

UC Office of the President

Bending the Curve: Climate Change Solutions

Digital Textbook

Title

Adapting California's Water Supply to a Changing Climate

Permalink

<https://escholarship.org/uc/item/3bx2534f>

Authors

Sedlak, David

Forman, Fonna

Publication Date

2023

Peer reviewed

CHAPTER 21

Adapting California's Water Supply to a Changing Climate

DAVID SEDLAK

UC Berkeley

Bending the Curve: Climate Change Solutions is a digital textbook published by the Regents of the University of California in 2019 that resides at the California Digital Library (<https://escholarship.org/uc/item/6kr8p5rq>).

This chapter, *Adapting California's Water Supply to a Changing Climate*, is an extension of the digital textbook. It was written in 2023 by Dr. David Sedlak, Professor of Environmental Engineering, UC Berkeley.

Copyright © 2025 by The Regents of the University of California. For certain images and other contributions, the copyright holders are named in the captions.

The views and opinions expressed in this and all chapters of *Bending the Curve: Climate Change Solutions* are those of the respective chapter authors and do not necessarily reflect the views and opinions of other book contributors or The Regents of the University of California.

This chapter and the 2019 textbook are published under a Creative Commons Attribution 4.0 International license (CC BY 4.0). This license allows you to share, copy, redistribute, and transmit the work for any purpose providing author and publisher attribution is clearly stated. Further details about CC BY licenses are available at <https://creativecommons.org/licenses/by/4.0>.



For inquiries, please contact:
Office of the Provost and Executive Vice President for Academic Affairs
University of California, Office of the President
1111 Franklin Street
Oakland, CA 94607
www.ucop.edu

Layout and production by BookMatters, Berkeley

CHAPTER CONTENTS

Learning Objectives	21-3
Overview	21-4
21.1 Background	21-5
21.2 California's Water Supply and Uses	21-8
21.3 Effects of Climate Change on California's Water Supply	21-15
21.4 Adapting California's Water Supply to a Changing Climate	21-20
21.5 Impacts of Adaptation on Communities	21-30
21.6 Summary and Global Perspective	21-35
Sources for the Figures	21-36
Sources for the Text	21-36

Learning Objectives

1. Explain the ways that California obtains the water needed for its cities, farms, and ecosystems.

You will learn how the water available to the state is captured, stored, and moved throughout the state. In the process, you will examine how the water infrastructure that has developed since the gold rush of 1849 is governed by laws, regulations, and practices that may make it difficult to adapt to changing circumstances.

2. Describe the ways that climate change is altering water availability and water needs.

Climate change is affecting precipitation patterns in ways that place considerable strain on California's water infrastructure. You will learn how periods with less precipitation coupled with increased rates of water evaporation driven by higher temperatures are causing aridification—a process that is exacerbating water stress throughout the American Southwest and similar worldwide.

3. Discuss the main approaches that California is employing in its effort to adapt its water systems to a changing climate.

After learning about California's water infrastructure and the climate-change-related challenges that it faces, you will become familiar with efforts to increase water use efficiency, capture more of the water that falls on the state, and employ advanced treatment technologies to recycle and desalinate water.

4. Explain the challenges that climate-change-induced water stress places on vulnerable communities and ecosystems.

Although decreases in water availability and water quality caused by climate change will affect the entire state, California's low-income city dwellers, rural residents, and ecosystems are particularly susceptible to increasing water stress. In the final part of this chapter, you will learn about ways to address these challenges and ensure that water is allocated in a manner that is affordable, safe, and equitable.

Overview

Throughout history, the struggle to obtain a reliable supply of water has been critical to human well-being. Early settlements were built in places where it was easy to obtain an adequate quantity of water suitable for drinking and growing food. Small towns grew into prosperous civilizations after they developed technologies for accessing, moving, and storing water. When a volcanic eruption temporarily altered rainfall patterns or when the inability of farmers to properly manage local resources led to water scarcity, hardship followed, often accompanied by declines in population and social instability. In the coming decades, a changing climate will stress water systems that met the needs of civilization during the twentieth century. In fact, water scarcity is one of the most immediate and challenging ways in which a changing climate will affect humanity.

The exact way that a changing climate will impact water systems varies considerably among locations due to differences in regional climate and geography as well as national laws, policies, and politics. As a result, understanding the problems and the solutions for the world's climate-related water issues requires knowledge about the local context that people face. Rather than attempting to provide a comprehensive but superficial understanding of water supply issues brought about by a changing climate, this chapter focuses on California—a place on the front lines of the struggle to adapt water systems to a changing climate.

California's development, much of which occurred during the second half of the twentieth century, was made possible by massive investments in infrastructure that brought water from places where it was plentiful to the cities and farms where it was used. In the process of building this infrastructure, ecosystems that depended upon seasonal water flows were inexorably altered. Simultaneously, the rights to use water were given to people who had political power and the wealth needed to build water infrastructure. This chapter describes the complex systems that currently supply California's cities and farms with water, as well as the expected changes in water availability and water quality resulting from a changing climate. It also explains some of the ways that California is already adapting its water system to climate change, and how those efforts are likely to affect California's most vulnerable communities and the ecosystems that rely upon the remaining flows within the state's waterways.

21.1 Background

Water is essential for almost everything that we do. At home, we use water for cooking, personal hygiene, clothes washing, and gardening. But the water that flows from our taps is only a small part of the story. Large quantities of water also are needed to produce the food that we eat, the products that we purchase, and the energy that powers our homes. For people in wealthy countries, household water use typically accounts for less than 10% of the water needed to maintain a modern lifestyle. People living in low- and middle-income countries typically use less water because they consume fewer goods and services, but if their economic fortunes continue to improve, their per capita water use likely will increase to levels comparable to those of wealthy countries.

The ability of the local environment to meet the water needs of its people is place dependent. In tropical and temperate regions with low population densities, rainfall alone, possibly supplemented by a few reservoirs, normally provides enough water to grow food and meet the needs of homes and businesses. In contrast, people living in drier climate zones, especially in regions with high population densities, often struggle with water supply. Historically, communities facing water supply challenges have invested in dams, water transmission canals, and groundwater wells—projects referred to as water infrastructure—to ensure that as much as possible of the precipitation falling on them is captured, stored, and sent to the places where it is needed. When a substantial fraction of the precipitation falling within a region is diverted by infrastructure projects, the flows of rivers, lakes, and wetlands decline. In many cases, these alterations in water flows place considerable stress on native fish and wildlife that are not accustomed to living under low-flow conditions.

Scientists often quantify the availability of water for humans and ecosystems with The World Resource Institute's water stress index (Figure 21.1.1). This simple metric can be used to identify places where human water use is close to exceeding local resources, as well as locations

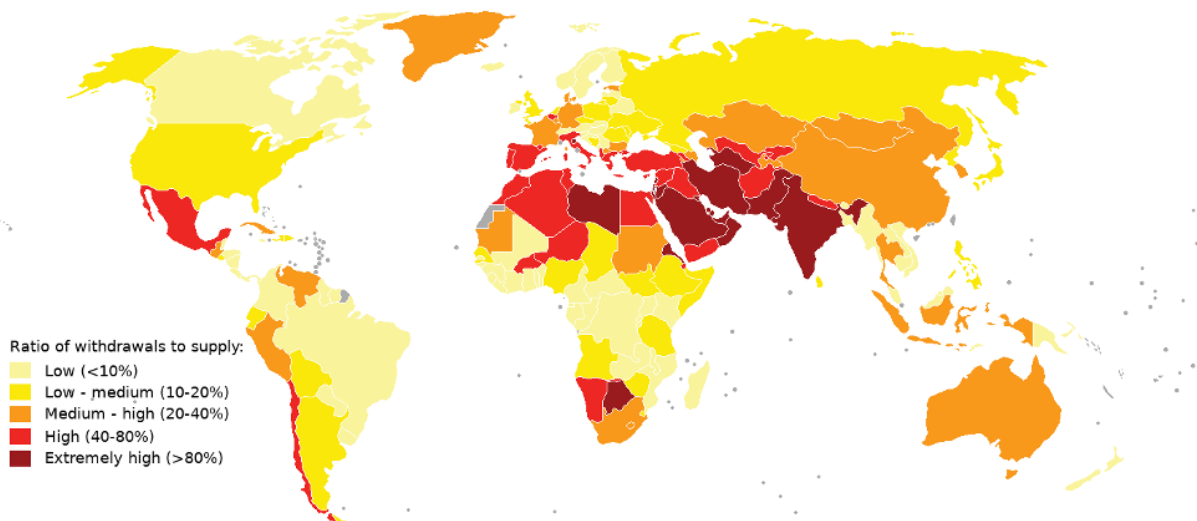


FIGURE 21.1.1 Water stress index for 2019 by country, using data from the World Resources Institute. Reproduced from Genetics4good (Wikimedia Commons).

