Lessons from California's 2012–2016 Drought

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Abstract: California's 5-year drought has ended, even as its aftermath lingers. From 2012–2016 much or all of California was under severe drought conditions, with greatly diminished precipitation, snowpack, and streamflow and higher temperatures. Water shortages to forests, aquatic ecosystems, hydroelectric power plants, rural drinking water supplies, agriculture, and cities caused billions of dollars in economic losses, killed millions of forest trees, brought several fish species closer to extinction, and caused inconvenience and some expense to millions of households and businesses. The drought also brought innovations and improvements in water management, some of which will better prepare California for future droughts. This paper summarizes the magnitude and impacts of the 2012–2016 California drought. The paper then reviews innovations arising from the drought in the larger historical context of water management in California. Lessons for California and for modern drought management are then discussed. Droughts in modern, well-managed water systems serving globalized economies need not be economically catastrophic, but will always have impacts and challenges, particularly for native ecosystems. In California and every other water system, droughts usefully expose weaknesses and inadequate preparation in water management. In this regard for California, managers of ecosystems and small rural water supplies had the most to learn. **DOI:** 10.1061/(ASCE)WR.1943-5452.0000984.

Introduction

Drought is a temporary reduction in water availability below normal quantities. Droughts can be for only a few weeks or endure for years or centuries—in which they blend with changes in climate. In rain-fed agricultural systems, droughts of a few weeks can be devastating. Places such as California, with a long summer dry season and a Mediterranean climate, each year face what would be the worst drought ever seen in more humid American states.

From 2012 to 2016, California experienced one of its deepest, longest, and warmest historical droughts. Many effects from this drought to forests, native fish populations, groundwater levels, and land subsidence will endure for decades. Lessons and innovations from the drought also will last for decades and improve California's ability to manage future droughts. Past and future droughts are always present in managing water in California. California enters each drought with management institutions, policies, infrastructure, water storage conditions, and water demands influenced by past droughts. Future droughts are also in the minds of water managers as they make agreements, contracts, storage, infrastructure, and marketing decisions to dampen potential drought impacts.

Drought has always been a risk to humans and natural organisms. Historically, drought has shaped and destroyed civilizations and ecosystems. Droughts and sometimes-accompanying climate change have been implicated in the decline and fall of civilizations (Shimada et al. 1991; Douglas et al. 2015; Krieger 2014; Staubwasser et al. 2003; Drysdale et al. 2005; Fagan 2009; Weiss 1997). For ecosystems, droughts can be pivotal events when invasive species become established or shifts occur in species composition (Winder et al. 2011). Yet, western US water management systems have become much more robust and adaptive than is commonly thought (Fleck 2016).

The onset of drought is slow. The water stored in soils, slowly diminishing springs, reservoirs, and aquifers dampens the onset of drought. The duration of droughts in California can be long and uncertain, perhaps lasting years, decades, and even centuries, compared with hours to days for fires and floods or minutes for earthquakes (Stine 1994). Therefore, signaling the onset and end of drought can be messy. Drought onset is usually slow, varying in local intensity, with an uncertain and often varying duration. Like all forms of disaster, preparation greatly diminishes drought losses, and organization is central to effective preparation and response.

For humans, the impacts of drought vary with economic, infrastructure, and institutional conditions, as well as the drought's hydrologic characteristics. The economic effects of drought depend on the economy's reliance on water and the extent of regional and global trade. Global economic connections greatly reduce the impacts of drought (Sumner 2015; Lund 2016a). Global food trade largely eliminates the existential threats of drought to civilizations, and greatly eases drought's economic and public health impacts. Infrastructure networks and institutions that store, move, and reallocate water flexibly also greatly reduce drought impacts (Lund 2016a). Regional hydrologic characteristics, such as large freshwater aquifers, can dampen drought effects.

However, actions taken to minimize the impact of drought for humans often further jeopardize vulnerable ecosystems and other environmental resources. California has arguably restructured its infrastructure and economy to accommodate droughts, but many of these actions have further altered habitats and streams in ways that harm native species, which once were well adapted to California's droughts using once-vast habitats connected to snowmelt, springs, groundwater, and seasonal floodplains. Losses to native species populations during drought are often not recovered before the next drought.

