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Managing Drought in a Changing Climate

Four Essential Reforms

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California's climate is changing. Hotter temperatures, a shrinking snowpack, shorter and more intense wet seasons, rising sea level, and more volatile precipitation—with wetter wet years and drier dry years—are stressing the state's water management system. Recent climate projections indicate that the pace of change will increase.

To avoid unwanted social, economic, and environmental consequences, the water system will need to adapt to greater climate extremes and growing water scarcity. While California is making good progress in some areas of drought management, a more focused plan of action is needed. Successful adaptation will require strong leadership at the state and local levels, and cooperation on all fronts.

The 2012–16 drought—the hottest in the state's recorded history and one of the driest—offered a window into the future under a warming climate and lessons for managing future droughts. Using these lessons as a starting point, this report offers a road map of essential reforms to prepare for and respond to droughts in California's changing climate. Key reforms include:

- **Plan ahead.** Stronger drought planning is critically important for urban water management, groundwater sustainability, safe drinking water in rural communities, and freshwater ecosystems.
- **Upgrade the water grid.** California needs a comprehensive program to address above- and below-ground storage, conveyance, and operational challenges by mid-century, including repairing facilities that are broken, expanding conveyance and storage capacity, and modernizing and integrating operations.
- **Update water allocation rules.** California should comprehensively update its water allocation governance. The goals should be to find equitable and efficient ways to allocate limited supplies among competing demands during dry times while promoting efforts to capture and store water during wet times.
- **Find the money.** Reliable funding is crucial for adapting to climate change. New sources are needed to pay for necessary water-management investments and to fill funding gaps in the state's water system.

The focus of this reform agenda is on drought, because drought—more than any other aspect of California's climate—reveals the vulnerabilities of water management systems. Importantly, these reforms will improve drought resilience for today's conditions, not just for the future.

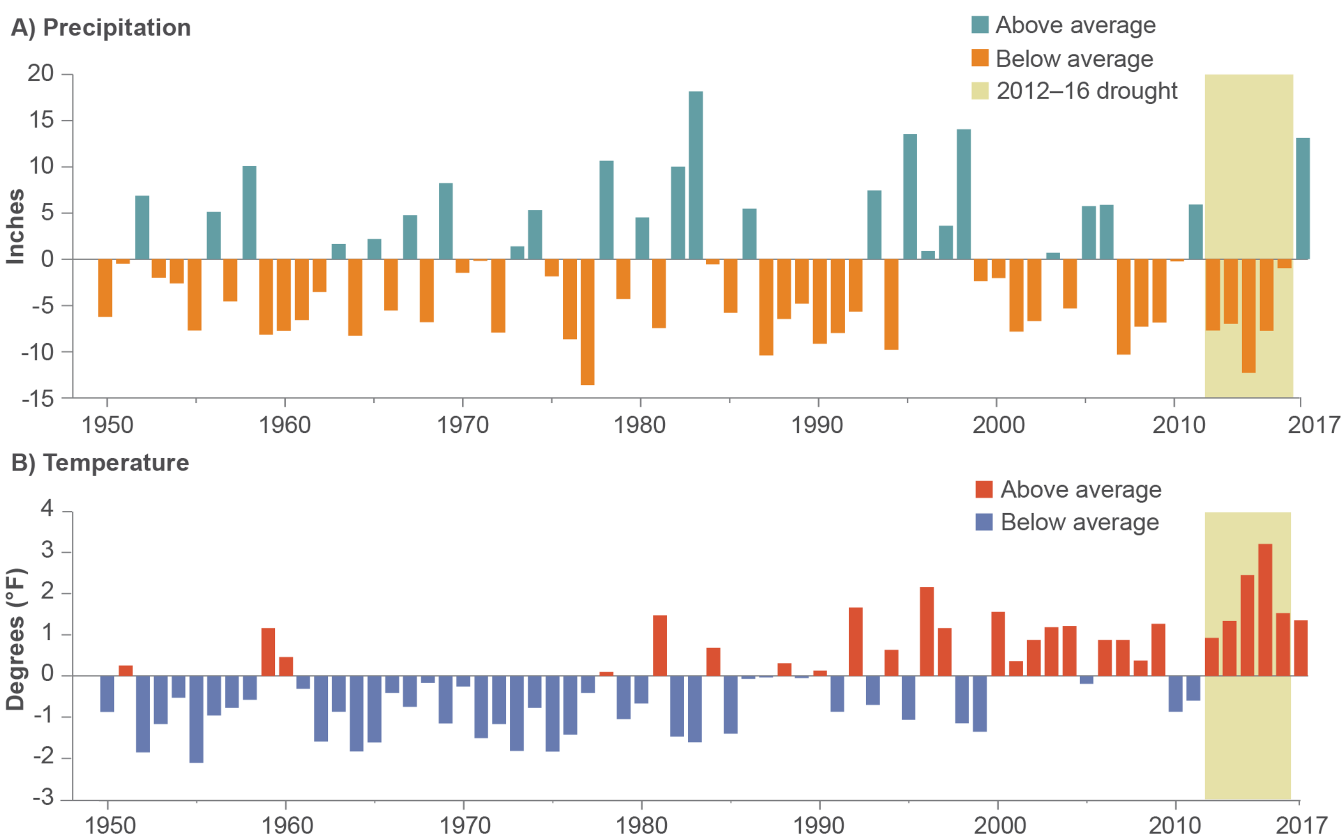
Introduction

California has a variable climate marked by large swings in seasonal and annual precipitation, severe multi-year droughts, and occasional but intense flooding. The state's water management system—including the laws and regulations that govern water allocation and use—was designed to cope with this variability (Hanak et al. 2011). Successful as it has been in the past, this system is facing an uncertain future. A growing body of evidence indicates that California's climate is becoming warmer and more variable, with significant changes on the horizon.[1] Managing water will be at the forefront of climate change adaptation in California. Droughts—which are expected to become more intense in the future—will test the vulnerabilities of the state's water supply system.

The drought of 2012–16—the hottest in California's recorded history and one of the driest—offered a window into the future under a warming climate (Figure 1). Climate projections show that the extreme high temperatures, loss of snowpack, and record-low stream flows of this drought are likely to become the norm. The drought ended in 2017 with one of the wettest years on record—an example of "precipitation whiplash" that is also likely to become more common (Swain et al. 2018).

FIGURE 1

Statewide, the 2012–16 drought was very dry, with record heat



SOURCE: Western Regional Climate Center.

NOTES: Bars in panel A show the number of inches above and below the 1981–2000 annual average of 25.8 inches, for the entire state. Bars in panel B show degrees above or below the average statewide temperature for 1981–2000 (57.8° F). Both series are measured in water years (October–September).

[1] See Dettinger (2016), He et al. (2017), Office of Environmental Health Hazard Assessment (2018), Swain et al. (2018), and Bedsworth et al. (2018).

This report employs new and recently published climate change simulations, along with lessons learned from the latest drought, to examine California's capacity for adaptation to greater climate extremes and growing water scarcity.[2] We conclude that California will need new policies and strategic investments to reduce the social, economic, and environmental costs of dealing with droughts of the future.

We begin by examining the challenges of managing scarce water supplies in four key sectors during the drought: cities and suburbs, irrigated agriculture, rural communities, and freshwater ecosystems. Based on climate model projections, we then examine additional pressures that are likely to challenge water management in these sectors over the next several decades. We next recommend a suite of policy and management reforms in four areas: drought planning, water infrastructure and operations, water rights administration, and funding. Finally, we examine where California appears to be on the right path in preparing for future droughts and where difficult course corrections may be needed.

Drought and California's Water Supply

Over the past 160 years, California's water supply system has evolved to meet the challenges of regional, seasonal, and annual differences in precipitation—including extended droughts—and growing demands for water (Lund et al. 2018). California's farms and cities rely upon the capacity to capture and store winter rain and snow in surface reservoirs and aquifers. To meet demand, stored water is conveyed in rivers, canals, and aqueducts to water users across the state. This network of above- and below-ground storage and conveyance systems—owned and operated by a diverse array of local, regional, state, and federal entities—serves as a "water grid" (loosely analogous to California's electrical grid) (Figure 2). This grid is critical to meeting water supply needs across much of the state as well as supporting aquatic ecosystems.

