices, the shortfall under current climate conditions costs $2.3 trillion to $4.0 trillion. The B1 climate scenario adds $350 to $620 billion; the A2 scenario adds $549 billion to $970 billion. At the higher price, A2 climate change turns a $4 trillion problem into a $5 trillion one.

On an annual basis, we project that by 2050, the increased water shortfall will cost $7 billion to $15 billion, or 0.3 to 0.6 percent of the region's GDP in 2009. For 2100, we project costs at $9 billion to $23 billion, or 0.4 to 0.9 percent of regional GDP in 2009. For comparison, several past studies have estimated the climate-induced increase in water resource costs at $7 billion to $60 billion per year by mid-century, or 0.1 to 0.9 percent of the most recent year's GDP, for the country as a whole.

The bottom-line question about water is not whether adaptation is difficult or expensive, compared to doing nothing. Rather, it should be compared to buying several trillion dollars worth of water over the next century; adaptation is a bargain that the region cannot afford to ignore. The implication for climate policy is similar: although doing something about greenhouse gas emissions is expensive, doing nothing would cost even more. Among the benefits of global emission reduction is a savings of hundreds of billions of dollars in the future cost of water, or the avoidance of water scarcity, in the five states of the Southwest.

1. Climate Change and the Southwest's Water Crisis

In the U.S. Southwest – Arizona, California, Nevada, New Mexico, and Utah – there is less rain and snowfall each year than the amount of water used in homes, businesses, farms, and for environmental purposes. Today that shortfall is made up for by pumping groundwater, and in at least two states, Arizona and California, the stock of groundwater is falling every year. Add the higher water use that comes with growing population and incomes, and the Southwest is expected to face a major water crisis in the coming decades. As the century progresses, groundwater reserves will run dry, and current trends in water use cannot possibly be continued.

And that's the prediction before considering the effects of climate change. With rising temperatures, a bad situation will become still worse. All sectors increase their water use as temperatures climb, but none more than agriculture. Even with mild climate change – now considered a certainty by the scientific community – farmers will need more water to produce crops and livestock. With the more serious temperature increases likely to result from current trends in world greenhouse gas emissions, demand for agricultural water will clash with other uses.

Climate change will lead to degraded conditions in other areas as well. In Southwestern forests, hotter, drier conditions are already leading to worsening wildfires and pest outbreaks. In California, under a scenario of "business-as-usual" emissions (A2), wildfires could increase by 100 percent or more by the end of this century (California Natural Resources Agency 2009). A study of eleven Western states found strong correlations between high temperatures, low precipitation, and wildfires (McKenzie et al. 2004). Even under the milder B2 climate scenario, that study found that by late in this century, the mean area burned by wildfires could increase by a factor of 1.4 to 5 in most states, with the largest increases in Utah and New Mexico.

A warmer climate also gives an advantage to plant pests and pathogens, which can be as devastating to forests as wildfires. Rising temperatures increase insect survival rates, accelerate their development, allow them to expand their range, and reduce trees' capacity to resist attack (Bentz 2008). In 2003, after prolonged drought and heat, more than 10 million acres of forests in the U.S. West were ravaged by bark beetles (USDA Forest Service 2004).

Other species will be harmed as well. Climate change will result in warmer freshwater temperatures and changes in seasonal stream flows, which are projected to cause sharp reductions in salmon populations and increased risks of extinction of some subpopulations; this is an important issue for northern California (Yates et al. 2008) as well as the Northwest.

Despite air conditioning and other forms of protection, human beings are not immune to rising temperatures. The California heat wave of July 2006 caused hundreds of deaths and thousands of hospitalizations and emergency room visits (Ostro et al. 2009; Knowlton et al. 2009). Rising temperatures are projected to increase the frequency of similar or worse heat waves in California (Cayan et al. 2009). In addition, climate change may worsen regional air quality in the summer and fall, a problem for both human health and agriculture (Leung and Gustafson 2005).

Water-dependent economic sectors in general may fare badly as temperatures rise and – according to at least some climate projections – the Southwest sees less precipitation on average. Two sectors dominate freshwater use in the Southwest: together, urban uses (residential and commercial users) and agriculture account for all but 2 percent of the region's water. Numerous studies have analyzed the impact of climate on Southwest water, but most focus on broad climate trends, or on detailed results for small areas or individual economic sectors. The new research presented in this report focuses instead on seeing the whole picture: the effects of climate change on water supply, demand, and scarcity for all major water uses, in each state and in the Southwest as a whole.

The water and climate crisis

A great deal is already known about water and climate change in the Southwest. For our purposes, the following are some of the most important findings:

- Climate change will worsen the region's water crisis even if, as some models predict, there is no change in total annual precipitation.
- Agriculture in the Southwest is almost completely dependent on irrigation; the greatest climate risk to agriculture is not the direct effect of temperature or precipitation on crops, but the potential lack of water for irrigation.
- Published estimates of the costs of climate impacts on water resources are in the tens of billions of dollars annually for the United States as a whole, or about $1 billion each for California and for the Colorado River basin.

Future water supplies

Climate change is already causing measurable and unfortunate impacts on water supplies. The mountain regions of the West are experiencing reduced snowpack, warmer winters, and stream flows coming earlier in the calendar year. Since the mid-1980s, these trends have been outside the past range of natural variation, but consistent with the expected effects of anthropogenic (human-caused) climate change (Barnett et al. 2008). In the past, snowmelt gradually released the previous winter's precipitation, with significant flows in the summer when demand is highest. The recent climate-related shift means that water arrives, in large volume, earlier in the year than it is needed. As a review of this problem observes,

> There is not enough reservoir storage capacity over most of the West to handle this shift in maximum runoff and so most of the 'early water' will be passed on to the oceans. (Barnett et al. 2005, p. 305)

California's water supply is critically dependent on the extent of snowpack and timing of snowmelt in the Sierra Nevada. Total annual precipitation in the state may remain roughly unchanged as the climate continues to change – but warmer winter temperatures will cause earlier snowmelt, and will transform some winter precipitation from snow to rain. This will shift streamflow toward the winter and spring months, moving peak water flows earlier by as much as a month. Climate models show that higher greenhouse gas emissions under the IPCC's A2 scenario, compared to the lower-emission B1 scenario, will worsen all of these trends (Maurer 2007). California's biannual assessments of climate change explore these and related climate trends (e.g. Cayan et al. 2009), drawing on detailed studies of watersheds and regions within the state (e.g. Purkey et al. 2008 on the Sacramento River Basin).

For the Colorado River, the principal source of surface water for the interior states of the Southwest and parts of southern California, the impacts of climate change will be even more severe, likely including a decline in runoff and streamflow throughout the river basin (Christensen and Lettenmaier 2007).While there is large year-to-year variation in river flows, the average is expected to decline; climate change is likely to cause larger and more frequent shortfalls in scheduled water deliveries, with shortfalls occurring in most years by 2050 (Barnett and Pierce 2009).

Climate, agriculture, and irrigation

In the past, many analysts believed that the early stages of climate change would be good for U.S. agriculture, thanks to the fertilization effect of increased CO_2 concentrations and the benefit of longer growing seasons in colder regions (U.S. Global Change Research Program 2000). Recent research, however, has led to sharply reduced estimates of the benefits of carbon dioxide fertilization (Leakey et al. 2009; Long et al. 2006; Cline 2007).

Studies of California agriculture and climate change have reached ambiguous conclusions – as long as water for irrigation is assumed to remain abundant. One study projects an increase in California farm profits due to climate change, with gains for some crops and losses for others, assuming that current policies, and the availability of irrigation, are unchanged (Costello et al. 2009). Perennial crops such as fruits and nuts are of great importance in California; individual crops differ widely in the impacts of climate on yields (Lobell et al. 2007). Among six leading California perennial crops, climate change through 2050 is projected to decrease yields in four cases, and to cause no significant change in the other two – again, assuming that irrigation remains unchanged (Lobell et al. 2006).

In contrast, a study of climate and California agriculture that focuses on the growing scarcity of water projects a drop in irrigated acreage and a shift toward higher-value, less water-intensive crops (Howitt et al. 2009). An analysis of potential water scarcity in California due to climate change estimates that there will be substantial costs in dry years, in the form of higher prices and/or shortfalls, to Central Valley agriculture and to South Coast urban areas (Hanemann et al. 2006).