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This paper reviews California's most recent drought, and places it in an historical and global context. Lessons are drawn for California and for drought management globally. Despite problems and revealed weaknesses, well-prepared water systems within globalized economies usually weather drought fairly well and improve over time with exposure to such extremes.

2012–2016 Drought's Hydrology

The California drought of 2012–2016 was unusually dry and warm with a frequency estimated between once in 20–1,200 years. As a large diverse state, this range of estimates is reasonable. The drought's unusually high temperatures depleted soil moisture more rapidly, yielding a drought frequency estimate of 1 in 1,200 years, relative to past temperatures (Griffin and Anchukaitis 2014). Snowpack also diminished from high temperatures, with a frequency estimate of 1 in 500 years, assuming past temperatures (Belmecheri et al. 2016). The drought was frequently the worst of record by many metrics, but local assessment varies widely with location, area, and drought metric. Far longer and more severe droughts occurred in the Middle Ages (Stine 1994). Regional precipitation, streamflow, and water delivery reductions, relevant for regional water supplies, were often new lows, but more frequently have been seen with approximate frequencies of 1 in 15–30 years across the state (Lund 2016a). The drought was unusually dry, hot, and severe, by any reckoning.

The drought's higher temperatures are important for how managers, engineers, and scientists prepare for future droughts. Warmer temperatures accounted for as much as 25% of the drought's cumulative moisture deficit (M. Dettinger, personal communication, 2017) and certainly reduced soil moisture and snowpack, reduced cold water in reservoirs, and increased river temperatures (Hanak et al. 2015b; Mount et al. 2017).

The California drought was caused largely by the formation of a "ridiculously resilient ridge" of high pressure in the Pacific Ocean off California, diverting atmospheric moisture away from California. The climatological causes of this ridge will be debated for some time (Swain 2015; Singh et al. 2016; Swain et al. 2017). The persistence of such a deep drought for several years over California is unlikely to be entirely random and is likely to have connection with some more Pacific-wide and global climate processes (Teng and Branstator 2017). Climate warming is thought to have had some role (Diffenbaugh et al. 2015) and the pattern is consistent with predictions of climate change downscaled to California (Cayan et al. 2008; Dettinger 2005).

California already has an unusually variable climate. The literature suggests that climate warming will magnify both the frequency and magnitude of floods and droughts in California. The warmer temperatures of the most recent drought might be a harbinger for future drought and nondrought years with climate warming. Higher temperatures will worsen many drought impacts, especially for soil moisture, snowpack, streamflow, and temperature-sensitive ecosystems.

Water Deliveries

The drought reduced water deliveries from local, regional, state, and federal water projects at a time of historically high water demands. Table 1 summarizes the reductions in Central Valley Project and State Water Project deliveries for each year of the drought (2012–2016) as well as the wet years before and after the drought (2011 and 2017), showing the drought's development. Even in wet years (2011 and 2017), the water projects cannot satisfy all water demands. In addition, different water users are often shorted differently, reflecting different legal priorities due to legislation and/or preproject water rights (e.g., Sacramento Valley "Settlement" and San Joaquin River "Exchange" contracts).

As the drought wore on, the water projects had less stored water and reduced their deliveries, reaching a low in 2014 and 2015. In these years, some water contractors (particularly Friant) received zero deliveries for the first time since the project began in the 1950s, and sometimes lacked alternative water sources, forcing users to drill new wells or purchase water from others with a contract allocation. Such adaptations reduced shortages and costs for many areas but brought their own costs and consequences.