where water use may be depriving rivers of natural flows needed to maintain healthy ecosystems. Although much of the world already faces water stress, changes in global air circulation patterns and increasing land surface temperatures will increase water stress in coming decades. Climate-change-induced alterations in water availability, coupled with increasing population and growing wealth, will likely increase water stress to critical levels in Asia, Africa, and South America. Simultaneously, arid regions in the Middle East, Australia, the Mediterranean, and the American West can anticipate even drier conditions. Currently, about 3.6 billion people face water scarcity for at least one month per year. Predictions made with the latest models indicate that this kind of annual water scarcity likely will become the norm for over five billion people by 2050 (WMO, 2021).

Developing effective responses to increasing water stress is one of the main challenges of climate change adaptation, but water scarcity is hardly new (Sedlak, 2023). Humans have already developed an array of creative approaches for addressing water shortages. In some cases, water efficiency measures, like drip irrigation and low-flow plumbing fixtures, along with cessation of wasteful habits like landscaping with

turfgrass in suburban neighborhoods and the use of flood irrigation on farm fields, have stretched the water supply and helped communities minimize the effects of water stress. In cases where infrastructure investments and efficiency measures have failed to alleviate scarcity, water stress has sometimes been addressed through trade. In other words, countries can use wealth generated by manufacturing, tourism or services to purchase food when they lack the water needed to grow sufficient amounts to feed their population.

Typically, the decisions about how to respond to water stress involve extensive consultation among water users, government officials, and members of the public, with the interplay between economics, politics, and technology determining the path that a community pursues. Because water stress manifests itself in different ways, it is difficult to make broad generalizations about the way that the adaptation process will play out. To provide a more tangible example of the way that water-stressed regions adapt to climate change, this chapter uses California as a case study.

California's water system offers an excellent opportunity to examine the challenges and solutions associated with climate change because the state has long been grappling with water stress. California is the most populous state in the United States. If it were a country, it would have the fifth-largest national economy in the world, with companies that are leaders in the technology, entertainment, and financial service sectors serving as major employers. California agriculture is extremely productive, with the state's farms providing much of the fruit, vegetables, and nuts grown in the United States. In addition to its robust economy and advanced food system, California has long been an innovator in water infrastructure, water conservation, and the development of new water technologies. It also has been at the forefront of environmental stewardship, with its early adoption of laws and policies for protecting the environment serving as a model for other parts of the world. By examining California's water adaptation challenge, the investments in adaptation that the state has already made, and the responses being developed to adjust to future changes, you will gain insights that can help you contribute to efforts to prepare California and other water-stressed locations for climate change.

21.2 California's Water Supply and Uses

Water allocations

California's water system was developed to address the mismatch between the locations where water is plentiful and the places where it is needed by cities and farms (Hanak et al. 2011). Much of California's precipitation falls on the northern coast and on the eastern mountains—the Sierra Nevada—that stretch from the Oregon border almost to Los Angeles. The two largest metropolitan regions, Southern California and the San Francisco Bay Area, which together are home to over 80% of the state's population, are located in the state's dry southwest and in the center of the state, respectively. The state's largest agricultural areas—the Sacramento and San Joaquin Valleys, which are set in climate zones classified as Mediterranean or semiarid—are located near the geographic center of the state. The two valleys together are sometimes referred to as the Central Valley. Starting in the early part of the twentieth century, investments made by cities and groups of farmers, along with state and federal government, created an extensive network of reservoirs and canals for storing and moving water from the wet areas in the north and east to California's coastal cities and Central Valley farms (Figure 21.2.1).

To track water at the regional scale, managers often use an unusual unit of measurement: the acre-foot. The origin of this unit is related to the ancient practice of flood irrigation. When farmers wanted to flood a 1 acre field to a depth of 1 foot, they diverted 1 acre-foot (that is, about 1,233 cubic meters or 326,000 gallons) of water onto the land. To put this quantity of water into perspective, a million acre-feet is enough water to flood Santa Clara County—home to many of Silicon Valley's technology companies—to a depth of about 0.3 meters. For simplicity, we will use the abbreviation **MAF** for **million acre-feet**.



FIGURE 21.2.1 California's water infrastructure moves water from reservoirs located in the mountain ranges in the north and eastern parts of the state to the cities and farms where it is used. It also brings in water from the Colorado River in the south. Reproduced from Wikimedia Commons.

During the wet season of a typical year, which lasts from early November until the end of March, between 100 and 300 MAF of water falls on California.

In wet years, about 90 MAF of water is actively managed, with about 35% diverted to agriculture and 8% being sent to cities. The remainder is dedicated to maintaining flows in rivers. These so-called environmental flow allocations involve either the release of water from dams to ensure healthy rivers or the enforcement of rules that prevent farmers and the operators of urban water systems from taking too much water from places where it is needed to support fish and wildlife. The need for environmental flows is especially crucial at the confluence of the two major rivers that run through the state's agricultural heartland—the Sacramento–San Joaquin River Delta, or in California water parlance, simply the Delta—a stretch of water that receives its own environmental flow allocation.

During dry years, water allocations shrink by about a third, to 60 MAF, because less precipitation makes it into the state's rivers and streams. Unless the dry year occurs during an extended drought, water use by cities barely changes when annual rainfall decreases. Dry year water use in agriculture shrinks by about a third as farmers cut back on low-value annual crops, like hay and alfalfa. Although these reductions may lower farm revenues, the largest reductions in water allocations during drought years involve environmental flows. Because many of the legal rights to water flowing in rivers were claimed by irrigation districts and cities during the late nineteenth and early twentieth centuries, agriculture and urban water users take priority over the environment during dry periods.

Agricultural water use

During the nineteenth century, the state's agriculture was not particularly lucrative. Farmers relied upon winter rains to grow wheat while ranchers grazed cattle. Their fortunes improved in the first decades of the twentieth century after groups of farmers came together to create irrigation districts—entities that financed, built, and managed dams and canals that brought water from distant watersheds (gray squares in Figure 21.2.1 depict some of those dams). During the Great Depression

of the 1930s, the federal government constructed a water project (red squares and lines in Figure 21.2.1) that provided additional water to farmers as part of an effort to foster economic development in the western part of the country.

To ensure that the ability of these infrastructure investments to deliver water would not be compromised by upstream users, farmers were often given legal rights to the distant water sources that they had begun to exploit. That legal system protected their infrastructure investments at the time, but it now poses a major challenge to adaptation efforts because farmers holding so-called senior water rights have little incentive to share or conserve water when cities, ecosystems, or more-recently established farmers face water scarcity.

During the second half of the twentieth century, the impacts of droughts coupled with a desire to grow more high-value crops, like fruits and nuts, drove farmers to adopt more-efficient irrigation methods. The least efficient way of applying water—flood irrigation—gave way to sprinklers and drip irrigation (also known as microirrigation) during this period. An extended dry period that started around 2010 placed additional strain on agricultural water resources. Growing water stress, increasing land values, and higher labor costs continue to drive California’s farmers toward the cultivation of high-value crops. Cultivation of these crops results in more jobs in agricultural communities, but unlike annual crops (that is, those that are planted and harvested in the same year) whose production can be curtailed when water becomes scarce, grape vines and trees require water during dry years, meaning that farmers have more to lose if they are forced to greatly reduce water consumption in response to scarcity.