Economic analysis has shown that the value of California farmland is closely linked to the amount of available irrigation water, but not to temperature or precipitation (Schlenker et al. 2007). It is often suggested that climate change will increase irrigation requirements, since dry areas of the world will generally tend to become even drier (Tubiello et al. 2007). On the other hand, a study of climate change and irrigation in California's San Joaquin Valley concluded that the early stages of climate change could lead to roughly constant irrigation requirements in that region, since higher temperatures mean crops will need more water per day, but also that they will grow to maturity in fewer days (Hopmans and Maurer 2008).

Increased costs for water[1]

A handful of studies have estimated the costs of climate-induced changes in water supply at a national level (Cline 1992; Titus 1992; Fankhauser 1995; Hurd et al. 1999; Hurd et al. 2004; Backus et al. 2010). While taking very different approaches to the question, they have come up with broadly similar answers: by the middle of this century, climate change will increase the annual costs of water supply by $7 billion to $60 billion, or 0.1 to 0.9 percent of U.S. GDP in the year when the study was conducted.

A study of the impact of climate change on California water users, based on a relatively dry climate scenario, projects water shortfalls of 17 percent of demand by mid-century (Medellín-Azuara et al. 2008). On average, water deliveries to agriculture will fall by 24 percent, and to urban users by 1 percent. The annual costs of climate-related water scarcity could amount to $1 billion, including $300 million of lost agricultural production.

For the Colorado River basin, an already arid region where climate change may cause a decrease in precipitation, runoff, and streamflow, water shortages will become routine and energy production may be cut by 18 percent by the 2080s (Christensen and Lettenmaier 2007). Differing climate scenarios imply annual losses to the river basin of $1.2 billion to $1.4 billion (Hurd et al. 1999) – similar to the estimate for California, but representing a larger burden on a smaller economy.

The Southwest as a whole

The goal of this analysis is to understand the impacts of climate change on the water problems of the Southwest as a whole. It differs from other studies in three fundamental respects.

First, our analysis is carried out at a mid-level of complexity and detail, focusing on state-level interactions of water supply and demand, and, for water use and agriculture, on county-level data. This provides more depth of insight into the problem than sweeping regional generalizations; it may also provide a better overview than extremely detailed studies of local areas. The wealth of data now available in geographic information systems (GIS) databases, combined with downscaled forecasts from major climate models, has allowed a proliferation of local studies relevant to water and climate change. Yet the mass of detail can draw attention to the individual trees rather than the forest; GIS analyses can include data for thousands of distinct locations within a state. County-level data represents California as 58 "points" on the map – more accurate than using one or two points for the entire state, and more comprehensible than using thousands.

Second, we ignore the numerous legal and physical obstacles to the distribution of water within states. The laws governing water rights in the Southwest are byzantine in their complexity, and allow some low-value uses of water to continue while others would gladly pay much higher prices for the same water, if it were available for purchase. The physical barriers of long distances and mountainous terrain often block transportation of water within a state, although

[1] This section is based on the helpful summary in Hurd and Rouhi-Rad (2011).

elaborate canals and aqueducts do move large amounts of water from northern to southern California, and from the Colorado River to the much higher elevation of central Arizona. The analysis in this report makes the (obviously unrealistic) simplifying assumption that all water can be freely transported anywhere within a state. Thus the balance between water supply and demand presented here is unrealistically optimistic: it is the balance that would exist if all legal and physical obstacles to intrastate water transport could be removed. It is all the more sobering to realize that, even on that optimistic basis, there is a vast potential shortfall in the region's future water supplies.

Third, we extend the analysis into the future, to cover a full century of climate change and water use. It is understandably common for discussion to be restricted to shorter time horizons, such as 2050. The limited attention spans and compressed electoral cycles of the political process impose a bias toward the very short run in policy debate. The year 2050, after all, is many elections and administrations from now; for many purposes, it *is* the long run. Yet the dynamics of climate change require a look at the even longer run. The earth's climate has immense inertia, and changes only gradually; the impacts of climate change over the next 20 years are virtually fixed, determined almost entirely by the past history of greenhouse gas emissions. To see the difference between a high-emission and a low-emission climate scenario – that is, to understand the difference that climate policy can make in the world that we will leave to our descendants – it is necessary to look well past mid-century.

This report presents the results of three intersecting models of water and climate change in the Southwest, all newly developed with funding from the Kresge Foundation. Two separate background papers describe these models and their full results in detail. The first (Stanton and Fitzgerald 2011) describes two models designed by the Stockholm Environment Institute – U.S. Center: a detailed depiction of California's supply and demand of water; and a model of water used in agriculture in the five-state region, with results for each state. These models are built on county-level climate projections, water modeling and agricultural data. The second (Fisher and Ackerman 2011) discusses a model, designed by Synapse Energy Economics Inc. in consultation with SEI-U.S., of water used in electricity generation throughout the Western states. All three models estimate water use and/or constraints under baseline conditions as well as under two projections of climate change over the next 100 years.

These models, together with additional projections of future water use for Arizona, Nevada, New Mexico and Utah, show water demand outstripping water supply in the near future – implying an unsustainable drawdown of groundwater that could dry up wells long before the end of the century. Recall that this result is obtained under the simplifying assumption that, within each state, freshwater can be transported anywhere without cost or delay. The results presented in this report, therefore, represent a "best case" with regard to the real-world difficulties of water distribution. In fact, geography, infrastructure limitations, and an intricate web of water rights mean that water cannot be transported everywhere and anywhere within a state's boundaries. Even with a very optimistic view of the potential for improvements in water distribution over the next century, water transportation will continue to be costly and constrained.

Because climate projections disagree about the future of Southwest precipitation, all three models incorporate the conservative assumption that average annual precipitation will remain constant; replacing this assumption with a decrease in average precipitation over time would, of course, tend to exacerbate the water crisis. The county-level modeling results – not shown in this report – that are the base unit of this analysis reveal far greater disparities than do state-level results; aggregation across states promotes this study's goal of seeing the forest for the trees, but disguises areas of extremes where the climate and water crisis looms even larger.

2. To the Last Drop: Unsustainable Water Mining

More than a third of all freshwater used in the Southwest comes from groundwater reserves; in Arizona and New Mexico, half the water is pumped from under the ground. In the five Southwest states, 19 million acre feet (6 trillion gallons) of groundwater are used every year (see Table 1).

Stocks of groundwater are refreshed very slowly – far more slowly than today's rates of extraction. How much groundwater is available, and how long can this pace of groundwater pumping continue? Very little precise information exists to estimate the amount of water stored underneath the Southwest. California – with the most detailed water systems analysis in the region – says repeatedly in its publications that a "comprehensive assessment" of the state's groundwater basins has not been conducted since 1980.[2] Estimates from just two states, California and Arizona, suggest that groundwater use exceeds the renewable level by at least 2.6 million acre feet per year; the true regional tally of unsustainable groundwater use may be much larger.

Table 1: Southwest groundwater extraction, 2005

	Southwest	Arizona	California	Nevada	New Mexico	Utah
Total water use (MAF)	55.6	7.0	36.8	2.7	3.7	5.4
Total groundwater use (MAF)	19.4	3.4	12.0	1.1	1.9	1.0
Groundwater as a share of total use	35%	49%	33%	41%	50%	18%

Source: U.S. Geological Survey (2009), http://water.usgs.gov/watuse/data/2005/.

Table 2: Colorado River use rights, 2005

	Southwest	Arizona	California	Nevada	New Mexico	Utah
Colorado River use rights (MAF)	10.1	2.9	4.4	0.3	0.9	1.7
Use rights as a share of total use	18%	41%	12%	11%	23%	31%

Source: Southern Nevada Water Authority (n.d.), http://www.snwa.com/html/wr_colrvr_apportion.html; U.S. Geological Survey (2009).

Rights to Colorado River water account for another 18 percent of these states' water use, although the actual amount withdrawn varies in any given year (see Table 2).[3] In Arizona, Colorado River water makes up two-fifths of the supply. Negotiators of the 1922 "Colorado River Compact" estimated the river's average annual flow to be 17 million acre feet, but more

[2] California Department of Water Resources (2009), http://www.waterplan.water.ca.gov/docs/cwpu2009/.
[3] Southern Nevada Water Authority (2009).

recent estimates of the long-range average Colorado River flow range from 9.1 to 14.3 million acre feet annually (Woodhouse et al. 2006). Rights to Colorado River withdrawals from the five Southwest states together with Colorado, Wyoming, and annual deliveries to Mexico total 16.5 million acre feet per year. Reservoirs along the Colorado River are gradually being sucked dry by annual withdrawals that are not being replaced by rainfall.