Many other local and regional water suppliers, which provide most water used by Californians, were affected by the drought. Some were less affected, due to sizable upstream reservoirs

Table 1. Major water project deliveries 2011–2017

Year	State water project (SWP)[a]	Central Valley project (CVP)[b]
2011	80%	100%, except south of Delta junior agricultural contractors (e.g., Westlands) 80%
2012	65%	100%—North of Delta, wildlife refuges, San Joaquin Exchange, and Eastside (New Melones) contractors 75%—South of Delta urban 50%—Friant; 40%—south of Delta junior agricultural contractors
2013	35%	100%—Wildlife, San Joaquin Exchange, and Eastside contractors 75%—North of Delta agriculture and settlement 70%–75%—Urban; 62%—Friant; 20%—south of Delta agricultural
2014	5%	75%—Sacramento Valley settlement and wildlife refuges 65%—San Joaquin Exchange contracts and wildlife refuges 55%—Eastside (New Melones) contractors; 50%—urban 0%—Other agricultural contracts (including Friant, Westlands)
2015	20%, except north of Delta urban 22–28%	75%—Sacramento Valley settlement, wildlife, San Joaquin Exchange contracts; 25%—urban 0%—Eastside (New Melones) and other agricultural contracts
2016	60%, except north of Delta urban 60–100%	100%—North of Delta, wildlife, San Joaquin Exchange contracts 75%—Friant; 55%—urban; 5%—south of Delta agriculture 0%—Eastside (New Melones) contractors
2017	85%, except north of Delta urban 100%	100%, all

[a]Data from California Department of Water Resources (2018a).
[b]Data from US Bureau of Reclamation (2018).

(e.g., Solano County and Colorado River users), banked groundwater, or water market transfers and conservation (particularly in cities in southern California and the San Francisco Bay areas). Some isolated local water supplies were more deeply affected.

Major Problem Areas

Droughts test water systems. The 2012–2016 drought was broad and deep enough to test all water management sectors in California. Areas with the most severe impacts, in rough economic order, were agriculture (particularly San Joaquin Valley), forests, hydropower, rural groundwater supplies, recreation, the Sacramento-San Joaquin Delta, aquatic ecosystems, protected fisheries management, and cities (particularly hydraulically isolated cities). The state's water accounting and water rights administration systems were also tested.

Agriculture

The drought was statewide and much of California's agriculture saw substantial drought effects, although local groundwater buffered most agricultural impacts (Howitt et al. 2014, 2015a, b; Medellín-Azuara et al. 2015a; Medellín-Azuara et al. 2016). Of the approximate 30% drought reduction of surface water available for agriculture statewide, about two-thirds was replaced by additional groundwater pumping, adding approximately $600 million per year in pumping costs (Table 2 for 2015). The remaining 10% shortage in statewide agricultural water use was accommodated by fallowing or idling about half a million acres (approximately 6% of statewide irrigated crop area) and through stress irrigation of crops, shifting crops, and improving irrigation efficiencies.

Total direct statewide economic losses to agriculture from the drought were approximately $3.8 billion for 2014–2016 (Howitt et al. 2014, 2015b; Medellín-Azuara et al. 2016). Estimates are unavailable for the less severe years of 2012–2013. This included lost net revenues from crop production, dairy and livestock, and additional pumping costs.

Statewide crop revenue losses were approximately $1.7 billion in 2014–2015, the deepest 2 years of the drought (Howitt et al. 2014, 2015a, b), for an approximate $45 billion dollar/year agriculture industry. Seventy-two percent of these losses were in the southern Central Valley (15% in the San Joaquin basin and 57% in the Tulare basin). These losses were concentrated in parts of the Valley lacking access to good groundwater. Agricultural areas adapted to the drought by fallowing sizable acres of annual crops, reducing irrigation applications to some crops (stress irrigation), and shifting some annual crops to new orchards (with approximately 40% less water use in their first years) (Sanchez 2017).