Urban water use

Like the Central Valley farmers, the state’s big cities built their own dams and canals to import water from the mountains during the early twentieth century (gray lines and associated squares in Figure 21.2.1 depict some of the reservoirs and canals operated by the state’s big cities). This enabled the growth of suburbs with single-family homes that are characteristic of modern California. Much of the water used in California’s metropolitan areas is imported from distant watersheds, using infrastructure operated

by publicly owned water utilities. Southern California cities receive about a third of their water from the Colorado River—a resource that the state shares with six other Western states and Mexico. In addition, a series of dams and canals the state starting built in the 1960s (depicted by the blue squares and lines in Figure 21.2.1) provided water to the state’s rapidly growing metropolitan regions as well as smaller cities that did not already have their own water importation systems. Cities and rural communities that were situated too far away to access the state’s canals relied upon local reservoirs and groundwater wells.

About two-thirds of water use in California’s cities and towns is associated with individual households, with the remainder of the water supplying industry, offices, and public spaces like schools and parks. Inside homes, about 200 liters of water per person per day are used for cooking, bathing, flushing toilets, and washing clothes. Lot sizes and local climate affect the amount of water used outdoors. Less is used in densely populated coastal cities, like San Francisco, where lot sizes are small and the climate is mild. The highest outdoor water use tends to occur in drier inland communities, where homes often have large lawns and gardens. Expressed on a per capita basis, outdoor water use in inland suburbs can be two to five times higher than water use inside homes (that is, expressed on a per capita basis, outdoor water use often exceeds 400 liters per day).

Environmental water use

As mentioned previously, laws and policies have been established to ensure that the fish and wildlife that rely upon the flow of water in rivers can coexist with California’s water infrastructure. This means that water suppliers must allow some water that they might otherwise capture to move downstream. Dam operators also are required to release water from dams during dry periods to maintain flows in rivers. These environmental flow allocations protect threatened and endangered species, like the Chinook salmon and the delta smelt. Because many of these fish spend part or all of their lives in the Delta, environmental flows and ecological conditions in this region are closely monitored. Concerns about the Delta extend beyond fish: if enough freshwater does not flow into the Delta during the dry season, tidal action will allow salty water

to flow in from the San Francisco Bay—a phenomenon that damages the ecosystem and creates problems for local farmers who rely upon this water to grow food.

Surface water resources

Water projects built by irrigation districts and cities along with the federal and state water projects meet about two-thirds of California's water needs in a typical year. The dams that regulate the flow of water out of the reservoirs also produce about 10% of the state's electricity. Because hydroelectric power can be switched on and off readily, dams play an important role in meeting demands on the electricity grid when solar power production decreases at the end of the day. Dams and reservoirs also protect downstream communities from flooding by capturing water during periods of high flow. A changing climate likely will put additional strain on the operation of dams, forcing operators to choose between three needs: storing and delivering water to downstream users, supporting a stable electricity grid, and protecting communities from floods that are more likely to occur as precipitation patterns become more unpredictable.

Groundwater resources

Not all of California's water comes from rivers, reservoirs, and canals. In a typical year, groundwater accounts for about a third of the state's water supply. During dry years, the contribution of well water increases. It is especially important to farmers and people living in rural communities that do not have access to a canal or a pipeline that carries surface water. Because groundwater's existence is not obvious until it is pumped to the surface, people sometimes have a hard time visualizing the massive quantities of water to be found in the pores and cracks in the soil and rocks under the ground. A lack of understanding of the finite nature of groundwater resources also impedes efforts to manage it in a sustainable manner.

During the early part of the twentieth century, groundwater seemed like an inexhaustible resource. Modern diesel-powered pumps and drilling equipment, much of which was developed to support the state's rapidly expanding petroleum industry, made it possible to exploit



FIGURE 21.2.2 A groundwater well supplies irrigation water for a farm in California's Salinas Valley. Photograph by Chris Austin on flickr.

groundwater located far below the Earth's surface (Figure 21.2.2). But an infinite water supply was an illusion: groundwater is derived from water that percolates into the ground in recharge zones—places where the soil and underlying sediments are particularly permeable. The rate at which water pumped out of the ground is replaced by infiltrating water is relatively slow, especially after the rivers and wetlands located in recharge zones have been diverted for other uses.

During the second half of the twentieth century, farmers in California's Central Valley extracted groundwater faster than it was being recharged. This caused the water level of wells to decline and the surrounding land to sink. Eventually some wells ran dry. In response, wealthy farmers drilled deeper wells, but this is unsustainable because the cost of drilling wells and pumping water increases with depth. Pumping water from great depths also consumes a lot of energy: the amount of energy needed to pump water from a depth of 1,000 meters is about equal to the energy required to desalinate seawater.

21.3 Effects of Climate Change on California's Water Supply

Predictions made with sophisticated climate models allow us to anticipate some of the ways that precipitation patterns, river flows, and soil moisture will change in the coming decades. To gain insight into how these changes are likely to alter the ability of California's water system to deliver water, as well as the impacts of climate change on the water demands of farms and cities, we need to consider the ways that climate change will alter precipitation patterns and the movement of water through rivers, soils, and aquifers.

Atmospheric rivers

Most of California is in a Mediterranean climate zone, which means it experiences warm, dry summers and wet winters. The state's dry summers are caused by a high-pressure system off the coast that diverts moist air from the ocean north, toward Oregon and Washington. When temperatures drop in the fall, this high-pressure system breaks down, allowing moist air to flow in from the west. Under certain conditions, the air masses that arrive in the state contain large amounts of water vapor that brings rain and snow. The movement of particularly moist air from the ocean to the land is referred to as an **atmospheric river**. Obviously, a band of moist air is not an actual river; the term refers to the fact that these air masses serve as conduits that deliver large quantities of water to the state. Atmospheric rivers are part of the complex, global air circulation patterns driven by ocean currents, Hadley cells (air circulation systems caused by the heating of air around the equator and its return to the surface at mid-latitudes), and the interactions of flowing air with local landforms.

When the wet air from an atmospheric river arrives in California, some of it condenses and falls as rain along the coast. The air and its remaining moisture continue their journey, flowing to higher elevations as the air mass crosses the mountain ranges in the eastern half of the

state. When the air cools, the remaining water condenses, causing rain and snow to fall on the mountains. A substantial fraction of California's annual precipitation arrives during a handful of atmospheric rivers.

The way that climate change will affect atmospheric rivers is uncertain. One possibility is that warmer ocean temperatures will delay the annual breakup of the high-pressure system that diverts moist air northward, in which case there will be fewer atmospheric rivers. Warmer ocean temperatures also mean that the atmospheric rivers that do arrive will likely contain more moisture. Given these conditions, California probably may experience more years with less than the historic average amount of precipitation. Paradoxically, the state occasionally could have winters when substantially more than the average amount of precipitation will fall over shorter periods. In other words, in a changing climate, droughts could occur more frequently, but wet years taking place between droughts could deliver a lot more water than usual in a small number of intense storms.