During multi-year droughts, elements of this grid change in importance. Initially, water in reservoirs is drawn down as water available from rivers declines. Depending on the severity of the drought, within two to three years the state's reservoirs are severely depleted, reducing surface water supplies. To compensate, water users—especially farmers—increase groundwater pumping. At the height of the latest drought, groundwater supplied nearly 60 percent of all water used by the state's cities and farms (compared to roughly a third in non-drought years).[3]

Water suppliers use a portfolio of water sources during drought. For example, as supplies from Northern California diminish, utilities in Southern California rely more on both groundwater and water from the Colorado River. Demand management is also a part of this portfolio. In urban areas, water conservation can play an important role in adapting to reduced supplies, as it did in the latest drought. In farm communities, fallowing is commonly used to cope with scarcity. Additionally, some suppliers take advantage of the grid to trade available water, moving it from low-revenue to high-revenue uses.

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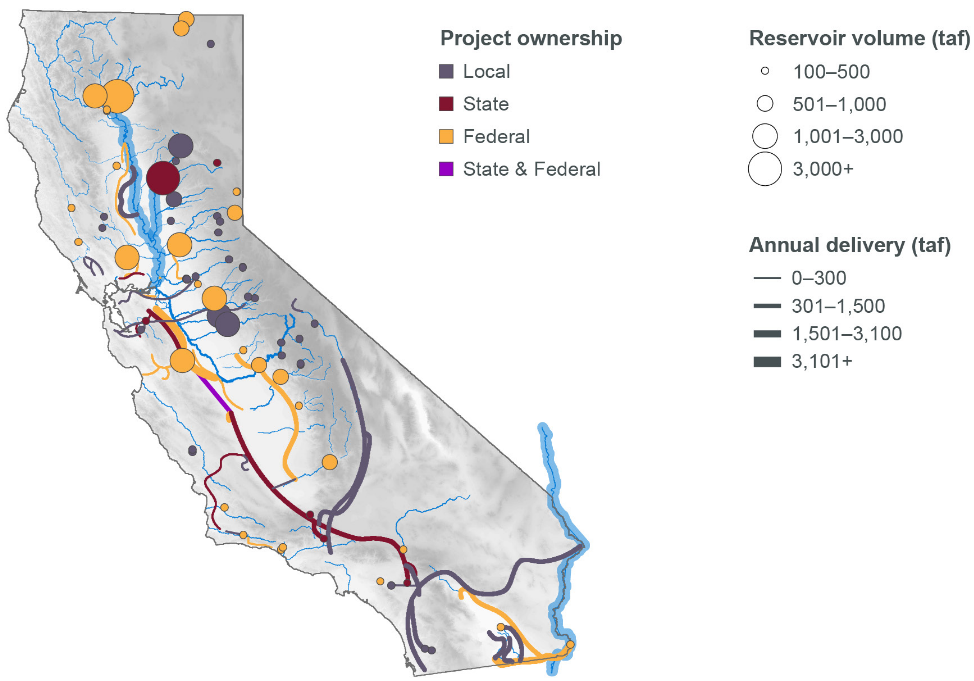
[2] Over the past three years the PPIC Water Policy Center has published 12 reports that examine the impacts of the latest drought and make recommendations for improving drought response in the future (see Box 4, page 23). Most of the recommendations made here are described in more detail in these publications.

[3] Author calculations using water balance data from the California Water Plan for 1998–2015.

FIGURE 2

California's "water grid" is a network of supplies and conveyance that connects most water use in the state



SOURCE: Developed by the authors using information from the California Department of Water Resources.

NOTES: "Taf" is thousands of acre-feet. The map shows reservoirs with storage capacity over 100 taf, scaled to size. Built conveyance facilities (canals, aqueducts) are scaled to their average annual deliveries. Rivers are shown in blue. Three major rivers—the Colorado, Sacramento, and Feather—are scaled to their annual deliveries. These rivers convey water from large surface reservoirs to users. Many areas of the state also have access to water stored in aquifers (not shown here).

Responses by Sector to the 2012–16 Drought

The 2012–16 drought highlighted significant differences in the consequences of water scarcity across the four sectors, with urban communities less vulnerable than agriculture, and rural communities and freshwater ecosystems most exposed (Mount et al. 2015, Hanak et al. 2015, Lund et al. 2018). This experience offers a useful guide to how a changing climate may affect the vulnerability of these sectors to future droughts.

Cities and Suburbs

The urban water sector fared best during the latest drought, with minimal social and economic disruption to residents and businesses (Mitchell et al. 2017). The resilience of the state's roughly 400 urban water systems reflects major improvements since the previous extended drought (1987–92).[4] These improvements included investments in new surface and groundwater storage, new conveyance to enable emergency supply sharing with neighboring water systems, water trading agreements to acquire new supplies, long-term reductions in indoor water use, and development of alternative water supplies such as desalination and wastewater recycling (McCann et al. 2018). As the drought wore on, urban utilities also saw historic declines in water use—principally through

[4] Water systems classified as urban generally serve at least 3,000 connections, and must adhere to a suite of state planning and reporting requirements.

reductions in landscape irrigation—responding first to voluntary calls for savings, and then to the governor's 2015 conservation mandate, which set targets for each utility.[5]

Yet several issues arose that may become more significant in the future. Not all urban utilities were well prepared for a drought of this severity and duration; several required extreme conservation measures or assistance with emergency supplies.[6] Many utilities experienced financial problems when water sales fell rapidly, reflecting inadequate preparation for the fiscal consequences of drought. The conservation mandate created friction between the state and local utilities, raising questions about their respective roles in managing future droughts (Mitchell et al. 2017).

Agriculture

California agriculture—including forage crops to support the large dairy and beef cattle industries—relies on large volumes of water for irrigation during the dry growing season, making it vulnerable to long droughts.[7] In the Central Valley—the state's largest farming region—farmers had a roughly 50 percent reduction in surface water supplies at the height of the drought (Howitt et al. 2015). They made up much of this deficit with additional groundwater pumping.[8] Water trading, selective fallowing of less productive fields, and unusually high commodity prices also reduced economic harm from shortages (Hanak et al. 2015 and 2017a).

Compared with urban utilities, agriculture relies less on drought planning and preparation and more on unmanaged use of groundwater to address deficits. In some areas—most notably within the San Joaquin Valley—this exacerbated long-term problems associated with groundwater overdraft, where pumping regularly exceeds replenishment (Hanak et al. 2017a). Problems included dry domestic and irrigation wells, and land sinking ("subsidence") that damaged water supply infrastructure. Areas with well-managed groundwater banks, such as parts of Kern County, showed greater resilience to shortages.

Concerns about the consequences of very high, unmanaged pumping spurred the enactment of the Sustainable Groundwater Management Act (SGMA) in 2014. This historic legislation requires local groundwater users to self-organize and meet an array of sustainability goals by the early 2040s (Box 1). While SGMA will also require changes from urban utilities, it will have especially far-reaching consequences for agricultural water management.[9] To bring basins into balance, many farms will have to find additional sources of supply, reduce their water use (principally through fallowing), or both.

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[5] Although there were reductions in indoor water use, cuts in landscape irrigation accomplished the bulk of water savings. This is reflected in the sharp decrease in summertime water use (Mitchell et al. 2017).

[6] Numerous communities in the Central Coast region—which is relatively isolated from the statewide water grid—were more vulnerable, as were some utilities in the Sacramento region that rely heavily on supplies from Folsom Lake (Mitchell et al. 2017).

[7] In this report we focus principally on irrigated agriculture. Rangeland management—which tends to be disconnected from the state's water grid—also faced considerable difficulties, principally due to declines in forage on rainfed pasture lands.

[8] Impacts varied depending on seniority of water rights, farming region, and availability and cost of pumping groundwater (Howitt et al. 2015). Farmers with junior surface water rights and lower priority contracts—particularly in the San Joaquin Valley—were hit the hardest and relied most heavily on extra groundwater pumping.

[9] Many heavily populated urban areas that depend on groundwater—including in Southern California and Silicon Valley—had already adopted local programs to manage groundwater in earlier decades, either through a legal process called adjudication or the creation of special groundwater management districts. Adjudicated basins are exempt from SGMA and the special management areas will generally be able to comply without major changes. SGMA will be especially important for groundwater-dependent urban utilities in other regions, including the Central Valley and the Central Coast.

Box 1: The Sustainable Groundwater Management Act

Groundwater is California's most important drought reserve. Groundwater storage capacity far exceeds the capacity to store water in reservoirs. But long-standing unsustainable management practices have left many groundwater basins in overdraft. As the climate changes and drought intensity increases, California will need to rely more heavily on groundwater to meet water demands.