Table 2. Summary of agriculture impacts of the 2015 California drought

Description	Base year	Drought change	% change
Surface water supply (10^9 m^3)	22.2	10.7 loss	−48%
Groundwater use (10^9 m^3)	10.4	8.0 increase	72%
Net water use (10^9 m^3)	32.6	3.3 reduction	−10%
Drought-related idle land (hectares)	500,000[a]	225,000 more	45%
Crop revenue ($)	$35 billion	$900 million loss	−2.6%
Dairy and livestock revenue ($)	$12.4 billion	$350 million loss	−2.8%
Groundwater pumping cost ($)	$780 million	$590 million rise	75.5%
Direct costs ($)	N/A	$1.8 billion loss	N/A
Total economic impact ($)	N/A	$2.7 billion loss	N/A
Direct farm jobs	200,000[b]	10,100 loss	5.1%
Total job losses	N/A	21,000 loss	N/A

Source: Data from Howitt et al. (2015b).
[a]NASA-ARC estimate of normal Central Valley idle land.
[b]Total agriculture employment is about 412,000, of which 200,000 is farm production.

Lower groundwater elevations from the drought will increase groundwater pumping costs for many years in parts of the southern Central Valley, with higher costs for dry wells and lost infrastructure capacity from subsiding land above heavily overdrafted aquifers (MacEwan et al. 2017).

The drought greatly increased overdraft-related land subsidence, a long-term problem in parts of the San Joaquin Valley (Faunt and Sneed 2015; Sneed et al. 2013; Borchers et al. 2014). In some areas, new land subsidence approached several feet during the drought. The greatest economic impact of subsidence has been reduced conveyance capacities for some major San Joaquin Valley canals by up to 60% (Farr et al. 2017; Friant Water Authority 2017). Ironically, another major impact of drought-related subsidence is disrupting slopes that reduce floodway capacities. This groundwater-caused land subsidence is mostly from one-time dewatering of aquifer clay layers with little reduction in ability to recharge aquifers (Borchers et al. 2014).

Forests

Perhaps the greatest impact of California's drought was the death of 102 million forest trees, which depend on soil moisture accumulated in the wet season for growth during the spring and summer (US Forest Service 2016; Stevens 2016). Low precipitation and snowpack greatly reduced soil moisture, and higher temperatures accelerated soil moisture depletion. Drier, weakened trees became more susceptible to disease and insect infestations. Similar losses of forest trees occurred from the shorter 1976–1977 drought (DWR 1978).

With a warming climate, this drought might be pivotal for ecological changes in California's forests, particularly in tree density and species composition (Young et al. 2016). The millions of dead trees in California's forests has implications for wildfires, erosion, and public safety. The economic costs of these forest impacts from drought have not been estimated, but will continue to affect ecosystems, fire, and public safety for many years. Costs from additional wildfires and their public health impacts could become the largest economic and public health impact of the drought, spread years after the drought ends.

Hydropower

California's hydropower production is closely tied to annual runoff upstream of hydropower plants, with little over-year water storage (Madani and Lund 2009). Higher energy prices in the summer encourage hydropower reductions in other seasons, which is fortunately compatible with summer releases for downstream water supplies.

The deepest years of the drought (2014–2015) reduced hydropower production by more than 50% from its long-term average, going from about 13% of California's electricity use to about 5% (Table 3). The economic cost of this lost hydropower from substituting more expensive gas–turbine generation was approximately $2 billion, plus additional air pollution and greenhouse gasses (Gleick 2016). California's 2015 hydropower production was almost as low as in the short deep drought of 1976–1977 (DWR 1978).

Rural Groundwater Supplies

The drought increased attention to problems of small water systems and rural domestic wells (Grossi 2017). These smaller systems lack

Table 3. Hydropower production in California during drought

Year	Net production (GWH)	Average hydropower (%)	Hydropower percentage of 2015 state electricity use
2011	42,731	124	16
2012	27,459	80	11
2013	24,097	70	9
2014	16,476	48	6
2015	13,992	41	5
2016	28,977	84	11
2017	43,333	126	16
1983–2016 Average	34,338	100	13

Source: Data from California Energy Commission (2017a, b).