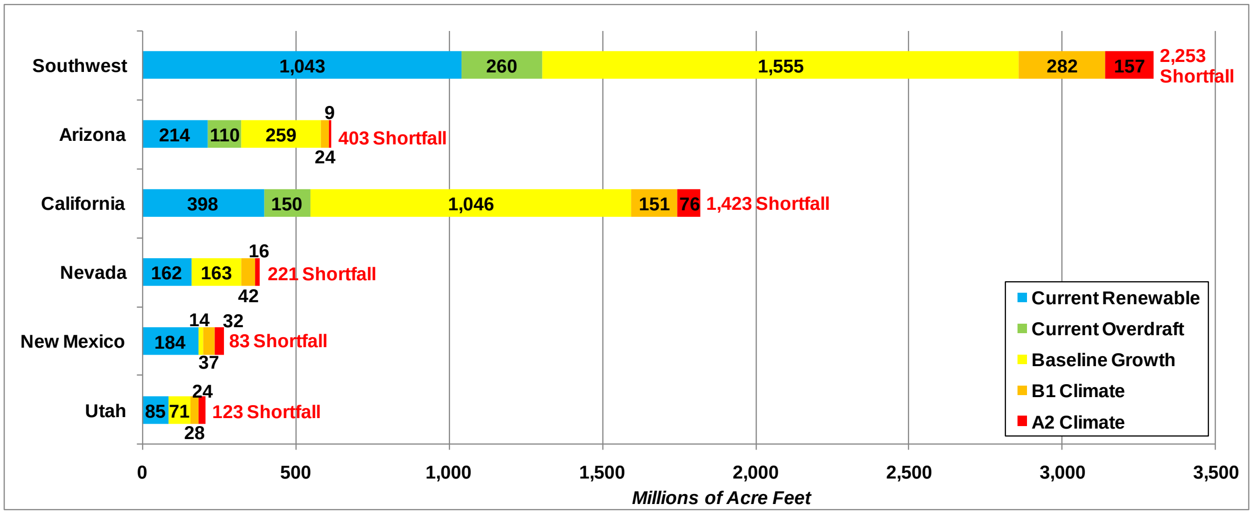
Tables 1 and 2 together show that groundwater plus Colorado River water rights account for more than half of the region's water use, rising to nearly three-quarters in New Mexico and nine-tenths in Arizona. Both of these major sources of water are being used beyond the sustainable level. Surface water is already used fully throughout the region, though there is some room for improvements in efficiency (such as reducing water delivery losses). Population and income growth are expected to increase Southwest water use dramatically over the next 100 years. And climate change will deepen the crisis, as hotter temperatures lead to greater withdrawals, particularly for agriculture.

More water can be extracted from underground stocks, but these reservoirs are finite and are already shrinking every year. Current groundwater extraction can be divided into two parts: renewable use and overdraft. Groundwater is renewable up to the level of "recharge" – precipitation that percolates in through the soil. Overdraft, or the net reduction in groundwater storage, is groundwater extracted over and above average annual recharge rates. Two states – Arizona and California – estimate that their current use of groundwater exceeds the annual rate of recharge (by 1.1 and 1.5 million acre feet, respectively); the same is likely true of New Mexico, although no estimate exists of this state's rate of overuse. Nevada and Utah attest that their current groundwater use matches the rate of recharge.[4]

Figure 1 forecasts the Southwest's future water use under three scenarios: first, with current temperatures and current trends of population and income growth (called "baseline growth"), and then adding (on top of baseline growth) increased temperatures due to mild (B1) and more severe (A2) assumptions about climate change. The total "shortfall" labeled in this figure is the current rate of overdraft extended for 100 years combined with increases to water use from population growth, income growth, and the more severe (A2) scenario for climate change.

[4] Arizona Department of Water Resources (2010); California Department of Water Resources (n.d.); Ivahnenko and Flynn (2010); Southern Nevada Water Authority (2009); New Mexico Office of the State Engineer (2009); Longworth et al. (2008); Utah Division of Water Resources (2001– note that Utah's water supply, as defined by the state, is reduced here by the 4.69 MAF used for environmental purposes); Wyoming Water Development Commission (2007; n.d.).

Figure 1: Southwestern States' Projected Groundwater Extraction, 2010 to 2110



Note: Shortfall = sum of all groundwater use, beyond the renewable (blue) level, under A2 climate assumptions. Source: Authors' calculations. For California, Stanton and Fitzgerald (2011).

At today's rates of water use, the Southwest is projected to use 1,303 million acre feet of groundwater in the 100 years starting in 2010 (the blue plus green segments of the top bar in Figure 1); of this a conservatively estimated 260 million acre feet would be overdraft (shown in green). Taking into consideration only baseline growth of population and income, the Southwest's shortfall of water (today's overdraft plus additional water needed beyond today's annual rates, or green plus yellow in Figure 1) reaches 1,815 million acre feet over the 100-year period. Using the B1 climate assumptions – the least climate change that is still thought to be possible – the Southwest's shortfall grows to 2,096 million acre feet (green, yellow, and orange). Under the A2 climate assumptions – the temperature increase expected if the current trend in global greenhouse gas emissions continues – the shortfall reaches 2,253 million acre feet (adding the red segment). This shortfall must be met either from increases to supply (perhaps the most difficult and most expensive options as discussed below), additional groundwater withdrawals, or reductions to use – planned or unplanned.

3. California: A Case Study of Unsustainable Water Use

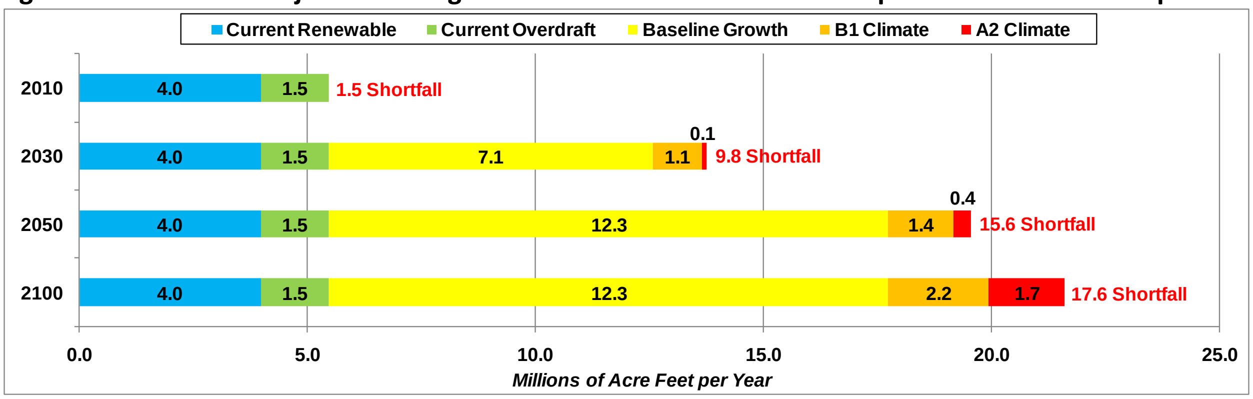
More than half of the region's current and projected groundwater withdrawals take place in California. At today's climate and rates of water use, the state's groundwater withdrawals would average 5.5 million acre feet per year over the next century.[5] California's Department of Water Resources (CADWR) estimates that the overdraft averages 1.5 million acre feet per year (or 150 million acre feet over 100 years).[6] The difference between the two is the portion of groundwater extraction that is renewable – so if CADWR's estimates are correct, most of California's groundwater use is replaced via recharge. A 2009 study by NASA, however, calls the CADWR estimates into question and suggests that 4.4 million acre feet are overdrawn from California

[5] Results of the CSWD model (Stanton and Fitzgerald 2011).
[6] California Department of Water Resources (2009).

every year.[7] NASA's higher overdraft estimates suggest that 100 years of water use at California's current levels would very nearly exhaust California's 450 million acre feet in estimated stored groundwater reserves.[8]

But California's water use is not projected to hold steady – far from it. Figure 2 shows a conservatively estimated annual shortfall (green plus yellow) of 1.5 million acre feet growing to 8.6 by 2030, and 13.8 by 2050, before accounting for climate change. Under B1 climate assumptions (adding orange), California's annual shortfall grows to 9.7 million acre feet per year in 2030, 15.2 in 2050, and 16.0 in 2100. Using A2 climate assumptions (adding red), the annual shortfall reaches 9.8 million acre feet per year in 2030, 15.6 million in 2050, and 17.6 million in 2100.