The Sustainable Groundwater Management Act (SGMA) directs local agencies and stakeholders to develop institutions, plans, and implementation strategies to sustainably manage their groundwater resources for the long run (Kiparsky et al. 2016). If local agencies fail to act, SGMA directs the state to intervene. The passage of SGMA is a historic breakthrough in California water management. But achieving sustainable groundwater use will be difficult and controversial.

The law defines sustainable management as the avoidance of six significant undesirable effects: (1) drawing down groundwater levels too far, (2) depleting storage in the aquifer, (3) degrading water quality, (4) allowing seawater intrusion, (5) causing land to subside, or (6) using groundwater in ways that reduce other people's surface water or harm ecosystems. Best management practices outlined by the Department of Water Resources include developing flexible operations that can accommodate changing climatic conditions.

Local agencies overlying the most stressed groundwater basins (those designated as medium- and high-priority, and critically overdrafted) are tasked with establishing groundwater sustainability agencies (GSAs) and formulating groundwater sustainability plans. If GSAs fail to prepare or implement plans the State Water Board can intervene and manage the basin.

The plans must characterize groundwater conditions and identify sustainability goals—with measurable objectives, thresholds for response, and undesirable results to be mitigated. With plans in place, GSAs will have a 20-year horizon to manage their basins to achieve sustainability.

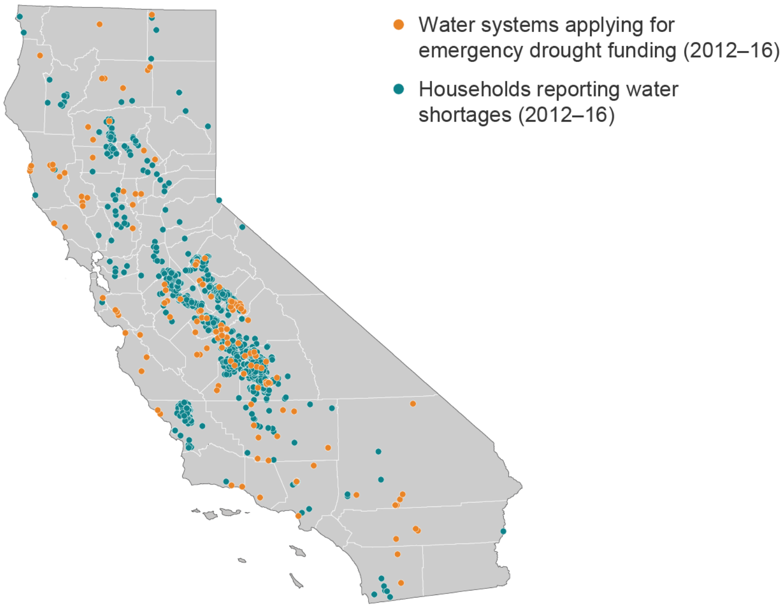
Rural Communities

Rural Californians are especially vulnerable to economic hardships when water is in short supply. As an example, drought-related land fallowing reduced farm employment in parts of the Central Valley in 2014 and 2015 (Howitt et al. 2015, Lund et al. 2018). Moreover, some communities outside the valley that depend on fisheries and outdoor recreation saw their livelihoods affected by drought, including restrictions on commercial and recreational salmon fishing (Hanak et al. 2015).

Rural residents are also more vulnerable to running out of water in droughts, because they are more likely to rely on groundwater from small community wells or domestic wells. Because these wells tend to be relatively shallow, they are susceptible to running dry when pumping lowers groundwater levels. During the 2012–16 drought, nearly 150 small community water systems had to request emergency support from the state to keep the taps running, and more than 2,500 domestic wells ran dry. Although problems were reported throughout the state, they were most pervasive in the San Joaquin Valley and in foothill communities in the southern Sierra (Figure 3).

FIGURE 3

Rural communities were vulnerable to drinking water shortages during the latest drought



SOURCES: Developed by the authors using data from the Department of Water Resources (household water shortages) and the State Water Board (small water systems).

NOTES: The figure shows 152 small community water systems (serving 15 connections or more) that sought emergency assistance. This total includes 6 urban water systems (serving more than 3,000 connections) that sought funds to consolidate with smaller communities, and 6 urban water systems that sought funds to address their own supply problems. The figure also shows households reporting water supply outages on a website the state set up to track dry domestic wells and other outages from systems serving less than 15 connections. After removing duplicates, DWR found a total of 2,598 cases, including 25 from surface water shortages, and the remainder from dry wells. It is very likely that some households did not report their well problems, resulting in an undercount.

Many rural communities lack the financial resources to address water supply and quality problems.[10] Efforts are underway to address these issues, including finding dedicated funding. And groundwater sustainability plans established under SGMA may begin to address problems of dry wells caused by extra agricultural pumping during droughts. But to date there is no long-term, comprehensive solution in place to address vulnerability of rural community drinking water supplies during severe droughts (Mitchell et al. 2017).

Freshwater Ecosystems

Managing rivers, streams, wetlands, and estuaries proved both difficult and controversial during the 2012–16 drought. (Drought-related problems in headwater forests present a different kind of management challenge, see Box 2 and summary in Butsic et al. 2017.) Changes in land use, water use, and water quality—along with the introduction of numerous non-native plants and animals—have degraded freshwater ecosystems (Mount et al. 2017). These changes have harmed many native species and reduced their populations. When droughts occur, these vulnerable species are most susceptible to significant further declines. To make matters worse, the recent drought was by far the hottest in recorded history. This added further stress, particularly to cold-water-dependent fishes like salmon.

[10] Rural water systems are also more likely to have levels of arsenic, nitrate, and other contaminants in well water that exceed state and federal drinking water standards. High levels of groundwater pumping during droughts contribute to arsenic problems (Smith et al. 2018). Solutions to both supply and quality problems can include drilling deeper wells and connecting to other sources of supply (Bostic and Chappelle 2018). Water quality problems can also be addressed by putting in treatment systems—something commonly done by urban utilities, which benefit from economies of scale that make the investments much less costly per resident served.

Box 2: Drought, Climate Change, and Headwater Forests

The drought of 2012–16 took a major toll on California's headwater forests. These forests—source areas for two-thirds of California's surface water—have been in decline for decades. Reducing their vulnerability to drought will require better management on a large scale.

Long-standing management practices—including logging methods and decades of wildfire suppression—have led to dense, dry forests that are susceptible to insects, disease, and increasingly intense wildfires. Hotter temperatures and more variable precipitation have made conditions worse. During the 2012–16 drought alone, 15 million trees died annually, surpassing anything in recorded history, and two of the state's largest wildfires occurred (Millar and Stephenson 2015, Asner et al. 2016).

Although progress is being made, correcting past management mistakes while coping with a changing climate will pose a formidable challenge to forest managers (Stephens et al. 2017). Extreme wildfires are likely to increase, potentially leading to the conversion of thousands of acres of conifer forest to shrublands, and harming air quality, water quality, habitat, recreation, and rural economies.

Adapting to climate trends and reducing the risk of severe wildfires will require major changes in forest management by federal and state governments, in cooperation with local agencies and landowners. This will involve strategic removal of forest fuels—most importantly, dead and downed woody debris and smaller trees in overly dense stands—through a mix of mechanical thinning, prescribed fire, and managed wildfire (Butsic et al. 2017). Accomplishing this task will require significant management, regulatory, and legal reforms—along with new funding mechanisms.

State and federal governments, local agencies, farmers, and environmental nonprofit groups all made extensive efforts to reduce the drought's harm to vulnerable freshwater species, especially salmon and waterbirds.[11] Monitoring has been insufficient to determine whether these efforts made a difference, but the drought clearly took a toll. The experience highlighted three basic problems for ecosystem management during drought (Mount et al. 2017). First, there is insufficient information—including biological monitoring and tracking of water availability—to effectively manage ecosystems under drought conditions. Second, there is insufficient planning for droughts, forcing federal and state agencies to undertake *ad hoc* actions, often with limited information. Finally, current approaches to allocating environmental water—which generally rely on minimum instream flow and water quality standards—are too inflexible for managing ecosystems during drought. Left unresolved, these issues will continue to impede effective ecosystem management in drought and non-drought years.