Aridification

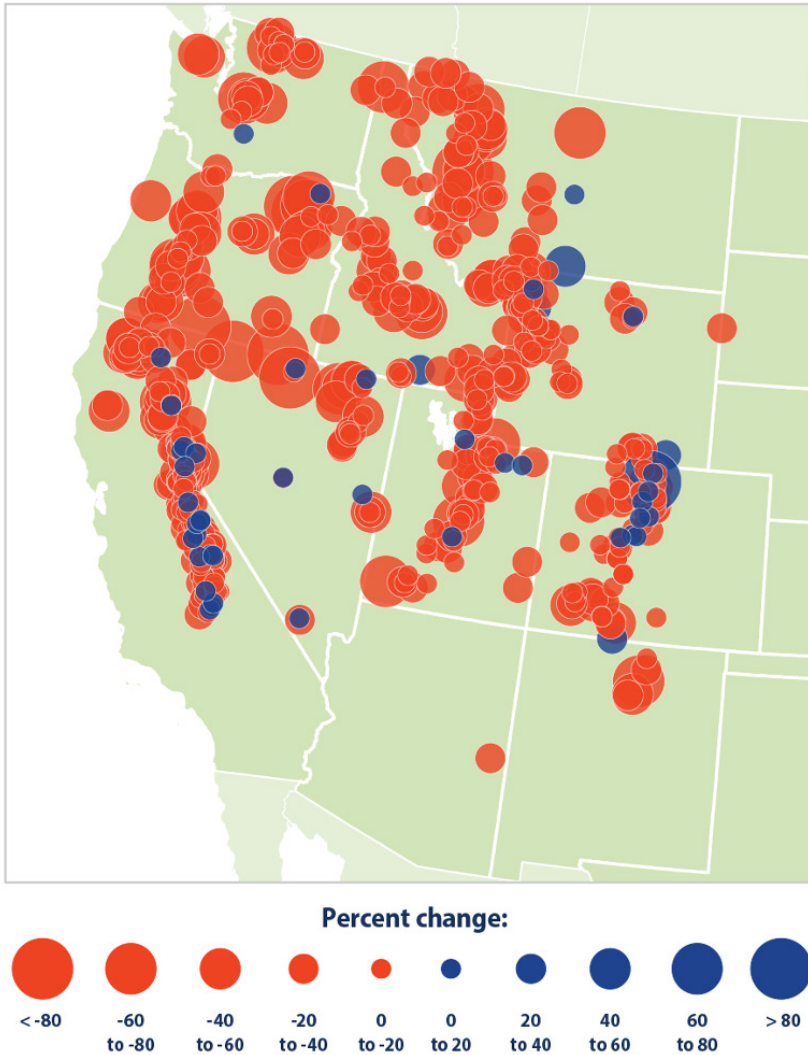
As the climate changes, the western and southwestern United States will become warmer. This will impact California's water system because the amount of water that air can hold increases as it warms; for each degree Celsius increase in temperature, air can hold about 7% more water. This means that at higher temperatures, water evaporates more quickly from soil and from the surfaces of reservoirs. Plants also consume more water at higher temperatures because they rely upon evaporation to stay cool. Warmer temperatures also lengthen the growing seasons, which in turn means that more water will be transferred to the atmosphere as trees, shrubs, and grasses undergo photosynthesis for a greater fraction of the year (Overpeck and Udall 2020). Because each of these processes returns water back into the atmosphere, the net effect of climate change is less water reaching the streams and rivers that fill the state's reservoirs. Drier soils will also reduce rates of groundwater recharge. Further, because evaporation of moisture from the soil is a cooling process, land surface temperatures increase when soil moisture levels fall. This complex process through which warmer temperatures result in drier conditions at a regional scale is referred to as **aridification**.

Even if climate change does not alter the average amount of precipitation arriving in California and the Colorado River basin, aridification is expected to stress the state's water system because less of the precipitation falling on the land will make it into reservoirs or infiltrate into the ground, land formations that hold water underground. Aridification also will increase the demand for water needed to grow food and maintain lawns and gardens. The effects of aridification on the state's water supply are particularly concerning in Southern California because the region obtains much of its water from the Colorado River. Starting in the early 2000s, water levels began to drop in Lake Mead and Lake Powell—the two main reservoirs that deliver water to California and other downstream users. By the summer of 2022, Lake Powell was at 26% of capacity, quickly approaching the point at which it could no longer generate power or deliver water downstream when needed. The situation on the Colorado has been exacerbated by growing water demands from western states that hold legal rights to river water. Irrespective of how the fight over Colorado River water is resolved, it is likely that Southern California will obtain less water from this important resource in the future.

Snowpack

A warming climate also means that snow will account for a smaller fraction of the precipitation arriving in the mountains. In addition to being bad news for winter sports enthusiasts, decreasing snowfall poses a serious challenge to California's water system because water managers rely upon melting snow to release water into reservoirs during the spring and early summer. The melting snowpack accounts for about a third of the state's surface water storage capacity. Warmer temperatures have already reduced the amount of water stored in the snowpack by about half relative to conditions observed in the 1950s (Figure 21.3.1). Predictions made with climate models indicate that the snowpack will continue to shrink, nearly disappearing by the end of the twenty-first century. Unless water managers can create ways to store all the rain that falls during warmer winters, the amount of surface water that the state's surface water storage system can deliver will shrink considerably.

Trends in April Snowpack in the Western United States, 1955–2022



Data source: USDA Natural Resources Conservation Service. 2022. Snow telemetry (SNOTEL) and snow course data and products. Accessed May 2022. www.wcc.nrcs.usda.gov/snow/index.html.

For more information, visit U.S. EPA's "Climate Change Indicators in the United States" at www.epa.gov/climate-indicators.

FIGURE 21.3.1 Snowpack has declined substantially since 1955 and is expected to continue to decline in the future. Another concern associated with the mountain snowpack is the possibility that a warm atmospheric river will rapidly melt the deposited snow. The combination of large quantities of rain and melting snow could bring huge volumes into reservoirs over short periods. The increased risk of such an event in a more unpredictable climate may force operators of dams to keep the level of water in their reservoirs lower during the winter. This would mean that less of the capacity of the reservoir could be used to store water. Image from USDA Natural Resources Conservation Service.

Groundwater depletion

As discussed above, in a typical year, groundwater accounts for about a third of California's water supply. However, statewide statistics from typical years obscure some important details about groundwater. Some regions of the state obtain nearly all their water from wells. Farms and cities that have access to both surface water and groundwater often increase their reliance on groundwater during drought periods. For this resource to continue to be available in the long term, groundwater needs to be recharged after the drought ends. If the rate of water being pumped exceeds the rate of recharge over a period of decades, groundwater levels will decline in a phenomenon referred to as **overdraft**.

Climate change is expected to decrease the rate at which groundwater is recharged by natural processes. When California does experience a wet winter, water will be returned to the ocean and atmosphere more quickly than in the past. This is because melting snowpack gradually feeds water into the ground, whereas rain arriving during big atmospheric river storm events tends to move directly into rivers and streams instead of soaking into the soil. Flood control infrastructure, such as levees that protect farms and towns, prevents high river flows from reaching the adjacent flat areas, where they would recharge groundwater.

21.4 Adapting California's Water Supply to a Changing Climate

With an understanding of California's water system and the ways that climate change is likely to alter it, we turn our attention to measures that the state can take to minimize the impacts of water scarcity. Adaptation strategies can be grouped into two categories: (1) adopting ways of using available water more efficiently, and (2) increasing water availability by modifying existing infrastructure or accessing new water sources that are less vulnerable to climate change. Given the scale of the challenge, the state is likely to pursue an “all of the above” strategy, with investments in different approaches determined by local conditions.

Agricultural water use efficiency

Since agriculture is the state's largest user of water, improving the way that water is used to grow food is one of the most important ways of responding to water scarcity. Although the potential power of conservation is obvious, the path forward is not as simple as it may seem at first glance. The shift from flood irrigation to sprinklers and microirrigation that took place in the latter part of the twentieth century greatly reduced the amount of water that was needed to grow fruits, nuts, and grapes—profitable crops that currently account for about 80% of California's farm-related employment (Lund et al., 2018). About half of the farmland in California has not transitioned to high-value crops, in part because it is in places where the soil and climate are not suitable for trees and vineyards. Furthermore, the market for these high-value agricultural products is nearly saturated, meaning that additional production of these crops might drive down the revenues that farmers would receive from selling their crops. Some of the farmers who have not yet made the shift to high-value crops feel no pressure to do so because they hold senior water rights, which give them little incentive to invest in more-efficient irrigation methods. For these farmers, it may

be more profitable to use their historic water allocations to grow alfalfa, hay, and corn for California's dairies, which, due to their proximity to over 30 million potential customers in Southern California and the San Francisco Bay Area, lead the nation in milk production.

Despite these limitations, many farmers are actively seeking ways to use water more efficiently. Advanced technologies, like soil moisture sensors that can determine when specific parts of a field need water, and other less sophisticated water-saving measures are being used to grow crops with less water. But the "more crop per drop" approach does not always translate into an increase in water available for other users: when farmers reduce their water use through efficiency gains, they may expand their operations or shift to more profitable crops that require more water. In addition, water-saving measures only have a net benefit if they reduce the amount of water that is lost through evaporation: when flood irrigation is employed, much of the water that is not used by crops recharges groundwater or is drained into canals and streams that eventually reach the rivers that serve as habitat for fish and wildlife.