Figure 2: California's Projected Average Annual Groundwater Extraction plus Shortfall – No Adaptation

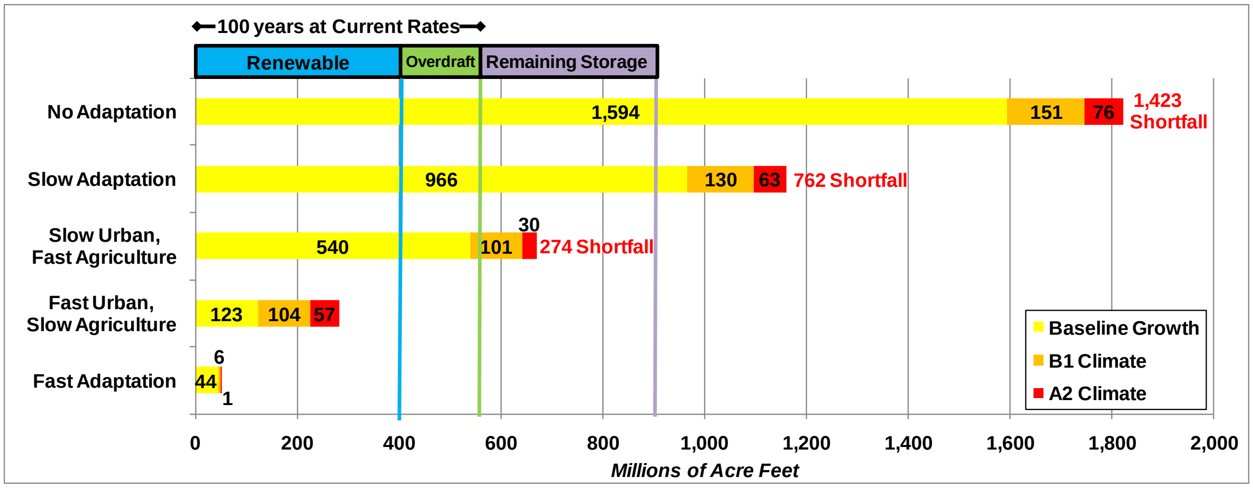


Source: CSWD model results (Stanton and Fitzgerald 2011).

Over the next 100 years, given today's rates of water use, and projections of population and income growth and future climate change, California will need 1,423 million acre feet more groundwater than can be renewed through recharge, and 973 million acre feet more than is thought to be available in groundwater reserves (see Figure 3). Put another way, unless some adaptation measures are taken to reduce the rate of water use, California's groundwater demands over the next century will be three times as large as its groundwater supply. And environmental damages from over-extraction of groundwater should be a large economic and cultural disincentive to continued overdraft, long before supplies literally run out (Zektser et al. 2004).

[7] NASA Jet Propulsion Laboratory (2009); Gleick (2009).
[8] California Department of Water Resources (1994).

Figure 3: California's Projected Groundwater Extraction plus Shortfall, 2010 to 2110



Note: Baseline growth (yellow) now includes renewable and overdraft (shown as blue and green in earlier figures). Shortfall is total water use, under A2 climate assumptions, minus renewable (blue line).
Source: CSWD model results (Stanton and Fitzgerald 2011).

Using the optimistic CADWR estimates of its groundwater stock, California can supply a cumulative total of 450 million acre feet beyond the renewable level. The actual projected shortfall for 2010 through 2110 is 1,196 million acre feet before taking climate change into account. At the mildest changes in climate that are still thought possible (B1), the 100-year shortfall reaches 1,347 million acre feet; using more severe, but by no means worst-case, climate projections (A2), this figure climbs to 1,423 million acre feet. That is, climate change does not create the problem, but it does make the water crisis harder to solve. With no adaptation, the cumulative impact of a century of climate change (A2 versus baseline) would – by itself – use up half of California's groundwater reserves.

Planned conservation and efficiency improvements are essential to avoiding unplanned water deficits and water use restrictions. Unless adaptation measures are taken to reduce California's water use, 7 out of 10 years will require water restrictions or additional (above current levels) overdraft by 2030 (under baseline, B1, or A2 scenarios) and every year will have a water shortfall by 2050.[9]

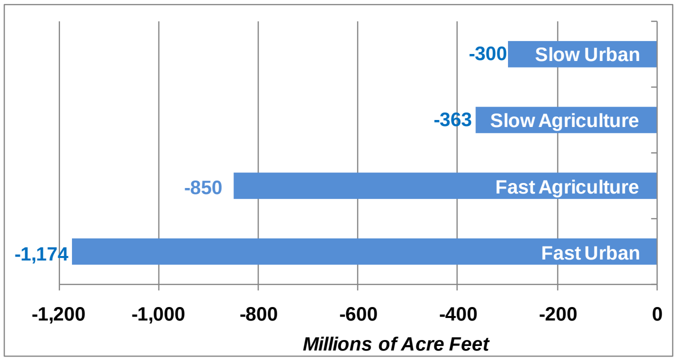
The Pacific Institute has modeled several adaptation scenarios for California's urban and agriculture water use; two such scenarios are discussed here as "slow" and "fast" adaptation.[10] Slow urban adaptation includes 10-percent reductions in water use from conservation and 5-percent reductions from efficiency measures, as well as consumers' response to a 20-percent increase in water prices by 2030. Slow agricultural adaptation includes 5-percent reductions in water use and growers' response to a 10-percent increase in water prices by 2030. The combination of slow urban (300 million acre feet reduction in water use, see Figure 4) and slow

[9] CSWD model results (Stanton and Fitzgerald 2011).

[10] The "slow adaptation" scenario follows the Pacific Institute's "current trends" scenario as calculated for the California Department of Water Resources (Groves et al. 2005), while the "fast adaptation" scenario follows the "high efficiency" scenario laid out in a subsequent report (Gleick et al. 2005). Our model extends the Pacific Institute's analysis to 2110 by continuing annual growth trends constant to 2050 and then keeping all annual values constant at 2050 levels.

agricultural adaptation (363 million acre feet) is not enough to bring California's shortfall down below the optimistic estimates of total groundwater storage. Even with both slow adaptation measures in effect, California would still experience a 762 million acre feet shortfall over the next 100 years.

Figure 4: California's Projected Adaptation Potential, 2010 to 2110



Source: CSWD model results (Stanton and Fitzgerald 2011).

Fast urban adaptation includes 39-percent total conservation and efficiency reductions in residential interior and commercial, industrial, and institutional water use, 33-percent reductions in residential exterior use, and consumers' response to a 41-percent increase in water prices. Fast agricultural adaptation includes 16- to 41-percent reductions in water use, depending on the crop, and growers' response to a 68-percent increase in water prices by 2030.[11]

As shown in Figure 4, either fast urban plus slow agricultural adaptation or slow urban plus fast agricultural adaptation is enough to shrink California's water shortfall to an amount that could be met from assumed current groundwater stocks. To bring California' groundwater use down to renewable levels, and even start to build up groundwater stocks over time, would require fast urban plus either slow or fast agricultural adaptation. Fast urban and fast agricultural adaptation combined would achieve a reduction of 1,770 million acre feet.

4. Southwest Water Use: Farms and Homes

All five Southwestern states use the majority of their freshwater for farming. One-fifth of agriculture's contribution to U.S. gross domestic product (GDP) comes from the Southwest – 16.4 percent from California and 3.3 percent from the other four states. California has the largest agricultural sector of any state, $17 billion; Texas is a distant second at $7 billion.[12] The Southwest is an important part of U.S. agriculture, but the sector is a very small part of the U.S. economy.

Farming made up just 0.8 percent of U.S. GDP in 2005. There is a wide range in the importance of agriculture among states, from 5 to 7 percent of GDP in South Dakota, North Dakota and

[11] The fast urban and agricultural scenarios also assume a greater responsiveness of consumers and growers to price changes (Gleick et al. 2005).
[12] Bureau of Economic Analysis (n.d.), using 2005 data.

Nebraska, down to less than 0.1 percent in New Jersey, Alaska, Rhode Island, Massachusetts, and the District of Columbia. In the Southwest, agriculture's contribution to GDP ranges from 1.6 percent in New Mexico down to 0.2 percent in Nevada. Overall, agriculture accounts for just 1 percent of Southwest GDP.