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[11] The appendix to Mount et al. (2017) provides eight case studies of freshwater ecosystem management actions. The website of the California Department of Fish and Wildlife (CDFW) provides summaries of emergency response actions undertaken by the department to reduce drought impacts to native animals across the state.

Drought Pressures from a Changing Climate

The unusually warm and dry drought of 2012–16 provided a crucial test of California's ability to manage severe water scarcity. It also provided a vivid illustration of conditions that may become more common as the climate warms. To better understand the pressures created by a changing climate, we used two approaches. First, based on existing literature (including a 2018 study by Swain et al.), we evaluated whether droughts similar to or more intense than the 2012–16 drought are more likely to occur in the future.[12] This included comparing preindustrial conditions (before 1850, when greenhouse gasses began to rise significantly) with future conditions, and evaluating the potential for increasing precipitation whiplash and drought intensity. Second, we used modeling described in Ullrich et al. (in review) to evaluate changes in the meteorologic and hydrologic characteristics of severe droughts in the future that could pose new management challenges. This work simulated the 2012–16 drought under mid-century conditions.[13]

We chose to focus on conditions at the middle of this century because it is the planning horizon for groundwater sustainability plans under SGMA, as well as for many urban and agricultural water system plans. Additionally, several of the policy recommendations outlined below are likely to take two to three decades to implement.

Five Climate Pressures

These modeling efforts provide insights on changing climate conditions that will increase pressures on water management in California. Here we focus on climate pressures that will have significant impact on California's water system: rising temperatures, shrinking snowpack, shorter and more intense wet seasons, more volatile precipitation patterns, and rising sea level. Most of these changes are already well underway, and climate modeling projects significant further change with moderate to high confidence (He and Guatam 2016 and Office of Environmental Health Hazard Assessment 2018).

- **Rising temperatures** (*high confidence*). Average temperatures in California—particularly during the winter—have been rising over the past 40 years (Office of Environmental Health Hazard Assessment 2018). A large and growing body of climate projections shows that the high temperatures of the recent drought will likely become more common (Figure 4a). This will have broad implications for water management (Diffenbaugh et al. 2015). Warming will also increase the number of extreme temperature days—when temperatures exceed 104°F—with serious risks to public health.[14] Finally, temperature plays a direct role in reducing runoff by increasing evaporation. This may become more important in the future in California and is already contributing to declines in flows on the Colorado River (Woodhouse and Pederson 2018).
- **Shrinking snowpack** (*high confidence*). California's water supply, hydropower, and flood control systems all depend on winter precipitation falling in the mountains as snow rather than rain, followed by a slow release of water in spring as snow melts. While average annual precipitation has remained unchanged over the past 100 years, the amount of water stored in the snowpack (called "snow water equivalent") has been

[12] The Swain et al. (2018) study relied on a large ensemble of climate models to examine the frequency and magnitude of droughts and wet periods—including severe floods—under a business-as-usual scenario for greenhouse gas emissions. The study used the Community Earth System Model Large Ensemble (CESM-LENS) under RCP8.5 greenhouse gas emissions and compared to preindustrial conditions. The ensemble approach allowed the authors to directly evaluate the probability of historically rare but high-impact extreme wet and dry events.

[13] The "drought of the future" is based on the basic meteorological character of the 2012–16 drought—including timing of heat waves and rain events—but modeled using the Weather Research and Forecasting (WRF) model for projected global climate conditions in the period 2042–46. This exercise also modeled the wet year of 2017 as it would look in 2047. The projected global climate conditions were derived from the Coupled Model Intercomparison Project (CMIP5): a coupled ocean-atmosphere general circulation model using Representative Concentration Pathway 8.5 (RCP8.5) for greenhouse gas emissions, which is considered the high end of likely emissions. A complete description of this modeling is contained in Ullrich et al. (in review).

[14] This is the threshold for temperatures considered extreme on the Cal-Adapt website (set to the 98th historical percentile of daily maximum/minimum temperatures between April and October from 1961–90). As Gershonov et al. (2009) note in their study of rising temperatures in California, there is no one objective and uniform definition of ''heat wave.'' Mortality increases sharply when extreme heat persists, but specific details vary regionally.

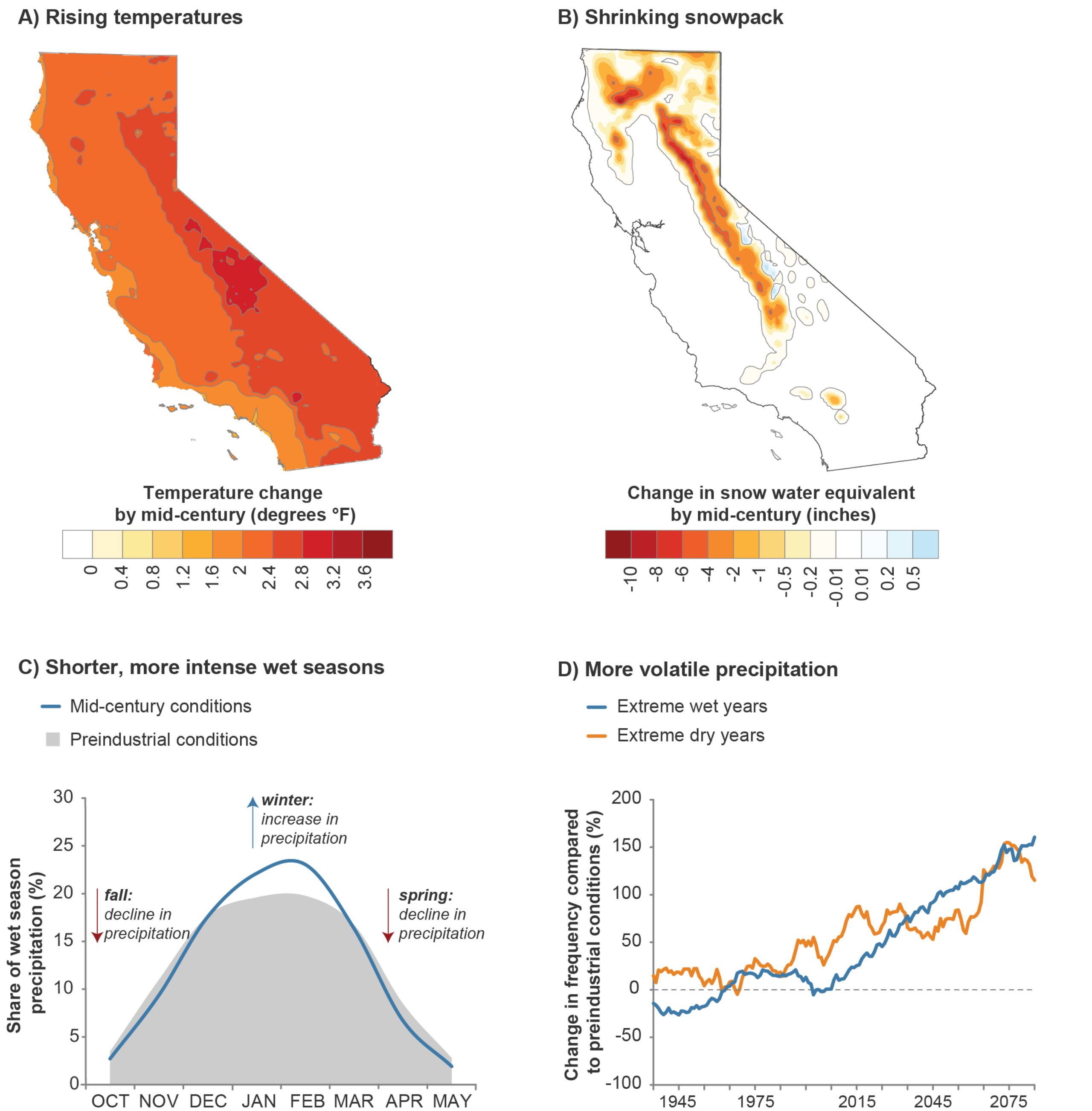
declining and the timing of peak snowmelt has been occurring earlier in the spring (He and Guatam 2016). Both changes reflect higher winter and spring temperatures. Modeling for this study, along with numerous other studies, project with high confidence that this trend will continue (Figure 4b).[15] As part of this trend, "snow droughts"—periods of little to no snowpack, as in 2015—will increase, even in relatively wet years (Harpold et al. 2017).