Urban water use efficiency

Although municipal water accounts for only about 20% of California's water use, there are ample opportunities to reduce water use in cities and suburbs. In fact, the state's water utilities have become quite proficient in getting their customers to save water. Reductions in per capita water use have been an effective way of meeting the needs of the state's increasing population without building additional infrastructure. For example, between 1970 and 2010 the population of Los Angeles grew by approximately 30% while the total amount of water that the city used remained nearly constant due to decreases in per capita water demand. Most of this decline was related to the replacement of inefficient plumbing fixtures and appliances with water-saving models, along with a reduction in the amount of water used in landscaping.

Over the next two to three decades, the greatest potential for reducing urban water use will be found outdoors, where about half of the water use by cities and suburbs takes place. Converting lawns into areas landscaped with native plants, shrubs, and trees reduces water use by

about 50%. To encourage citizens to transition to landscaping that consumes less water, utilities often establish “cash for grass” programs, with customer rebates offsetting much of the cost of the conversion. The money spent on rebates can be justified by utilities because everyone benefits from water savings that help the community avoid the need to build new infrastructure, which can be much more expensive in the long run. Despite the attraction of cash-for-grass rebates and the aesthetic beauty of trees and native plants, many homeowners will not voluntarily part with their lawns. Utilities can try to nudge homeowners into converting their landscaping by raising the prices that they charge for excessive water use, but this is difficult because a voter initiative passed in 1996 requires that municipal services like water supply reflect only the cost of providing water (Hanak et al., 2014). High water rates designed to change behavior are considered a luxury tax that cannot be levied by a utility in its effort to reduce per capita water demand. In other words, Californians who already have lawns have the right to keep them even if their neighbors consider them to be a waste of water.

Reductions in outdoor water use also can be realized by establishing building codes for new construction that prohibit big lawns or that outlaw water-consuming landscaping altogether. Despite the potential for saving large amounts of water by paving over lawns or by limiting plantings to species that are well adapted to arid climate zones (for example, cacti, succulents), such drastic changes may not be desirable. In addition to their aesthetic benefits, trees, shrubs, and grasses reduce ground temperatures by providing shade and through the cooling that takes place when water evaporates. Thus, a modest amount of water use in cities can help combat the **urban heat island effect**—elevated ground temperatures caused by the absorption of the sun’s energy by concrete, asphalt, and other surfaces. Shady streets, urban parks, and landscaped areas make cities more attractive while reducing ground temperatures. This is particularly important in less affluent parts of cities where many people cannot afford air conditioning. By minimizing the absorption of energy that is released by heated surfaces at night, the health impacts of the urban heat island effect can be minimized.

Although the most obvious water savings are found outdoors, there are still opportunities to save water indoors, as older plumbing

fixtures—mainly showers and toilets—are replaced by low-flow models. Additional water savings will take place as old washing machines and dishwashers are upgraded. It is also possible to save water indoors by encouraging people to change their behavior—taking shorter showers and fixing leaky faucets. In California, efforts to educate children and adults about the value of water have reduced in-home water use. When people pay more attention to water use during droughts, additional, short-term water savings can be realized. But these reductions often dissipate after the rain returns.

Water reuse

Only a small fraction of the water applied to a farm field is taken up by crops. Water that does not travel through the roots of a plant flows off the field, percolates into the ground, or evaporates from wet soil. Except for the water that evaporates, this excess irrigation water has the potential to be reused. Water that percolates through the soil is relatively easy to reuse because it recharges aquifers underneath the farm. Water that drains from an irrigated field can either be captured and pumped back onto the same field or be diverted onto the next farm, or a city located downstream, or it can contribute to the flow of a river. Due to the extensive use of groundwater and the fact that most farms drain to waterways that need additional environmental flows, much of the irrigation water applied on California's farms is already being reused. The greatest potential for increasing the reuse of irrigation water involves technologies that minimize evaporation by applying water closer to the roots of crops with drip irrigation and precision sprinklers. Although more-efficient irrigation methods may have large benefits to individual farmers, they reduce the amount of water percolating into aquifers and reaching waterways where it can be reused. The true savings from precision irrigation are related to its ability to reduce water lost by evaporation. Thus, further saving in agricultural water use may be hard to realize in California, because much of the flood irrigation of high-value crops has been replaced by sprinklers and drip irrigation.

The more important opportunity for water reuse involves the treated sewage flowing out of towns and cities. Historically, California's coastal cities sent much of their wastewater out to sea through long underwater

pipes. By the 1970s, inland cities, like Fresno and Bakersfield, were already using most of their treated wastewater for irrigation or percolating it into the ground (Figure 21.4.1). As water shortages became more acute in the 1990s, coastal cities started to reuse their wastewater for nonpotable purposes, like watering golf courses, irrigating highway medians, and supplying sprinkler systems in housing developments. As treatment technologies improved and cities turned their attention to reducing the use of their limited water supply for landscape irrigation, more exhaustive treatment technologies were used to further clean the treated wastewater prior to injecting it into aquifers, where it eventually returned to the drinking water supply. Starting in the 2020s, San Diego built pipelines to return its highly treated wastewater to its water supply reservoirs. In places where it is impractical to pump treated wastewater up to a reservoir or inject it into an aquifer, California’s cities are considering projects that directly pipe highly treated wastewater to homes, in a practice referred to as direct potable reuse. Currently, water reuse accounts for about 10% of the water supply of California’s cities. If this practice continues to spread, nearly all the wastewater in the state will be reused, and it will account for 30% to 40% of the urban water supply. It cannot go any further than that because some water is lost during

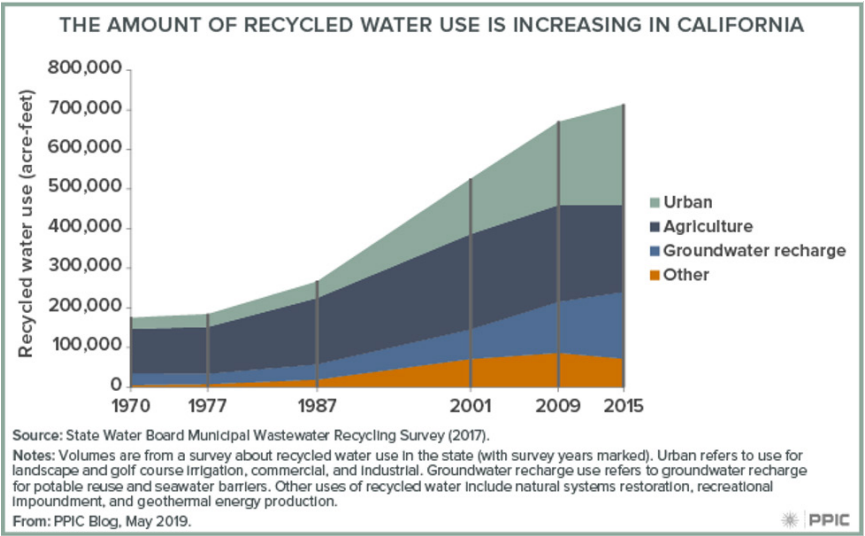


FIGURE 21.4.1 Trends in the uses of recycled water (that is, treated wastewater) in California. Reproduced from Public Policy Institute of California.

the recycling process and water used to irrigate lawns and playing fields does not return to the sewer.

Managed aquifer recharge and recovery

Although California's reservoirs control the flow of a substantial fraction of the precipitation that falls on the state, large volumes of water flow out to sea, especially during wet years, after the state's dams reach their maximum storage capacities. In addition, much of the precipitation that falls downstream of dams enters rivers and streams that have been engineered to send water downstream as quickly as possible to minimize risks of flooding cities, towns, and farms. This stands in contrast to conditions that existed prior to the construction of flood control infrastructure, when winter rains and spring floods had the opportunity to inundate floodplains and recharge aquifers. Rather than building more dams and reservoirs or removing flood control levees, it may be possible to capture and store some of this excess water underground in a process known as **managed aquifer recharge and recovery (MARR)**.