And yet nearly four-fifths of the Southwest's water is used for agriculture. Another fifth goes to homes and commercial businesses (grouped together here as "urban" uses), and less than one percent goes to each of the electricity generation, mining and industrial sectors (see Table 3).

Table 3: Southwest water use by sector, 2005

	Southwest	Arizona	California	Nevada	New Mexico	Utah
Irrigation and livestock	78%	77%	77%	64%	87%	85%
Urban	21%	19%	23%	30%	10%	13%
Industrial	0%	0%	0%	0%	0%	1%
Power	1%	1%	0%	2%	2%	1%
Mining	1%	2%	0%	4%	2%	0%

Source: U.S. Geological Survey (2009).

Many Southwest agricultural products are very profitable, and some (such as certain nuts and fruits) make an important contribution to total world supply. Other products of the region's agriculture are much less profitable. One useful measure of the value of each crop, in a water-scarce environment, is the value of farm revenues per acre foot of water. Cutting back on the least valuable crops (per unit of water) would have little impact on U.S. or world agricultural markets, but a big impact in balancing water use with water supply in the Southwest.

A surprising share of Southwest agricultural water is used to grow hay: from 29 percent in California, to 94 percent in Utah. The main use of hay is to feed cattle, an important part of the region's agriculture. But the share of agricultural water going to hay, 42 percent, is greater than the share of dairy and cattle in the value of Southwestern agriculture, 31 percent (see Table 4).

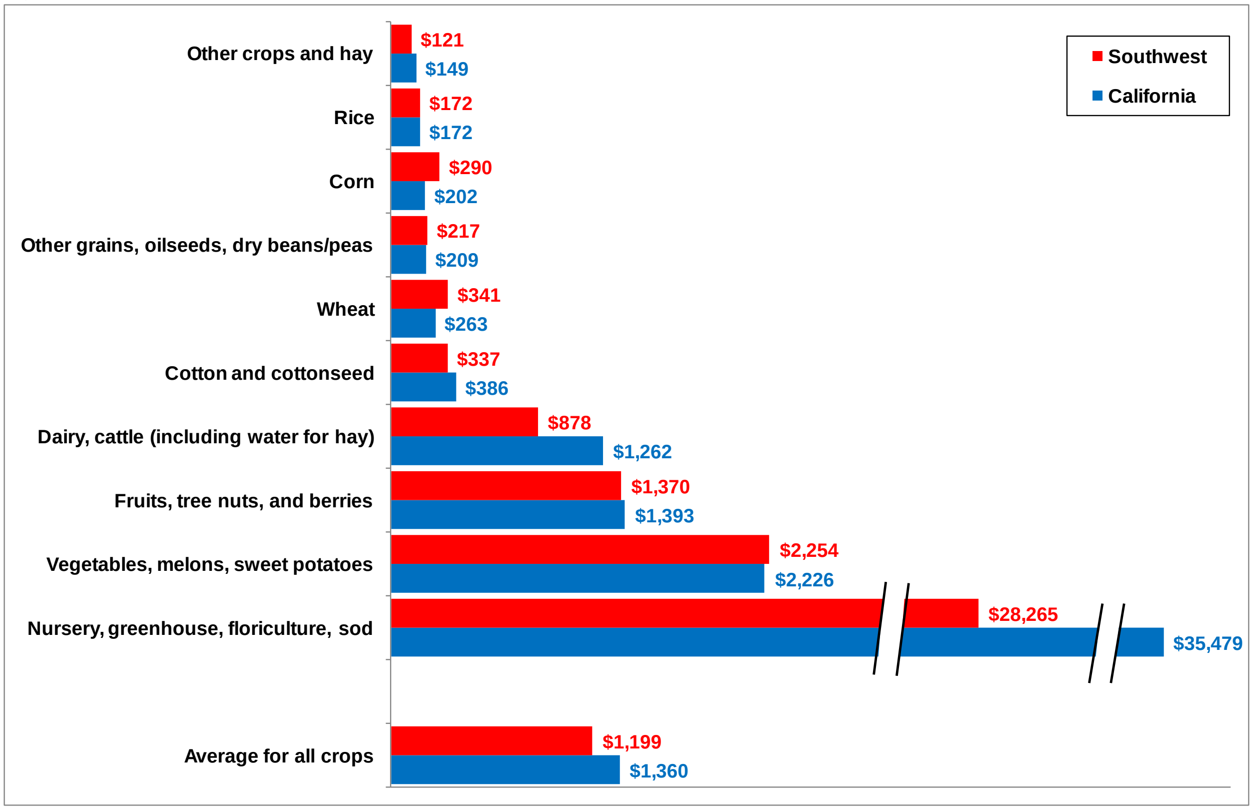
Table 4: Current agriculture water use and value

	Southwest	Arizona	California	Nevada	New Mexico	Utah
Total agricultural water use (MAF)	34.3	2.9	24.9	1.9	1.8	2.8
Hay's share of water use	42%	54%	29%	97%	76%	94%
Value of agricultural sales (billions)	$41.1	$3.2	$33.9	$0.5	$2.2	$1.4
Dairy and cattle's share of sales	31%	39%	27%	55%	74%	45%

Source: National Agriculture Statistics Service (2009), http://www.agcensus.usda.gov; and authors' calculations.

More than four-fifths of the value of Southwest agricultural production comes from California, and today California uses 74 percent of all Southwest agricultural water. In all Southwestern states, hay is the crop with the lowest value per acre foot of water, $149 in California (see Figure 5). Because most hay is sold locally to nearby dairies and cattle ranches, it might be more appropriate to combine these sectors, looking at the average sales of dairy and cattle farming compared to the water used for both cattle and hay. When water used for hay is considered as an input into the dairy and cattle industry, the value of dairy and cattle products for California rises to $1,262 per acre foot, while the regional average is $878.

Figure 5: Value of crops per acre foot of water, California and Southwest average



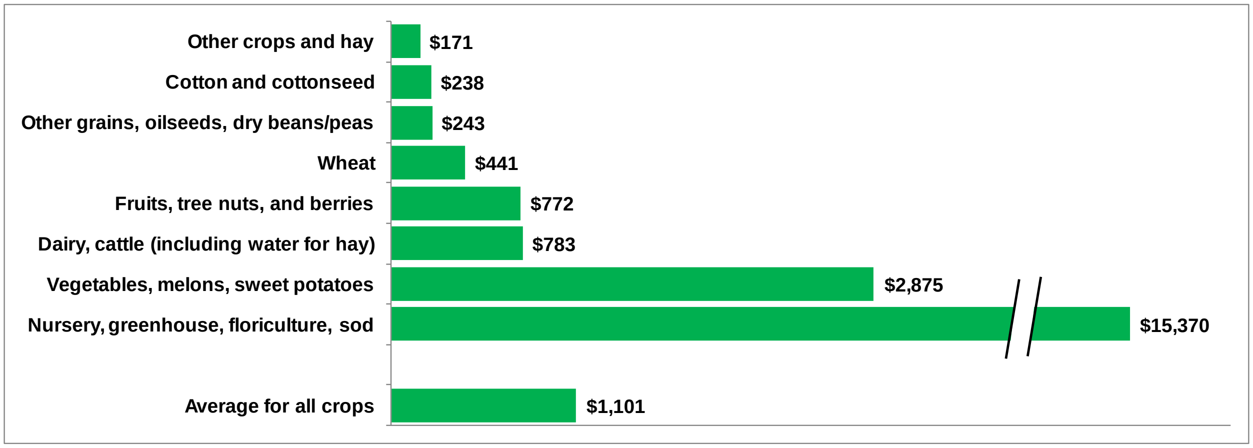
Source: CSWD model results (Stanton and Fitzgerald 2011).

Dairy and cattle account for only 27 percent of agricultural sales in California, and three other categories of crops are more valuable, greenhouse and nursery ($35,479 per acre foot – the most valuable category anywhere in the Southwest); vegetables and melons ($2,226); and fruit and nuts ($1,393).

Arizona's current annual groundwater overdraft per person is more than four times that of California, and half of this state's water demand is met from groundwater, compared with one-third in California. Arizona is also far more dependent on Colorado River use rights (41 percent of all water use) than California (12 percent), and the extraction of this resource simply cannot continue at the current rate – annual withdrawals are greater than average annual flow, and Colorado River reservoirs are shrinking. In both states, 77 percent of water is used for agriculture and most of the remainder in the urban sector.