- **Shorter, more intense wet seasons and longer dry seasons** (*moderate confidence*). Climate simulations used for this study and others highlight changes to "seasonality"—the temperature and precipitation differences between seasons—as the climate warms (Berg and Hall 2015). Although average annual precipitation is unlikely to change, the wet season is expected to become both shorter and more intense, with less precipitation in the late fall and early spring (Figure 4c). This includes an increase in intensity of winter storms.
- **More volatile precipitation** (*moderate confidence*). California has large year-to-year swings in precipitation, which appear to be increasing in magnitude (He and Guatam 2016). Despite showing no significant change in annual average volume of precipitation, projections point toward a significant increase in the frequency of whiplash events, when extreme dry and extreme wet years occur in succession (Figure 4d). Extreme wet events are also expected to become particularly pronounced by mid-century. These will likely contain intense "atmospheric rivers"—geographically concentrated storms that, when clustered together, increase the potential for very large, damaging floods, similar to the historic floods of 1861–62 (Dettinger 2013).[16]
- **Rising seas** (*high confidence*). The planet's seas have been rising since the end of the last Ice Age. But on average, they have been rising faster for much of the past century—a trend projected to continue into the indefinite future (Office of Environmental Health Hazard Assessment 2018). Depending on the level of greenhouse gas emissions, mean sea level is expected to rise between 0.5 and 1.2 feet by mid-century relative to the year 2000, with much larger rises after 2050 (Sweet et al. 2017). Rising seas have indirect consequences for drought management, principally by increasing the likelihood of saltwater intrusion in coastal aquifers and estuaries, including the Sacramento–San Joaquin Delta.

[15] See for instance Walton et al. (2017), Hatchett et al. (2017), Berg and Hall (2017), and Huang et al. (2018).
[16] These results are from Swain et al. (2018). Although the study projects an increase in the frequency of extreme dry years, it does not find large changes in the occurrence of consecutive lower precipitation years. Confidence in this projection is moderate.

FIGURE 4

Climate change will affect temperatures, snowpack, and seasonal and yearly precipitation patterns



SOURCES: Panels A and B: Ullrich et al. (in review); panels C and D: Swain et al. (2018).

NOTES: Panel A shows average temperature increases relative to the 2012–16 drought for a similar drought in mid-century (2042–46). Panel B shows the decline in snowpack relative to 2017 for a similar wet year in mid-century (2047); the total statewide decline is 25 percent. Panel C shows how the distribution of precipitation during the wet season changes by mid-century relative to preindustrial (circa 1850) conditions. Fall and spring precipitation declines while winter precipitation increases. Panel D shows projected changes in the likelihood of a year being extremely wet (similar to 2017) or extremely dry (similar to 1977). Extreme wet years have a 1-in-25 chance of occurrence in any given year under preindustrial conditions; for extreme dry years, the chance of occurrence is 1-in-100. The likelihood—or percentage change in frequency—is increasing with the changing climate.

It is important to note that most long-range projections for California's climate do not show major changes in average precipitation—only seasonal and annual changes in its distribution and form (more rain and less snow). Yet each of these five climate trends, alone and in combination, will affect the availability of water.

Impacts on Water Management

Reducing California's vulnerability to these five climate pressures will require federal, state, regional, and local institutions to take action on multiple fronts. Major challenges for the state's water grid include the following:

- **Operating multipurpose reservoirs.** Large multipurpose reservoirs are an essential part of California's water infrastructure. Reservoir operating rules seek to balance the need to keep reservoirs partially empty to capture winter and spring floodwaters against the need to fill them to supply water during the dry season and keep some water in reserve as a hedge against droughts. Several climate pressures—including reductions in the share of water stored as snow, greater intensity of winter storms, and increasing risk of extreme wet years—may shift the emphasis from water supply to protecting the public against flood risk, reducing the water available from reservoirs in some years. Increasing temperatures and reduced snowpack will also warm the water stored in reservoirs, making it harder to manage for temperature-sensitive species downstream. During the recent drought, salmon and trout—including endangered winter-run Chinook salmon—were harmed by poor management of cold water in reservoirs (Mount et al. 2017).
- **Managing the Sacramento–San Joaquin Delta.** The Delta—which is an important hub for water supply—will be affected by climate change in several ways. Sea level rise and greater drought intensity will increase salinity in the Delta. This will require more releases from upstream reservoirs to keep water fresh enough for in-Delta farm and urban uses and water exports. Since this additional water flows to the sea, it will reduce available water supplies (Gartrell et al. 2017, Mount et al. 2018). Increasing intensity of atmospheric rivers and large floods, in conjunction with rising sea level, will also increase the risk of failures of the Delta's fragile levees. These levees help keep Delta waters fresh enough for human uses. Warmer Delta temperatures will further stress some native fishes and encourage invasive plant and animal species.

In addition to these statewide challenges, each sector faces its own unique issues:

- **Adapting urban water systems.** Although most urban water systems already have effective drought management programs, climate change will require continued adaptation. Systems that rely on water imported from mountainous regions—including the drought-affected upper Colorado River watershed—may see declines in supply reliability from changes in precipitation and reservoir operations. Without changes in urban landscaping, rising temperatures and shorter wet seasons will increase water demands for landscape irrigation—now roughly half of urban water use. More intense local storm runoff, concentrated in fewer months, will make it harder for communities to capture stormwater for use as a local water supply. Increasing drought intensity—combined with conservation efforts that reduce indoor water use—will impact wastewater systems that rely upon certain volumes of flow to meet collection and treatment plant requirements. These same pressures will also reduce the volumes of recycled water.[17] Sea level rise will also require adjustments at wastewater treatment plants that discharge into coastal waters (Hummel et al. 2018).
- **Managing farm water demands.** Today, farmland irrigation uses roughly four times as much water as California's cities and suburbs. Rising temperatures and shorter wet seasons are likely to raise agriculture's demand for water by lengthening the growing season and increasing early-season demand for irrigation water. The types of crops farmers can grow in some regions are also likely to change.[18] The growing demand for agricultural water will increase the competition over scarce water supplies and raise production

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[17] Wastewater utilities already faced some of these challenges during the latest drought (Mitchell et al. 2017, California Urban Water Agencies 2017, and Tran et al. 2017).

[18] There are many uncertainties about the amount of water to be used by crops in the future. Many of the crops likely to experience the biggest climate-related constraints are not currently major crops in California, and it is unclear how some existing crops will respond to warming (Pathak et al. 2018).

costs. It will also make it more difficult for farmers to bring groundwater basins into balance under SGMA because less water will be available for recharging aquifers. And if the trend toward expanded acreage of perennial crops such as nuts and fruits continues, it will become increasingly expensive to fallow land in response to water shortages (Adamson et al. 2017).

- **Supplying safe and reliable water to rural communities.** Groundwater is the main source of water for many rural communities. Although SGMA should ultimately help stabilize long-term groundwater levels, many basins are likely to reduce overdraft gradually, leading to continued lowering of the water table between now and 2040. And the increasing intensity of drought in farming regions could lead to pressures to slow the pace of SGMA implementation, worsening the impacts on shallow wells.
- **Protecting freshwater ecosystems.** The most difficult challenge will be managing freshwater ecosystems. Problems encountered during the latest drought—high water temperatures, low flows, insufficient cold water stored in reservoirs, and degraded habitat—will all likely worsen as droughts become more intense. Management of cold-water-dependent species—including salmon, trout, and some native Delta fishes such as Delta smelt—is likely to be most vexing. These species will be affected by both rising temperatures and more frequent low-flow events, conditions that could make it impossible for some to remain viable in their historic locations (Moyle et al. 2013). In rivers where reservoirs provide cold water for fish, this will exacerbate conflicts over using water to support ecosystems versus urban and farm economies. Rising water temperatures will also increase the likelihood of harmful algal blooms, which affect fish and wildlife, drinking water quality, and recreation.

Reforms Needed to Prepare for Future Droughts

The following suite of reforms in water policy and management can reduce the social, economic, and environmental consequences of future droughts. This program should seek to follow several core principles:

- **Manage supply and demand together** rather than taking actions that focus solely on one or the other.
- **Create multiple benefits** whenever possible.
- **Build flexibility into operations** to allow more nimble response to changing drought conditions.

In addition, many actions will require making trade-offs. These need to be made explicit and, where possible, mitigated. Finally, all actions should have clearly defined local, regional, state, or federal responsibilities.