In MARR, the natural process through which groundwater is recharged is relegated to a smaller area where it cannot cause damage, either by pressuring captured water and injecting it into aquifers or by turning less valuable land into recharge basins—shallow ponds that retain water and allow it to slowly percolate into the ground (Figure 21.4.2). MARR is especially attractive in parts of Central and Southern California where groundwater has been depleted by overpumping, because the aquifers have excess storage capacity, and an existing network for wells is available to bring the recharged groundwater to the surface (that is, recover it) during dry years. When MARR is practiced on dormant farm fields, it is sometimes referred to as flood MARR. MARR is also being used in urbanized Southern California: close to a third of the water supply of Los Angeles is from excess water the city sends to its urban infiltration ponds from reservoirs in the surrounding mountains, from one of the aqueducts coming into the city, or from rainwater that runs down city streets during winter storms.

Recovered groundwater can be used above the land where it was recharged, or it can be exported to distant farms and cities if there is a

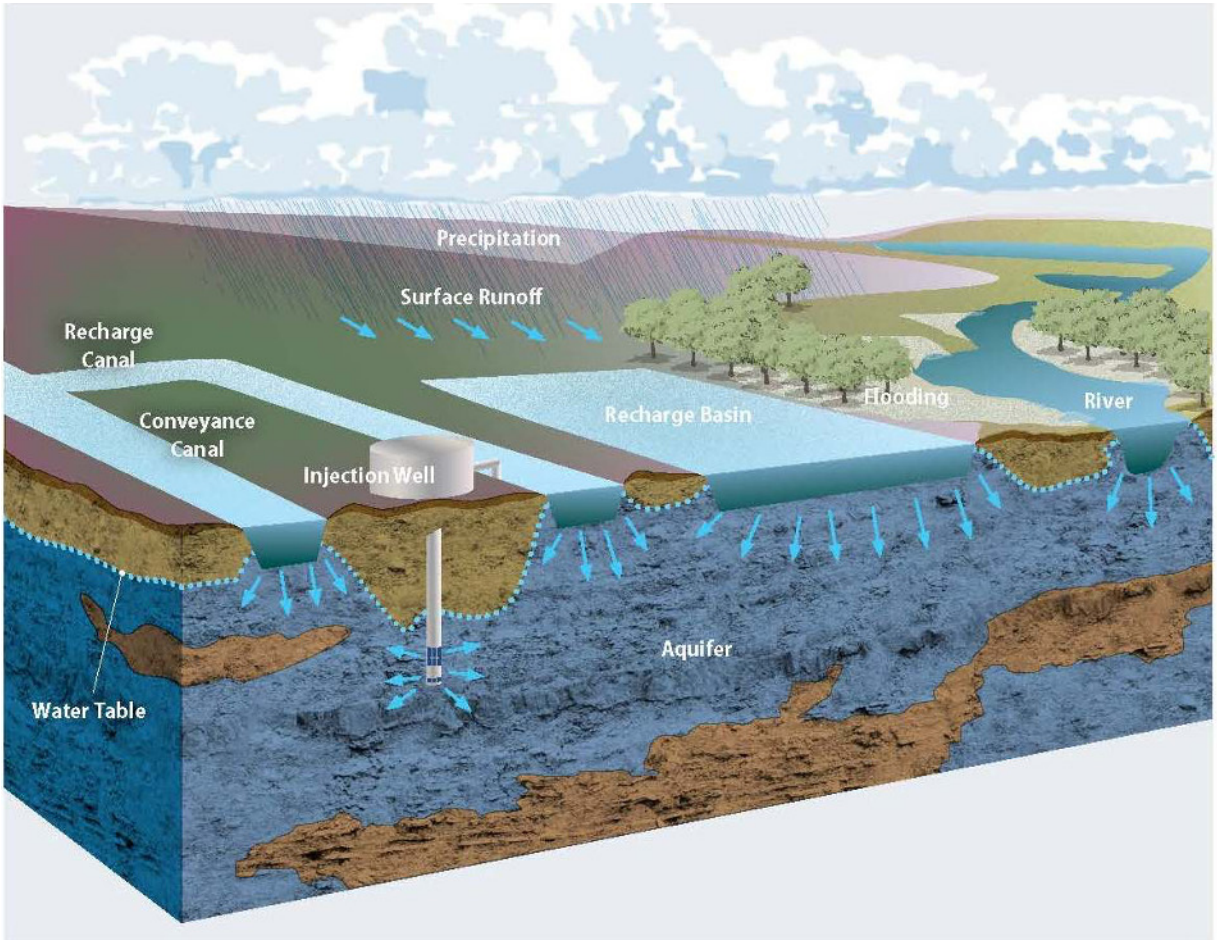


FIGURE 21.4.2 Managed aquifer recharge and recovery (MARR) is employed in California to capture water during wet years. Reproduced from California Department of Water Resources.

canal, river, or pipeline nearby that can be used to transport the water to the location where it is needed. Groundwater banking provides a mechanism for landowners who operate MARR systems to make profits by selling water to the highest bidder. Groundwater banks that store several million acre-feet of water were built in the San Joaquin Valley in the late 1980s. The use of MARR for local water users and to provide water to downstream cities is likely to become more important to California in the future, provided that the state is willing to continue to make investments in the percolation ponds and injection wells.

Desalination

The final strategy for increasing the state's water supply is **desalination**. Most modern desalination plants employ reverse osmosis—a process in which water molecules are pushed through a thin sheet of plastic through which salts and other contaminants cannot pass. The process turns water that would otherwise be too salty to use for drinking into clean, salt-free water. As it does so, the desalination plant creates a briny waste that is referred to as reject or reverse osmosis concentrate. Reverse osmosis has come a long way since it was invented by researchers at UCLA in the late 1950s. As reverse osmosis and other technologies for desalinating water have matured, their costs have dropped to the point that hundreds of millions of people in water-scarce parts of the Middle East, Caribbean, and Australia are drinking desalinated seawater.

Although it was invented in California, the practice has seen fewer applications in the state than it has in other wealthy, water-scarce places because seawater desalination has been mired in controversy due to concerns about energy use and the damage to the environment associated with operation of desalination plants. With respect to the potential for the technology to harm ecosystems, regulators have focused on the fate of larval-stage marine organisms living in the water that gets sucked into desalination plants. Scrutiny also has been directed at the potential effects of exposure of marine organisms to hypersaline reverse osmosis concentrate discharged by the plants. The designers of desalination plants have attempted to address these concerns by purchasing the power needed to operate their facilities from renewable sources, by installing water intake structures that are less likely to pull in marine organisms, and by equipping their plants with long pipelines that gently dilute the briny waste back into the seawater without perturbing local salinity patterns.

Despite opposition from groups that were concerned about environmental impacts of the process, the largest desalination plant in the Western Hemisphere was built south of Los Angeles, in the city of Carlsbad in 2015. A second seawater desalination plant, capable of producing less than 10% of the amount of water generated by the Carlsbad plant, was opened in Santa Barbara 2 years later. Several additional small

desalination plants also are in operation or are in the permitting phase in other water-stressed coastal communities. The volume of water produced by all the existing and proposed plants only adds up to about 0.2 MAF, which is less than 3% of the water used by California's cities.

Although seawater desalination is the most visible application of desalination technology, the process can be used to treat water from other sources. For example, reverse osmosis can be used to desalinate brackish water at the mouths of rivers, where seawater mixes with freshwater, as well as groundwater in coastal areas where seawater intrusion has made the water too salty to use. Desalination can also be employed in inland areas where weathering of minerals has released large quantities of salt to groundwater. Desalination of brackish water usually requires substantially less energy than seawater desalination because the lower salt content makes it easier to separate salts from water. In addition, brackish water desalination projects tend to be less controversial than seawater desalination because the volume of water being treated at any single facility is typically only a fraction of the amount being handled at larger seawater desalination plants. Most of California's existing brackish water desalination plants are located near the coast or in places where it is possible to pipe the reverse osmosis concentrate produced by the process to the ocean. If brackish water desalination is going to meet the water needs of inland communities, it will be necessary to develop a cost-effective way to manage the briny waste produced by the process.