In Arizona – where 54 percent of agricultural water is used to grow hay – this crop alone is worth $171 per acre foot of water, higher than in the other Southwest states, but lower than other crops grown in Arizona: greenhouse and nursery crops earn sales of $15,370 per acre foot in the state, and vegetables and melons earn $2,875 per acre foot (see Figure 6). In Arizona, dairy and cattle farming is worth $783 per acre foot of water (including water for hay), close to the regional average of $878 per acre foot.

Figure 6: Value of crops per acre foot of water, Arizona



Source: CSWD model results (Stanton and Fitzgerald 2011).

According to state reports, Nevada currently uses groundwater at exactly the renewable rate. Future growth in population and income, along with the higher temperatures caused by climate change, will quickly push Nevada's water use into shortfall. Nevada is projected to have the fastest population growth of all five states, 2.6 percent each year in the next few decades, compared with 1.3 percent in the region as a whole.

Among Southwest states, Nevada uses the greatest share of its water in the urban sector (30 percent) and has the highest per capita domestic (including both inside and outside of residences) water use. Indeed, Nevadans use more water per capita than anyone else in the United States, 190 gallons per person per day (see Table 5). New Mexico uses the least domestic water per capita in the Southwest and ranks 16th in the United States. (Nationally, Maine uses the least domestic water per person, at 54 gallons per day.[13])

Table 5: Southwest per capita water us, total and domestic, 2005

	Southwest	Arizona	California	Nevada	New Mexico	Utah
Total water use (gallons/person/day)	1,014	1,051	909	985	1,728	1,893
Domestic water use (gallons/person/day)	132	140	124	190	107	186

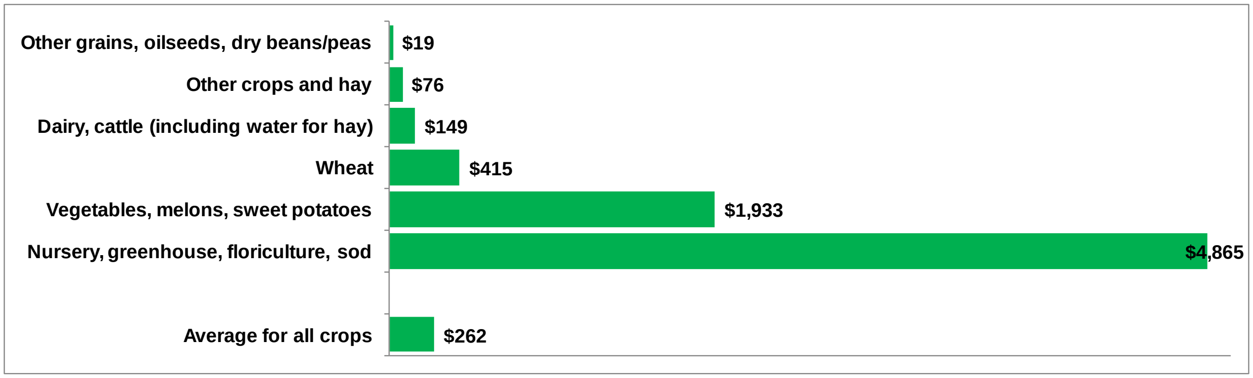
Source: U.S. Geological Survey (2009).

By 2110, urban use is expected to more than double in the Southwest, while agricultural use, even in the A2 climate scenario, grows by 17 percent; this means that if current trends continue, 100 years from now, urban water use will account for almost one-third of total use. That is, urban use will become as important in the region as a whole as it is in Nevada today. To reduce future shortfalls and restrictions, reductions to water use must take place in homes, businesses, and farms.

[13] U.S. Geological Survey (2009).

Still, two-thirds of Nevada's water currently goes to the agricultural sector, and 97 percent of that water is used to grow hay. The value per acre foot of water of Nevada's hay is just $76 per acre foot (see Figure 7). Even the value per acre foot of dairy and cattle is low in Nevada, at $149. Other crops grown in the state are far more valuable: greenhouse and nursery crops, $4,865 per acre foot; vegetables and melons, $1,933; and wheat, $415. Nonetheless, the dairy industry accounts for more than half (55 percent) of total agricultural sales in Nevada.

Figure 7: Value of crops per acre foot of water, Nevada

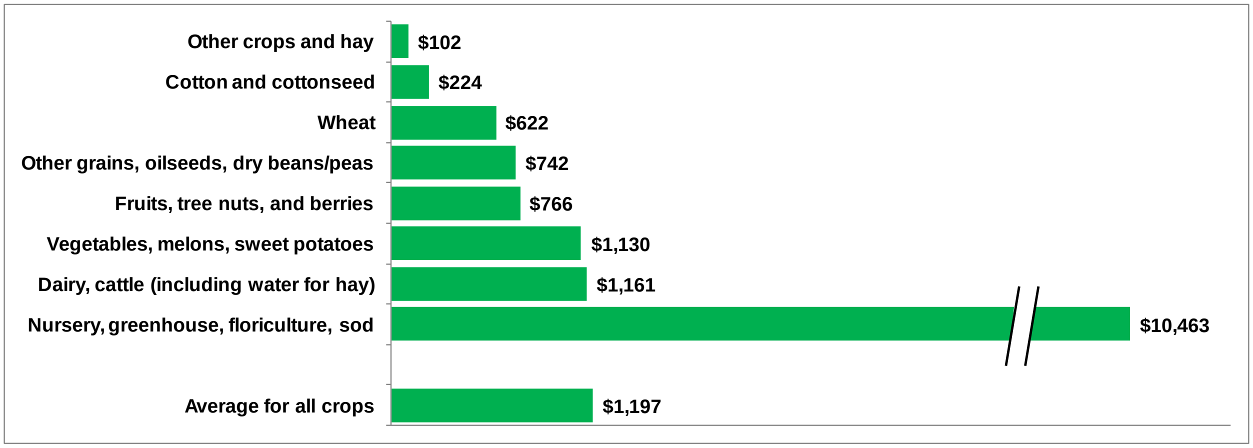


Source: CSWD model results (Stanton and Fitzgerald 2011).

Half of New Mexico's water needs are met by groundwater, and little is known about the current annual overdraft or the size of the state's underground water reserves. Nearly nine-tenths of the state's water is used for agriculture; the remaining tenth goes to the urban sector, where domestic water use per capita is the lowest among the Southwestern states.

Three-quarters of New Mexico's agricultural water is used to grow hay, with sales of $102 per acre foot of water (see Figure 8), and dairy and cattle account for three-quarters of the state's agricultural value, by far the greatest share among the five states. New Mexico, however, has high dairy and cattle sales, $1,161 per acre foot of water, including water for hay – higher than the state's vegetables and melons ($1,130 per acre foot) but still much lower than greenhouse and nursery production ($10,463).

Figure 8: Value of crops per acre foot of water, New Mexico

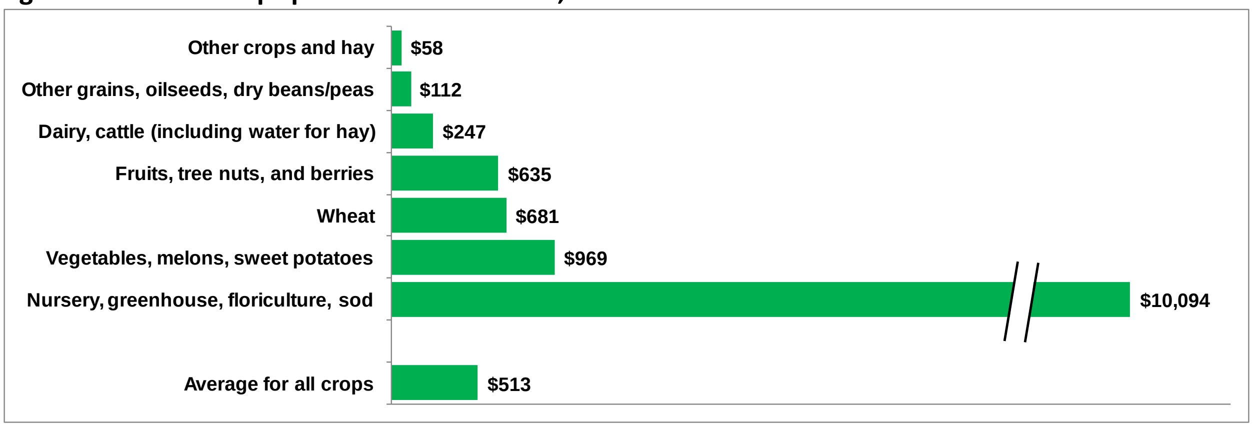


Source: CSWD model results (Stanton and Fitzgerald 2011).