The good news is that many needed reforms are already underway in some form, either as initiatives of local and state agencies, as proposals in the current California Water Plan, or in Governor Brown's California Water Action Plan. But several essential reforms are not yet on the agenda and should be incorporated in policies and planning. Equally important, clear responsibilities for action have not yet been assigned.

We offer four areas of reform for improving drought preparation and response. We also suggest the entities and agencies that should be responsible for implementation, noted in italics. Specific recommendations are explained in more detail in past PPIC studies, which are listed in Box 4 (page 23).

Reform 1: Plan Ahead

Successful adaptation to changing conditions—including increased drought intensity, precipitation whiplash, and rising sea level—will require serious advance planning. A common finding of the studies of institutional responses to the 2012–16 drought was that planning for drought response and recovery paid off (Mount et al. 2017, Lund et al. 2018). It reduced water conflict and economic and environmental costs. Although state and local agencies have tried various approaches to drought planning, the results have been uneven and, in some sectors, insufficient. One essential—and often missing—element is the need to do drought planning not only at the local scale, but also at the regional scale. Cooperation among multiple agencies makes it possible to take advantage of broader opportunities such as trading, changes in operation, and regional investments in supplies, thereby reducing drought impacts. Top priorities for improving drought planning include:

- **Strengthen urban water management plans.** All plans should go beyond current state requirements and include "climate stress tests" to evaluate supply reliability in light of longer droughts and increased warming (Mitchell et al. 2017). Standardized approaches to planning for increasing drought intensity and precipitation whiplash should be adopted to guide this effort, while recognizing the diverse supply conditions of utilities in different parts of the state. *Urban utilities should take the lead on this reform. The state should continue to set planning requirements, and provide oversight, incentives, and guidance on incorporating climate change projections into stress tests.*
- **Ensure effective groundwater sustainability plans.** Successful implementation of SGMA is the most important step toward drought security for California agriculture. Sustainability plans should describe preparations for groundwater drawdowns during severe droughts, similar to 2012–16. They should also pursue regional approaches—including coordinated supply and land fallowing efforts—to help meet sustainability goals (Hanak et al. 2017a, 2018). The proliferation of GSAs—particularly in large, critically overdrafted basins—is an impediment to coordination (Figure 5). In some basins, consolidation of GSAs will be needed to meet SGMA's objectives and manage costs.[19] *Local GSAs, counties, and regional water associations should take the lead on regional integration. The state should promote these efforts through planning requirements, oversight, incentives, and guidance on incorporating climate change projections into sustainability plans.*
- **Develop drinking water plans for rural communities.** Drinking water vulnerabilities in small rural communities arise in every major drought, and could worsen as the climate changes. Small rural systems do not have the financial capacity for drought planning and mitigation. State and local partners should use the experience from the recent drought to identify communities at highest risk, connect them to larger systems where feasible, and devise drought response programs for the others (Hanak et al. 2015). *The state, with local partners (such as counties, GSAs, and nonprofit organizations) should help fund and coordinate this activity. GSAs should incorporate measures in their sustainability plans to mitigate wells that go dry from local pumping.*[20]
- **Prepare ecosystem drought plans.** Reducing the impacts of future drought requires watershed-level ecosystem drought plans (Mount et al. 2017).[21] To protect at-risk species during severe drought, these plans should identify actions to be taken in advance—such as strategic investments in water acquisitions and critical "refugia" (habitat that is resilient to climate change, such as cold-water springs). They should also identify actions that would speed recovery after drought, and opportunities to reduce impacts through actions such as water trading and groundwater banking. Such opportunities should be integrated into regional and local water supply management plans. *Ecosystem drought plans should be developed at the watershed scale, through a cooperative process including state, federal, and local agencies, tribes, and stakeholder groups. The state should provide technical and financial support and, where required, regulatory oversight.*

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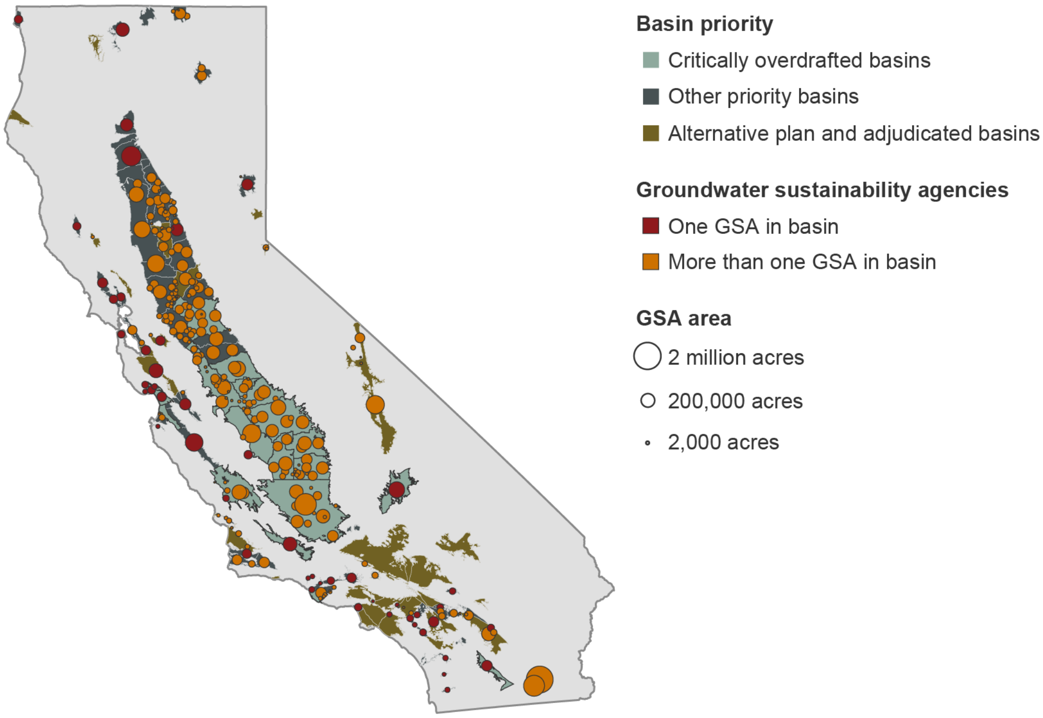
[19] As an example, water users established 121 GSAs within the 15 priority basins in the San Joaquin Valley. See Escriva-Bou and Jezdimirovic (2017) and Conrad et al. (2018) for discussions of the benefits and challenges of consolidation.
[20] See Pottinger (2018a) for an example of how a groundwater bank in Kern County is mitigating pumping impacts on neighboring wells.
[21] Planning approaches such as these helped Victoria, Australia manage difficult ecosystem issues and trade-offs during the Millennium Drought (Mount et al. 2016b).

FIGURE 5
The proliferation of groundwater sustainability agencies will complicate SGMA implementation



SOURCE: Escriva-Bou and Jezdimirovic (2017), using data from the Department of Water Resources' SGMA Portal.

NOTES: As of July 2017, there were more than 250 GSAs formed for 140 basins. SGMA established different procedures for adjudicated basins (where courts settled disputes over how much groundwater can be extracted by each landowner) and for local groundwater agencies that have operated their basins sustainably for at least 10 years and have submitted alternative plans. Some changes to basin boundaries and priority levels are likely as a result of a basin prioritization update that is now underway.