Transitioning cities to local water sources

Putting all of these pieces together, it becomes clear that there are many strategies available to help California's cities and farms transition from a water system that made more sense at a time when there were fewer people, less awareness of the needs of the environment, and more predictable weather patterns. We are now aware that climate change and the inability of nature to supply all the state's water needs necessitate a different approach. In the coming decades, it is likely that water scarcity will change the mix of crops grown on California's farms, while MARR will be used to make more efficient use of water available during wet years. The state's cities likely will obtain less of their water from distant reservoirs or aquifers. New water sources, like recycled wastewater and

aquifers within cities that are recharged with local stormwater, are likely to make up much of the shortfall. When these new approaches are coupled with further efforts in conservation and possibly the construction of a few more desalination systems, it is likely that California's cities will be ready to meet their water needs despite the effects of climate change on the imported-water system created in the nineteenth and twentieth centuries.

Transitioning farms to stored groundwater

With respect to water scarcity, California's farms are facing a more challenging situation than the state's cities because agricultural operations require a lot of inexpensive water to survive. The profits generated by most of California's farms cannot justify the type of infrastructure investments needed to make up for decreases in water supplies due to climate change. Thus, California agriculture will change as it adapts to a future with less imported water. It is likely that some water-stressed farmers will shift production to more valuable crops and that others will fallow or convert marginal farmland to other uses, like housing, solar farms, or nature reserves. More-efficient approaches for irrigating crops and reusing irrigation water also will be part of this transition, much as they have already helped farmers grow more food with less water. The big opportunity for California to adapt its food production system to climate change will involve more-effective use of groundwater. Managed aquifer recharge and recovery provides an opportunity to exploit the excess surface water that is available during the rainy season, especially during wet years. But efforts to get this water into aquifers need to be approached with caution due to their potential to reduce environmental flows. The flow of water through the Sacramento–San Joaquin River Delta and other critical water bodies is key to the survival of threatened and endangered fish. It also helps transport salt and sediments that accumulate in farm fields and rivers to the ocean.

21.5 Impacts of Adaptation on Communities

Although the state has a myriad of tools available to help it to adjust to water scarcity and the increase in water demand attributable to a changing climate, there is no guarantee that adaptation will be an equitable process. The challenge that California faces is complicated by the way that population, wealth, and political power are distributed across the state and by the historic inequities inherent in its established system of water rights. Disparities in wealth and power have existed in California for many generations. They are partially responsible for the disproportionate impacts of pollution on the health and economic well-being of marginalized communities, as well as for the degradation of the environment. Policies and investments designed to help the state's water system adapt to a changing climate provide an opportunity to address some of these long-standing problems. By understanding current water-related problems and anticipating the ways that historically disadvantaged communities and ecosystems that share water with California's cities and farms will be affected by different types of solutions, we may be able to ensure more-equitable outcomes.

Water for California's rural communities

The first challenge is related to the provision of safe water for California's rural communities. Except for water conservation, most water supply adaptation strategies can only be employed by people who live in towns and cities that are served by municipal utilities. Although most people receive their tap water from such systems, about 6% of Californians obtain their drinking water either through community water systems—usually a well or surface water supply shared among a cluster of homes—or from wells that serve individual households. Many of the people who rely upon these small water systems are historically marginalized agricultural laborers who live in California's Central Valley. Not only is it difficult for

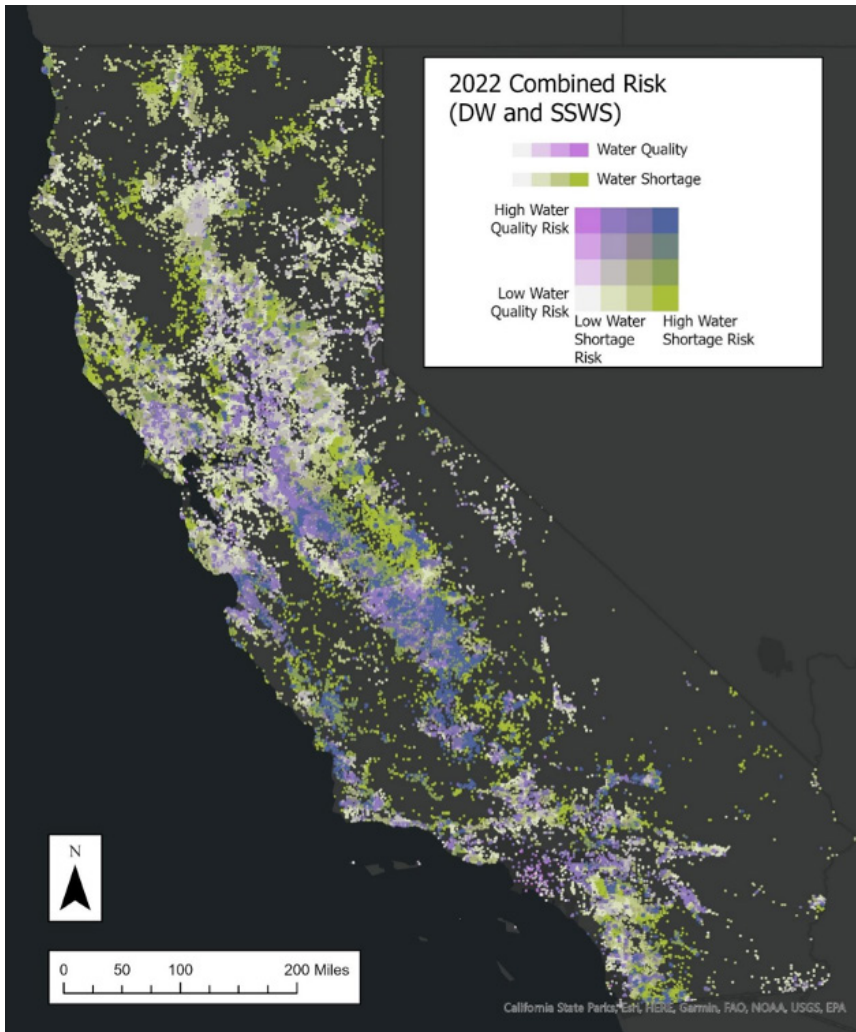


FIGURE 21.5.1 Locations of drinking water wells (DW) and small water systems (SSWS) that face water quality issues or are likely to run dry during extended droughts. Reproduced from California State Water Boards.

people who rely upon such water systems to take advantage of technologies like water recycling and desalination, but small systems are more likely to deliver water that is contaminated with nitrate and pesticides from farms, or arsenic and uranium—toxic, naturally occurring elements that are difficult to remove from well water. The map in Figure 21.5.1 shows where over a million people in California are at risk of exposure to contaminated drinking water (pink: high water quality risk), face the

prospect of running out of water during an extended drought (green: high water shortage risk), or are subject to both risks (blue).

In recognition of the fact that many rural residents cannot afford to drill deeper wells or to install water treatment systems for their existing water supplies, the state passed legislation in 2012 guaranteeing the right of every Californian to safe and affordable water (California State Water Resources Control Board, 2022). In 2019, the legislature set aside about \$1.4 billion to help realize this aspiration. Much of this money will be used to build pipelines to connect people who lack municipal water to neighboring communities that can provide them with safe water. Funds also will be used to drill deeper wells in places that are located above deep groundwater that is free from contamination. The funds currently set aside to fund the Human Right to Water program are just a start. It is estimated that ten times as much money as is currently available will be needed to address this challenge. Guaranteeing access to safe water will be particularly challenging for people who live too far away from towns and cities for pipelines to be cost-effective, as well as for those who live in areas where it is impractical to drill deeper wells to reach clean groundwater. For these users, it might be necessary to adopt complex and expensive solutions—like rainwater collection or the installation of point-of-use reverse osmosis systems—to purify drinking water.

Paying for new water supplies

A second challenge is related to the ways that Californians fund projects designed to adapt their water supply to a changing climate. Due to the historic system that governs the way that municipal water supplies collect money, as well as state laws that determine how taxes are levied, most of the funds for building water projects come from the monthly bills that citizens pay for water service. When water bills alone cannot provide utilities with enough money, assessments can be added to property tax bills, provided that enough voters approve of the new water project.