As in Nevada, reports from the State of Utah indicate that groundwater is currently being used at exactly the renewable rate. Utah relies on the smallest share of groundwater to meet demands in the Southwest, just 18 percent. The state ranks second only to Arizona, however, in its reliance on Colorado River water, which supplies 31 percent of Utah's water needs. Utah uses more domestic water per capita than any state but Nevada (185 gallons per person per day), and a greater share of agricultural water than any state but New Mexico (85 percent).

Growing hay takes up 94 percent of the state's agricultural water while earning the lowest value in the Southwest, $58 per acre foot (see Figure 9). The value of Utah's dairy and cattle is $247 per acre foot, lower than fruit and tree nuts ($635 per acre foot); wheat ($681); vegetables and melons ($969); and greenhouse and nursery production ($10,094).

Figure 9: Value of crops per acre foot of water, Utah



Source: CSWD model results (Stanton and Fitzgerald 2011).

5. Solutions: How to Make a Big Enough Difference

The growing difference between water supply and demand in the Southwest can be addressed only in one of the following ways:

Solution #1: Increases to supply from desalination or water imports.

Solution #2: Additional groundwater extraction (above current annual rates of extraction).

Solution #3: Reductions in water use, through planned conservation and efficiency measures.

Solution #4: Reductions in water use, through unplanned shortfalls requiring water use limitations in certain years.

Each approach is discussed in detail below. The first two are not viable long-term solutions for the Southwest, and the fourth would cause regrettable – and avoidable – hardship. Only the third solution, planned conservation and efficiency measures in the urban and agricultural sectors, has the potential to solve the Southwest's water crisis, even in the face of severe climate change.

Solution #1: Increase the water supply

If enough water could be produced or imported, it would be possible to solve the regional water crisis by increasing supply. This solution is thwarted in practice by the high economic and environmental costs of producing fresh water, and the very limited availability of imports.

Desalination of ocean water could in theory provide an inexhaustible option for increasing the supply of water in the Southwest. The technology for desalination exists and has been extensively tested in other countries, particularly in the Middle East. Unfortunately, desalination is expensive and energy-intensive, and disposal of salt wastes poses environmental concerns.

A 1997 State of California study contrasted the existing cost of water deliveries ($195 to $300 per acre foot) to the expected price of desalination ($1,300 to $2,200).[14] In 2008, the nation's first large-scale ocean desalination plant came on-line in Tampa Bay, Florida, generating 25 million gallons of freshwater every day. But the project was years behind schedule and many millions of dollars over budget, problems that also seem to be on the horizon for planned San Francisco/Marin County and San Diego desalination plants. Owners of the San Diego plant – still in the planning stages after more than a decade – have stated an intention to sell water for $950 per acre foot (compared with $700 per acre foot commonly paid by local agencies, according to the Wall Street Journal).[15] Tampa Bay sells its desalinated water for $1,100 per acre foot, but outside analyses have estimated the true costs of producing water at $1,500 per acre foot for Tampa Bay, $2,600 for San Diego, and $2,700 for San Francisco/Marin County.[16] Prices this high call into question the affordability of desalination in comparison to other methods of balancing the Southwest's water use with its water supply.

Importing additional water from neighboring states could be accomplished – if there were any excess water to import. Most of the states (U.S. and Mexican) surrounding the Southwest are arid, with little or no surplus water (Oklahoma, Texas, Baja California, Sonora, and Chihuahua). Others are extremely mountainous, making water transport prohibitively expensive (Colorado, Idaho, Wyoming). Oregon, which borders on both California and Nevada, is an exception, and California already receives small annual transfers of water from the Klamath River basin – less than one tenth of 1 percent of its total water supply. Doubling or even tripling these flows would hardly make a dent in projected shortfalls, and in any case, there are ongoing conflicts over the use of the Klamath River. There is no reason to think that imports from Oregon, let alone any of the other neighboring states, can solve any significant part of the region's water crisis.

In short, increasing the water supply is not a viable solution for the Southwest. Desalination and increasing water imports are either not feasible or are far more costly than other solutions.

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[14] California Ocean Resources Management Program (1997), http://www.resources.ca.gov/ocean/97Agenda/Chap5Desal.html.

[15] Hsu (2010), Kranhold (2008).

[16] Fryer (2010).

Solution #2: Additional groundwater extraction

This is, in effect, the solution that has been applied in the past: potential shortages of surface water have been met by increased use of groundwater. If limitless supplies of groundwater were available, this would be an appealing answer for the future as well. The amounts that would be needed, however, appear to be impossibly large. Our model results show that without adaptation, the Southwest would need to extract 2,253 million acre feet of groundwater in the next century, over and above the renewal rate, given baseline growth in population and income and A2 climate forecasts. Little is known about the actual stock of groundwater under the Southwest, but detailed modeling for California shows that the state's projected shortfall is at least three times the size of current groundwater reserves, and perhaps far more.

Additional groundwater extraction will, no doubt, play a part in meeting future increases to water use in the Southwest, but there can be no confidence – given existing data – that groundwater reserves will meet increasing water demands over the next 100 years and beyond. The stock of groundwater is finite, and the natural rate of recharge is small in comparison to future needs. "Planned recharge" – injecting water into the ground – would increase the stock of water in storage, but at the expense of other uses of surface water. Planned recharge makes the largest contribution in wet years, when surface water is abundant, but climate change may mean that wet years will become less frequent.

Additional groundwater extraction is not a viable solution for the Southwest. Too much reliance on unmeasured groundwater stocks would be a very risky "solution" to the Southwest's water shortfall.

Solution #3: Planned reductions to water use

Energy adaptation

As the economy of the Southwest grows over the next century, it will need expanding supplies of energy as well as water. Both fossil fuel and nuclear power plants, the backbone of the existing electricity system, need constant flows of cooling water to regulate their internal temperatures and prevent overheating. Carbon capture and storage, a still-experimental new technology which could eliminate greenhouse gas emissions from power plants, would require even more water to produce the same amount of energy. It seems possible, therefore, that designing future energy systems to minimize water needs could be part of the solution to the water crisis.

We analyzed the implications of future energy options for the region's water use, in collaboration with Synapse Energy Economics. The results of that analysis are presented in a separate report (Fisher and Ackerman 2011). We modeled eight scenarios for electricity supply through 2100, based on differing combinations of assumptions about energy efficiency, greenhouse gas reduction goals, and water conservation. The scenarios show important differences in energy technology choices and costs, but the amounts of water involved are quite small relative to the overall supply and demand for water in the Southwest.

As seen in Table 3 above, power generation uses only 1 percent of the region's water at present. Similarly, the maximum difference in water use, between the most and least water-intensive scenarios in our energy modeling, was only about 700,000 acre feet per year for the Southwest in 2100. That difference was concentrated in Arizona (about 300,000 acre feet) and California (almost 250,000 acre feet). Even in Arizona, this represents only 3 percent of projected water demand in 2100; in California, and in the region as a whole, it is a fraction of one percent of water use.

In short, water constraints will undoubtedly shape the future energy system of the Southwest, but energy choices can make only a minor contribution to solving the region's water crisis.

Urban adaptation

Modeling for California demonstrates that "slow" urban adaptation – with 10-percent reductions in water use from conservation and 5-percent reductions from efficiency measures, as well as consumers' response to a 20-percent increase in water prices by 2030 – is an essential first step in reducing the Southwest's water shortfall, but far from enough to solve the problem. In our California research, only plans that included "fast" urban adaptation – with 39-percent total conservation and efficiency reductions in residential interior and commercial, industrial, and institutional water use, 33-percent reductions in residential exterior use, and consumers' response to a 41-percent increase in water prices – can succeed in reducing water use to a sustainable rate.

Today, households and businesses use one-fifth of the Southwest's water; in 2110, urban uses will account for one-third of the region's freshwater use. Without extensive planned reductions to urban water use, unplanned restrictions and shortfalls cannot be avoided.