Reform 2: Upgrade the Water Grid

During drought, California relies heavily on its network of surface and groundwater storage and conveyance facilities to manage supplies and, in some regions, to provide water to meet ecosystem needs for native species. This water grid will become an even more important asset in the more intense droughts of the future. Yet elements of this grid are in trouble, and the climate pressures outlined above will make it harder to simultaneously store more water for drought while managing flood risk and protecting freshwater ecosystems. California needs a more robust, better-integrated water grid. The state has made important advances in assessing and improving its water supply infrastructure, but it still lacks a comprehensive program to address storage, conveyance, and operational challenges by mid-century. Wherever possible, infrastructure investments should seek to achieve multiple benefits (e.g., setting levees back to reduce flood risk, promote groundwater recharge, and improve habitat for native fish and birds). Top priorities are:

- **Improve conveyance and storage capacity.** As illustrated by the recent Oroville Dam crisis, the state's water management infrastructure is aging and needs repair.[22] California needs to comprehensively assess

[22] For example, following the Oroville Dam spillway failures in 2017 the state ordered a review of 93 "high risk" dams that could pose a risk to life and property downstream due to failure during floods (see coverage by the *Sacramento Bee*). This ongoing investigation will examine the status of these dams and repairs or upgrades needed to meet safety standards. Conveyance in the San Joaquin Valley is another problem area, where groundwater pumping has reduced the capacity of many canals to convey water. Most significant is the loss of more than half of the capacity of the Friant–Kern Canal—the main vehicle to move water from the San Joaquin River to the southern part of the valley for water use and groundwater recharge (Hanak et al. 2018).

weaknesses in the storage and conveyance system—including important canals and aqueducts that help recharge groundwater, deliver surface water, and manage floods—and undertake a multi-decadal upgrade of this network.[23] Aquifers—with their large capacity for storage—will become much more important as a drought reserve, as will partnerships to store more water in "groundwater banks" (Hanak et al. 2018).[24] Strategic investments can help California store water more effectively and take better advantage of opportunities to trade and share it—an important way to reduce the social, economic, and environmental costs of using less. The controversial and costly proposal to improve water conveyance in the Delta, known as California WaterFix, could facilitate statewide adaptation to changing runoff from Northern California mountains—a critical water supply source. It would make it easier to recharge overdrafted aquifers, and enable more water users to benefit from planned storage investments in the Sacramento Valley.[25] *Agencies from the state (DWR) and federal government (US Bureau of Reclamation and US Army Corps of Engineers) should lead a comprehensive, integrated drought and flood infrastructure assessment and rehabilitation effort. Regional coordination and cooperation will be needed to develop and fund new water infrastructure. The state should provide planning assistance and, where appropriate, financial help.*

- **Modernize and integrate operations.** Currently, many reservoirs have their own set of rules—based on outdated hydrologic assumptions—and are operated by an array of federal, state, regional, and local agencies. Adapting to a more volatile climate—including more intense atmospheric rivers—will require more operational flexibility of conveyance facilities and above- and below-ground storage to ensure they work together as an integrated water supply and flood management system. One important opportunity for better integration is to merge the Central Valley Project (CVP) and State Water Project (SWP) into a single entity that functions as a regulated, independent wholesale water utility (Box 3). Within regions, there are also numerous opportunities to further integrate the operation of local water systems (Gray et al. 2015). This modernization must be accompanied by investments to update hydrological assumptions for reservoirs. Measures are also needed to improve water accounting. This includes strengthening monitoring of flow and water quality, documenting water rights, increasing transparency of water data, and tracking net water use and groundwater recharge.[26] *State and federal governments should take the lead on system integration, starting with the merger of the CVP and SWP into a single water utility. The state (especially DWR and the State Water Board) should lead the modernization of water accounting systems and reservoir operations through a combination of regulations and incentives.*

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[23] The state has recently updated the Central Valley Flood Protection Plan, which seeks to improve flood protection and habitat conditions in Central Valley floodplains, including adapting to increasing precipitation variability. Although this plan identifies water supply as part of a multi-benefit strategy, it has limited specifics on how to jointly address flood and water supply management issues.

[24] See Hanak and Stryjewski (2012) and Hanak et al. (2018) for information on how these banks operate. The largest efforts to date are in Kern County.

[25] California WaterFix is an ambitious effort to improve conveyance in the Sacramento–San Joaquin Delta while reducing environmental consequences of water export operations. It involves the construction of tunnels to take water from the Sacramento River and deliver it to export pumps in the south Delta. It will increase the reliability of supply and is a hedge against climate change and sea level rise. But its benefits for the environment are uncertain. For a brief summary, see California's Water: The Sacramento-San Joaquin Delta.

[26] Escriva-Bou et al. (2016) provide an overview of accounting needs and comparison with accounting efforts in other drought-prone states and countries. Gartrell et al. (2017) describe improvements to environmental water accounting, using the example of the Sacramento–San Joaquin Delta. Mount et al. (2016a) describe federal priorities for action, given key federal roles in generating water system information.

Box 3: Uniting the State's Largest Water Projects

The state's largest water management projects are the Central Valley Project (CVP), run by the US Bureau of Reclamation, and the State Water Project (SWP), run by the California Department of Water Resources (DWR). Although each project has its own operating rules and obligations, they share a Coordinated Operating Agreement.

Having parallel systems—with occasionally conflicting objectives—has long been viewed as inefficient. It was a major challenge for managing water supply and ecosystems in the Delta during the latest drought (Mount et al. 2017). It has also complicated state efforts to improve conveyance in the Delta and the Central Valley. The separate management of these projects hinders efficient water allocation and use, ecosystem management, and climate adaptation.

In a 2010 review of the SWP, the Little Hoover Commission recommended that the project be separated from DWR and managed as an independent wholesale water utility. Hanak et al. (2011) built upon the commission's proposal and recommended a structure modeled after the California Independent System Operator (ISO) that manages California's electrical grid. This would involve uniting the SWP and CVP into a single nonprofit, public benefit corporation to hold and manage both projects' assets and water rights. The single project would be unencumbered by conflicting operating rules and would increase capacity to adapt to changing conditions.

Uniting the CVP and SWP—whether as a water ISO or through some other structure—meets the core principles needed for successful drought adaptation reform. It allows for simultaneous management of supply and demand (particularly through trading), it has greater capacity to manage water for multiple benefits, it can be nimble and responsive to dry conditions and wet year opportunities, and, as a unified system, can more efficiently manage the inevitable trade-offs that will occur.

Ultimately, further gains could be had by incorporating local projects as well as California's Colorado River facilities into a unified system.

Reform 3: Update Water Allocation Rules

California should comprehensively update its governance of water allocation systems, including rules governing water trading and groundwater recharge, the setting and enforcing of environmental standards, and the administration of the state's century-old water rights system. The goals of this update should be to find equitable and efficient ways to allocate supplies among competing demands during times of scarcity, while promoting efforts to capture and store water during times of abundance. Priority reforms include:

- **Promote groundwater recharge.** The rules governing diversion of water from rivers for groundwater storage projects are unclear, and permitting needs to be more expeditious to take advantage of surplus flows. More clarity is needed on the volumes of water that can be diverted during high flow events without causing harm to downstream water-right holders, environmental uses, and natural recharge of local groundwater basins (Hanak et al. 2018). *The State Water Board should take the lead in updating rules governing capture and recharge during high flows.*

- **Streamline trading and banking.** Limitations in conveyance infrastructure are compounded by difficulties in securing permits for trades and groundwater banking. Both tools are necessary to make efficient use of storage and conveyance infrastructure and to maximize the capture and storage of water. While it is important to ensure that trading and banking do not harm other water users or the environment, it is difficult to receive approvals for these activities in a timely manner. New administrative approaches are needed to simplify the approval process—such as through programmatic environmental reviews and pre-approvals of some types of trades (Gray et al. 2015). *The State Water Board should lead a comprehensive update and streamlining of rules governing trading and banking of water. Federal, state, and local agencies should expedite the approval process for using their conveyance facilities to move water for recharge.*
- **Give the environment a water budget.** Current practices that rely on minimum instream flow and water quality standards do not provide enough flexibility to support freshwater ecosystems during drought. A new approach is needed that grants ecosystems a water budget that can be flexibly managed like a water right—including storing and trading of water within the budget (Mount et al. 2017). Negotiated settlements and financial incentives can be used to augment ecosystem budgets above current regulatory baselines. This approach allows environmental managers to prepare for drought and to have assets for response. It will create new opportunities for partnerships with other water users, and can help reduce conflict over scarce supplies.[27] *The State Water Board, with legislative support, should set ecosystem water budgets as part of water quality control plans.*
- **Improve water rights administration.** The State Water Board faces many challenges in administering water rights during droughts. To effectively and efficiently manage droughts of the future, the State Water Board must have more clearly defined and comprehensive jurisdiction over water rights (Gray et al. 2015). This includes permitting authority over all surface water rights—including riparian water rights (granted to users with property connected to a river) and pre-1914 rights (established before the adoption of the modern Water Code)—as well as groundwater pumping that has a significant effect on surface water resources.[28] Today the board's jurisdiction over these rights is more limited than for surface rights established since 1914, which restricts its ability to effectively oversee water allocations when supplies are tight. *The legislature should clarify the State Water Board's water rights authority over all surface water and any groundwater that is connected to surface water.*

Reform 4: Find the Money

Although most public attention focuses on state and federal funding for water projects, local revenue—from water and sewer bills and local taxes—accounts for roughly 85 percent of the more than $30 billion spent annually on water management (Hanak et al. 2014, 2016). Following the long tradition of local ratepayer funding of water supply projects, water users will need to cover the bulk of investments needed to repair and upgrade the water grid.[29] However, the state's water system also has numerous "fiscal orphans"—areas where available funding is far below ongoing needs and there is no straightforward way to fill the gap. These include several areas where climate pressures will increase vulnerability: safe drinking water in poor rural communities, freshwater

[27] The State Water Board's recent proposal to dedicate a share of unimpaired flows for the environment on tributaries to the San Joaquin River is a step in this direction, but more flexibility would likely be needed—including the ability to trade and store water—to improve environmental outcomes (Mount et al. 2017).