This approach works reasonably well in Southern California and the San Francisco Bay Area, where there are plenty of wealthy residents who can afford the extra expense of new water projects. But not everyone

in the community can comfortably absorb higher water costs: over the past two decades, as the state has begun to address issues associated with water pollution and the need to adapt the water system to climate change, water bills have been increasing at rates that are significantly faster than inflation. Depending upon the community, between 10% and 30% of Californians, usually the poorest people in the community, cannot afford their water bills. These same people also struggle to pay rent and other household expenses. Existing laws make it difficult for utilities to shift a greater share of the costs of new water projects to wealthier community members, because existing laws consider assessments that make wealthier people subsidize their less-fortunate neighbors to be a form of taxation—a power that is not available to municipal utilities.

The problem is even more challenging for rural residents, people living in small cities, and farmers in the Central Valley. For all but the most profitable farms, the extra costs of adapting water systems to a changing climate might be enough to put them out of business. Cities and towns outside of the affluent urban centers also struggle to fund new water supply projects because they have fewer wealthy residents. If wealthy Californians are going to subsidize the adaptation of water systems, the funding will most likely come in the form of voter-approved bonds. Although this may be a more equitable solution, bonds are paid back over a period of several decades, meaning that much of the cost of climate change adaptation will be shifted to future generations—a group of Californians who already will inherit many other serious climate change challenges.

Protecting and restoring ecosystems

A final challenge is related to the need to protect and, in many cases, restore California's climate-change-stressed ecosystems. Due to a lack of water, increased temperatures, and shifts in vegetation patterns, many of the state's aquatic ecosystems are at risk of collapse. These stresses, coupled with changes in land use patterns and water diversions that took place throughout the nineteenth and twentieth centuries, have had major impacts on fish populations. Since the 1970s, the Endangered Species Act has provided Native American tribes, regulators, and advocates for ecosystem restoration with a way of forcing water managers

to change the ways that they operate dams to ensure that flows of water in rivers and estuaries are sufficient to avoid unnecessary stress on fish species that are in danger of extinction. If warmer temperatures and changes in precipitation patterns were not adding additional stress to the system, it might have been possible to find a way to allocate water in a manner that balances the interests of farmers, cities, and the endangered species, but the added stress of climate change means that a greater share of the state's water may need to be used for environmental protection.

To protect threatened and endangered species and to restore damaged ecosystems, it may be necessary to make bigger changes in the way that existing water infrastructure is operated. In addition to releasing more water from reservoirs during dry periods, managers may be required to take down existing dams that block the migration of fish, as is the case on the Klamath River near California's northern border, in order to save endangered species and ensure healthy ecosystems. It is unclear whether the groups fighting for ecosystem protection and restoration will have the power to bring about these changes, but legal arguments premised on the idea that nature has a legal right to water are starting to gain traction in California's courts. In addition, growing recognition of the rights of California's Indigenous communities in matters of land and water management means that these activities may become a higher priority.

21.6 Summary and Global Perspective

As we have seen, a complex system of dams, canals, groundwater wells, and water treatment plants has been established to provide water to California's cities and farms. The allocation of water for different purposes is dictated by a complex set of water rights and laws that developed during the nineteenth and twentieth centuries. More recently, this system has begun to change, to expand ecosystem protection and the provision of safe, affordable water to historically disadvantaged communities. Due to changes in precipitation patterns and increasing temperatures, this system struggles to meet the needs of all its users.

Climate change adaptation strategies are critical to California's water future. Efforts to increase water use efficiency on farms and in cities and towns will be important adaptation strategies, while multibillion-dollar investments in water reuse, managed aquifer recharge, and recovery and desalination will expand supplies and create a less drought-prone water supply. As these strategies are implemented, it will be important to pay attention to the needs of rural communities, low-income communities, and ecosystems—all of which have historically had less wealth and political power when it has come to managing the state's water.

The lessons learned by considering the impact of climate change on the water system that serves California—a state with a population, land area, and economy bigger than those of many nations—can be applied to other parts of the world, provided we recognize that every place has different climates, geographies, and political and social systems that affect efforts to adapt to climate change. The knowledge obtained from studying one region as well as the technologies, policies, and social systems that influence adaptation strategies will be useful to you as you consider strategies for minimizing the adverse impacts of a changing climate.

Sources for the Figures

Figure 21.1.1: Image from the World Resources Institute. Reproduced from Genetics4good (Wikimedia Commons). <https://commons.wikimedia.org/w/index.php?curid=81237832>.

Figure 21.2.1: Image reproduced from Wikimedia Commons. https://en.m.wikipedia.org/wiki/File:California_water_system.jpg.

Figure 21.2.2: Photograph by Chris Austin. <https://www.flickr.com/photos/mavensnotebook/13974874158/in/photolist-nhUTdb-nxmBxW-nzaofE-nzpAzV-nhUE4p-nzadJf-nhVeCa-nz7hsH-nza1as-nzpvMY-nhUa92-nhVgjf-nhUfke-nhUq2Q-nz6Y3r-nzqhwC-nhUv1A-nxniUC-nxmpxU-nhVcAf-nBbLa8-nhUZhN-nhUMoK-nz7ziX-nhUFwr-nzpHsw-nxmWE3-nzpdaz-nzpmxr-nBbbzn-nzambj-nBbakP-nhUCSX-nz9U7L-nhUUc4-nzarS9-nz7Pxi-nzqqRo-nBb4fH-nzpNeM-nz7UzH-nzb8Dd-nhVJXS-nhVL99-nxnnYQ-nzaVRf-nxnpuW-nBc3g6-nxnkd9-nhVQR7>.

Figure 21.3.1: Image from USDA Natural Resources Conservation Service. Reproduced from US Environmental Protection Agency. 2023. Climate Change Indicators: Snowpack. <https://www.epa.gov/climate-indicators/climate-change-indicators-snowpack>.

Figure 21.4.1: Image from Public Policy Institute of California. 2019. California's Growing Demand for Recycled Water Has Ripple Effects. <https://www.ppic.org/blog/californias-growing-demand-for-recycled-water-has-ripple-effects/>.

Figure 21.4.2: Image from California Department of Water Resources.

Figure 21.5.1: Image from California State Water Boards. 2022. *2022 Drinking Water Needs Assessment*. Figure 24: Combined Risk for State Small Water Systems (SSWS) and Domestic Wells (DW). https://www.waterboards.ca.gov/drinking_water/certlic/drinkingwater/documents/needs/2022needsassessment.pdf.

Sources for the Text

California State Water Resources Control Board. 2022. *Drinking Water Needs Assessment*. https://www.waterboards.ca.gov/drinking_water/certlic/drinkingwater/documents/needs/2022needsassessment.pdf.

Hanak, E., et al. 2011. *Managing California's Water: From Conflict to Reconciliation*. Public Policy Institute of California, San Francisco, CA. <https://www.ppic.org/publication/managing-californias-water-from-conflict-to-reconciliation/>.

- Hanak, E., et al. 2014. *Paying for Water in California*. Public Policy Institute of California, San Francisco, CA. <https://www.ppic.org/publication/paying-for-water-in-california/>.
- Lund, J., et al. 2018. Lessons from California's 2012–2016 drought. *Journal of Water Resources Planning and Management* 144(10), 04018067.
- Overpeck, J. T., and Udall, B. 2020. Climate change and the aridification of North America. *Proceedings of the National Academy of Sciences USA* 117(22), 11856–11858. <https://doi.org/10.1073/pnas.2006323117>.
- Sedlak, D. L. 2023. *Water for All: Global Solutions for a Changing Climate*. Yale University Press, New Haven, CT.
- World Meteorological Organization. 2021. *2021 State of Climate Services: Water*. WMO Publication 1278. <https://library.wmo.int/idurl/4/57630>.

Chapter Glossary

Following is a list of terms and acronyms used in the chapter.

TABLE 21.4.1 Glossary Items

Term	Definition
Aquifer	A layer of rock, sand, or gravel that contains groundwater
Aridification	The process through which climate change creates drier conditions
Atmospheric river	An air mass that carries a large amount of precipitation to land
Desalination	The process of removing salt from water
Million acre-feet (MAF)	Volume needed to cover an acre of land to a depth of 1 foot
MARR	Managed aquifer recharge and recovery
Overdraft	Decline in groundwater levels when pumping exceeds recharge
Subsidence	Decrease in surface elevation due to compaction of aquifers
Urban heat island effect	Absorption of sunlight and heat by pavement and other hard surfaces resulting in higher surface temperatures, especially at night