Agricultural adaptation

By 2110, if there is no adaptation, Southwest agricultural water usage will grow by 10 percent under the B1 climate scenario and 17 percent under A2.[17] Today, one-third of the Southwest's water is used to grow its least valuable crop, hay. But local supplies of this low-value crop are essential to the far more profitable dairy and cattle industry. In most Southwest states, farming cotton, grains, oilseeds and dry beans and peas brings in less value per acre foot of water than would the sale of the water itself. To be clear: some Southwest farmers could make more selling water than using that same water to grow and sell crops. Eliminating the lowest value-per-unit-water crops (excluding hay) from the Southwest would lower agricultural water use by 24 percent while reducing agricultural receipts by less than 5 percent.[18]

By far the most profitable crops (measured as sales per unit of water) are nursery, greenhouse, floriculture and sod. Vegetable, melons and sweet potatoes; fruits, nuts and berries; and dairy and cattle are a distant second, third and forth in terms of value per acre foot. In Nevada, dairy

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[17] CSWD model results (Stanton and Fitzgerald 2011).

[18] The lowest value per acre foot crops are rice and field corn in California; cotton and cottonseed in Arizona, California, and New Mexico; Wheat in California and Nevada; wheat in California and Nevada; and "other grains, oilseeds, dry beans, and dry peas" in Arizona, California, Nevada and Utah.

and cattle production yields an especially low value ($149 per acre foot), while in New Mexico this value is especially high ($1,161). The value of water used to grow hay should be considered on a state-by-state basis – in some areas, growing hay in a desert may make economic sense in the context of regional markets for dairy and cattle. In other areas, however, dairy and cattle production is simply not as valuable as the water itself.

The sale of agricultural products for less than the price of the water used to grow them may seem counterintuitive and, indeed, it could not happen if there were a free market for water. But the vast majority of Southwest water is not bought and sold on an open market. Instead, farmers and municipalities have longstanding rights to use – but not to sell – water, most often for a fee set by the state or by a local water utility. Some municipalities pay $2,000 or even $3,000 per acre foot to supply water to households and businesses,[19] and utilities have paid prices as high as almost $5,200 per acre foot in Utah – a price that would add only a cent per kilowatt-hour to electricity bills.[20] At the same time, farmers throughout the Southwest are growing crops worth $100 per acre foot, or even less, and half of all agricultural water is used to grow crops worth less than $1,200 per acre foot.

Extension of detailed modeling for California shows that "slow" agricultural adaptation – with 5-percent reductions in water use and growers' response to a 10-percent increase in water prices by 2030 – will be essential to solving the Southwest's water shortage over the next century. "Fast" agricultural adaptation – with 16 to 41-percent reductions in water use, depending on the crop, and growers' response to a 68-percent increase in water prices by 2030 – is a powerful tool for making large reductions in Southwest water use. Using "fast" agricultural adaptation would relieve the need for the most stringent urban adaptation measures.

The numbers are worth repeating: Farming supports just 1 percent of the Southwest's economy, and food production manufactures add another 0.8 percent of GDP. Even in California, farming plus food manufactures accounts for only 1.9 percent of state GDP. But agriculture uses 78 percent of all Southwest water, and more water will be required as temperatures grow with climate change. Extensive agricultural adaptation cannot remove all need for conservation and efficiency measures in and around Southwest homes, but it can greatly reduce the need for urban adaptation while providing an important safety net against water shortages and restrictions in dry years.

Solution #4: Unplanned reductions to water use

The last, least desired and most costly "solution" to any water crisis is unplanned shortfalls, and water limitations to homes and businesses, including farms. (The costs of this option are explored in Hanemann et al. 2006.) Drought restrictions are a hardship that can be avoided, even with projected future climate change, by implementing sensible conservation and efficiency

[19] Cooley et al. (2010).

[20] Fisher et al. (2010) reports that the highest price paid in Utah through 2008 was $5,182 per acre foot. The same source also shows that the average water consumption by coal plants in Utah is 630 gallons per MWh; this implies that an acre-foot of water is consumed to generate 517 MWh, or 517,000 kWh, of electricity. At $5,182 per acre-foot, this is almost exactly $0.01 per kWh.

measures. The sooner that water use reduction technology and cultural practices are adopted in Southwest homes and farms, the more groundwater can be saved to eke out supplies in future droughts.

6. The Bottom Line: Failing to Act is the Most Expensive Option

The cumulative water shortfall for the Southwest is displayed in Figure 1 above. From 2010 through 2110, without adaptation, the five-state region will have a shortfall of:

- 1,815 million acre feet due to baseline population and economic growth, under current climate conditions, and
- an additional 282 million acre feet under the B1 climate scenario, *or*
- an additional 439 million acre feet above baseline under the A2 climate scenario.

The adaptation required to address this shortfall and solve the Southwest water crisis may seem expensive and uncomfortable. It is not, however, optional; doing nothing would be worse.

The cost of inaction, of waiting for unplanned shortages, is difficult to predict in advance, but it would be large and painful; it would involve unexpected, unplanned disruptions and losses. At some point, in a dry year, crops that had been planted would fail due to lack of irrigation in mid-season. Urban areas would boil over with resentment at sudden, draconian cutbacks. Subsidence and other damages from over-pumping of groundwater would become widespread. Nor would these problems cure themselves: continue to do nothing, and they would only get worse.

One way to understand the size of the water shortfall is to calculate how much it would cost to buy that much water, if it were for sale. Suppose, for example, that the entire amount could be bought at the average cost to build new reservoirs and distribution systems in California, including the anticipated growth in prices to 2050; this amounts to $1,252 per acre foot in today's dollars.[21] It is coincidentally similar to the current average value of agricultural sales in the Southwest, $1,199 per acre foot.[22]

Another approach, yielding a higher price, is based on a 2003 study of the average cost of water delivery in 12 Southwestern municipalities, again with the anticipated growth in urban water prices to 2050; this amounts to $2,211 per acre foot.[23]

Even higher prices could reasonably be considered, as suggested above. The one seemingly inexhaustible source of water for the region, ocean desalination, might cost as much as $2,600 per acre foot. Prices paid for water in the desert areas of the interior Southwest have, on occasion, exceeded $5,000 per acre foot.

[21] Cooley et al. (2010); urban water prices are projected to grow 68 percent by 2050.
[22] CSWD model results (Stanton and Fitzgerald 2011).
[23] Western Resource Advocates (2003); urban water prices are projected to grow 68 percent by 2050.

We will, however, use the more moderate estimates based on California reservoir construction costs, and on water delivery costs in Southwestern municipalities. At these prices, $1,252 and $2,211 per acre foot:

- The baseline water shortfall over the next century, before considering climate change, would cost $2,273 billion to $4,013 billion.
- The milder B1 climate scenario imposes additional water shortfall costs of $353 to $623 billion; and
- The more severe A2 climate scenario imposes additional water shortfall costs above baseline of $549 to $970 billion.

That is, at the higher water price, A2 climate change – a likely result of current greenhouse gas emission trends – adds about a trillion dollars to the cost of water shortages in the Southwest over the coming century, converting a $4 trillion problem into a $5 trillion one.

To allow comparison with other studies, it is useful to examine the single-year cost estimates from our analysis. Recall from Section 1 that several past studies have estimated the climate-induced increase in water resource costs at $7 billion to $60 billion per year by mid-century, or 0.1 to 0.9 percent of the most recent year's GDP, for the country as a whole. Our estimates fall within a similar range for the five states of the Southwest: for the year 2050 we project increased water shortfall costs, above baseline, of $7 billion to $15 billion, or 0.3 to 0.6 percent of the region's GDP in 2009. For 2100, our one-year projection is $9 billion to $23 billion, or 0.4 to 0.9 percent of regional GDP in 2009.[24]

The bottom line question is not whether adaptation is difficult or expensive, compared to the unsustainable option of doing nothing. The question for water planning is, are there adaptation scenarios that will solve the Southwest's water problem at a cost, over the coming century, of less than several trillion dollars? If so, then adaptation is a bargain that the region cannot afford to ignore. There will be many debates about the best way to pursue adaptation, but there is no debating the fact that it is an urgent necessity.

The implication of our analysis for climate policy is similar: here, too, doing nothing to control emissions would lead to steadily worsening conditions; here, too, the available strategies may look expensive, but their benefits are large. Among the benefits of emissions reduction are the reduced costs of water supply in a more moderate climate. Over the coming century, unchecked climate change would worsen the Southwest water crisis, imposing additional costs on the region of up to a trillion dollars. Even if climate policies only shift us from the A2 to the B1 climate scenario, the reduction in the Southwest water shortfall will be worth roughly $200 billion to $350 billion in savings. This is, of course, only one part of the worldwide impacts of climate change – but it is one that could make all the difference for the communities of the Southwest.

[24] In each case, the lower figure is the B1 scenario cost at $1,252 per acre foot, and the higher is the A2 scenario cost at $2,211 per acre foot.

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