[28] It is also likely that the State Water Board will need to revise some water rights permits to account for changes in hydrology. Most appropriative rights are limited by season and water-year type, and many junior appropriators may divert water only when flows are relatively high. Even if overall volumes of precipitation remain unchanged, more concentrated winter and early-spring runoff will result in less water available for some permittees to divert during late spring and early summer (Null and Viers 2013). To compensate for this hydrologic shift, the board may have to amend some permits to allow greater diversions during the briefer high water periods. In doing so, it will have to consider senior rights and ecological requirements at these times.

[29] Contrary to popular perception, most investments in water storage and conveyance projects in California have been funded by water users. The main exception is irrigation water supplies from the Central Valley Project, which was built with federal subsidies. Most of today's farmers do not benefit from those subsidies, however, because they are factored into land values. See Hanak et al. (2009, 2011).

ecosystems and headwater forests, and flood and stormwater management. Adaptation to more extreme droughts and precipitation whiplash will require well-defined, reliable sources of funding. Several reforms are needed:

- **Use general obligation bonds for public benefit.** The state has come to rely on general obligation (GO) bonds to support its contributions to water projects. These funds are often directed to the fiscal orphans, but there is ongoing pressure to use bonds to substitute for investments that water users could readily cover through water rates.[30] GO bonds should be used for projects that address environmental or social justice concerns or provide other demonstrable public benefits such as flood protection and restoration of groundwater basins (Hanak et al. 2014). *The state legislature and the voters should take the lead in requiring public benefit from general obligation bonds.*
- **Fill the gaps for fiscal orphans.** The funding gap for fiscal orphans is $2–$3 billion per year, and water bonds are insufficient to close this gap.[31] California needs a broader, more reliable mix of state and local funding sources, including new fees and taxes. Examples include parcel taxes, small surcharges on water and chemical use, and small increments to the sales tax.[32] Such measures are already used in some California communities and in other states (Hanak et al. 2014). *State and regional action is required to secure adequate funding for rural drinking water supplies, ecosystems, and flood and stormwater management.*
- **Reform water pricing law.** Proposition 218, a constitutional amendment approved by voters in 1996, limits the ability of publicly owned water utilities to implement drought-responsive pricing, such as charging higher prices when supplies become scarce and water use goes down (Mitchell et al. 2017). This makes it harder to maintain fiscal solvency and to encourage conservation. In addition, these utilities need more flexibility to implement lifeline rate relief programs to maintain affordability for poor residents. California's investor-owned water utilities do not face these constraints, nor do its energy or telecommunications utilities. *The legislature and state voters should address obstacles to efficient and equitable water pricing created by Proposition 218.*

Conclusion: The Work Ahead

A changing climate is one of many factors that will affect water management in California in the years and decades to come. Population growth, land development, water quality changes, new regulations, energy costs, new invasive species, global agricultural markets: these and many more changes will affect the way water is used and managed. In this report we have focused on the pressures that California's changing climate will put on supplies to cities, farms, rural communities, and freshwater ecosystems, recognizing that other factors will also play a role. Anticipating and preparing for droughts of the future—with higher temperatures, shrinking snowpack, shorter and more intense wet seasons, more frequent extreme wet and dry years, and rising seas—will help manage an array of other challenges, including growing risk of extreme flooding. It is *drought* that tests the vulnerabilities of water supply systems, and so drought should be the unifying focus of reforms. Equally important, the reforms outlined here will improve drought resilience for today's conditions, not just for the future.

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[30] Hanak et al. (2014) provide a detailed review of how more than $15 billion in water bonds passed from 2000 to 2006 were spent. Jezdimirovic and Hanak (2016, 2017) review expenditures under Proposition 1, a $7.5 billion bond approved by voters in 2014.

[31] This includes annual gaps of $30–$160 million for safe drinking water in poor rural communities, $800–$1,000 million for flood protection, $500–$800 million for stormwater management, $400–$700 million for aquatic ecosystem management, and $200–$300 million for integrated water management efforts such as SGMA (Hanak et al. 2014). By comparison, annual spending from water bonds rarely exceeds $1 billion per year.

[32] One public finance expert has proposed that GO bonds include an appropriation of general fund dollars to cover ongoing operations and maintenance costs related to bond investments for some fiscal orphans, such as safe drinking water in disadvantaged communities (Pottinger 2018b).

The drought of 2012–16 raised awareness of the many challenges California faces in drought management. Yet it is important to note that California is making good progress on many fronts. With their strong ratepayer base, the state's urban water utilities—which serve more than 90 percent of all residents and most businesses—have shown their capacity to respond to extreme drought through diversification of sources of supply and programs that reduce demand. The reforms recommended here—better stress tests, upgrades to storage and conveyance infrastructure, system integration across multiple water agencies, streamlined trading and banking, and reform of Proposition 218—will help this sector continue to adapt.

Agricultural water management has also shown progress toward building resilience. Farmers have steadily increased the economic efficiency of their water use.[33] But over-reliance on unsustainable use of groundwater threatens this progress and increases this sector's vulnerability to future drought. Continued progress on SGMA—a landmark change in water policy—is an important hedge against a changing climate. Many of the reforms recommended here—including better planning, upgrading storage and conveyance, improving operations and accounting, merging the CVP and SWP, streamlining water rights administration, facilitating trading and banking, and clarifying how much water is available for recharge—will help achieve SGMA's sustainability objectives.

Progress has also been made on providing safe drinking water to vulnerable rural residents. The state committed extensive resources to managing this issue during the 2012–16 drought and legislation enacted in the past few years will help promote consolidation of small water systems and make it easier for these systems to access funding.[34] But these efforts are a work in progress. The state still lacks good information on populations at risk of losing water supplies during drought, and no reliable funding is available to help support ongoing operations and maintenance. Finally, groundwater sustainability plans need to protect drinking water supplies when farmers resort to extra pumping during droughts. The planning and funding reforms recommended here will go a long way to resolving this problem.

Despite progress on many fronts, there are still unresolved challenges ahead. At the top of the list is management of freshwater ecosystems that are vulnerable to more intense droughts. Efforts to date have been unsuccessful in arresting the decline of native fish species, and no current plans are likely to resolve this problem. The state—in cooperation with federal and local partners—needs a change of course. The reforms recommended here—ecosystem planning, ecosystem water budgets, new and more reliable funding sources—hold promise for tackling this difficult problem.

To meet the challenge of changing conditions, it is also essential that the state manage water rights efficiently and flexibly. Our recommendation to improve water rights administration—including clarifying the State Water Board's authority over pre-1914 and riparian surface rights and groundwater pumping that has a significant impact on surface water—will help all sectors respond to drought. But changing water rights administration is notoriously difficult.

Finally, responding to these many challenges requires something that cannot be legislated: leadership. Strong leadership from state and local institutions has guided the development of the water system that California relies on today. Despite its many problems, this system has served California well, supporting robust economic growth

[33] Adjusted for inflation, the value of farm output and related food processing has more than doubled since the late 1960s despite little change in acreage or irrigation water used. See *California's Water: Water for Farms*.

[34] For recent legislation, see McCann and Chappelle (2015, 2017) and McCann and Hanak (2016). Bostic and Chappelle (2018) describe progress in water system consolidations.

even in the face of occasional severe drought. Leadership—an essential ingredient for continued progress in water management—will be needed to prepare for droughts of the future.

Box 4: Drought Lessons In Depth

As part of a project aimed at drawing lessons from California's 2012–16 drought to improve preparation for future droughts, the PPIC Water Policy Center has published a series of reports looking at specific sectors and cross-cutting issues. These studies informed the recommendations in this report and contain more complete descriptions of drought impacts.

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