Table 4. Delta export pumping during drought

Water year	Delta export pumping, 10^9 m^3 (maf)
1986–2010 average	6.2 (5.0)
2011	8.0 (6.5)
2012	5.8 (4.7)
2013	4.9 (4.0)
2014	2.3 (1.9)
2015	2.2 (1.8)
2016	4.0 (3.3)
2017	7.6 (6.2)

Source: Data from California Department of Water Resources (2018b).

economies of scale and are frequently poorer and less well organized. These factors make rural water systems (and rural public services generally) more vulnerable to high costs, contamination, operation and maintenance problems, and drought. Rural water systems typically depend on shallower wells. Unlike larger water systems, small systems are not required to have drought contingency plans. Additionally, most small systems lack emergency or permanent connections to other water systems that can help during droughts.

As nearby water users with deeper wells pumped more during the drought, many rural households and small communities found their wells going dry. Tulare County alone reported almost 2,000 domestic well failures in 2015 (Tulare County 2017). Costs for additional pumping and rehabilitation for domestic and community wells in Tulare County from drought-related groundwater declines were estimated to be $10–$18 million. Further costs occurred from actual dry wells. Overall, these costs are greater than for previous droughts due to lower initial groundwater levels (Gailey 2018; Kwon 2017; Medellín-Azuara et al. 2016).

Many small water systems were unprepared for the drought (Fencl and Klasic 2017). Bottled water was often used or potable water was delivered by trucks for household storage tanks (Hanak et al. 2015b). Various state departments provided financial and technical assistance for private domestic well owners and small systems with drought-related issues (Fencl and Klasic 2017). The Draft Executive Order Framework, issued by the California Department of Water Resources, gives counties 2 years to determine how to provide drought supplies for households currently outside of the drought contingency plans (Fencl and Klasic 2017).

Recreation

Outdoor recreation also suffered from the drought. The skiing industry was particularly affected by the lack of snow and higher temperatures, particularly in 2014–2015, with shorter seasons and significantly fewer customers (Barber 2015; Kirkpatrick 2015). Whitewater rafting was somewhat buffered by upstream reservoirs. Lake recreation was affected by lower reservoir levels, particularly in 2014–2015. Some marinas in the Delta were overrun by alien aquatic plants prohibiting boat passage (Durand et al. 2018). No detailed analysis or quantification has been done on the effects of drought on recreation for the 2012–2016 drought. A California Department of Water Resources report on the 1976–1977 drought demonstrates such an analysis (DWR 1978).

Sacramento–San Joaquin Delta

The Sacramento–San Joaquin Delta is the major hub of California's water system and a continuing source of controversy (Lund et al. 2010; California Department of Water Resources and US Bureau of Reclamation 2016). During the drought, low inflows from northern California greatly reduced the ability to move water from wetter northern California to drier southern regions and San Francisco Bay area cities. Water exports from the Delta were greatly reduced. In 2011, before the drought, Delta water exports peaked at 6.5 MAF, dropping to 1.8 MAF during the worst year of the drought (Table 4).

In May 2015, DWR installed a temporary rock barrier to close False River in the western Delta to reduce the need for additional freshwater outflow to San Francisco Bay to maintain low salinity in the central Delta. The barrier was removed in October 2015. This followed decades of permanent flow barrier studies from the 1920s (Lund et al. 2010) and annual use of seasonal barriers in the southern Delta for fish and agricultural water quality purposes since the 1990s, use of temporary drought barriers in the 1976–1977 drought, and proposals for drought barriers in the 2009 and 2014 drought years (California Department of Water Resources 2009). The barrier helped maintain only slightly relaxed water-quality standards for Delta agriculture and urban use and some south of Delta water exports with reduced fresh water releases from upstream dams. The barrier affected in-Delta water quality and flow circulation, which continue to be studied (Durand et al. 2018). Export of zooplankton from the south Delta to Suisun Bay may have slightly reduced summer food resources for the Delta smelt. In addition, reduced water circulation may have increased salinity in the lower San Joaquin River.

Regulatory Delta outflows to support native ecosystems were also reduced during the drought by the State Water Board, allowing the salinity zone to move eastward. This reduced environmental outflows by about 1.4 billion m^3 (1.1 million acre-ft, MAF) over the drought, but did not greatly reduce in-Delta water quality for export, agriculture, and urban use (Gartrell et al. 2017a, b). Much of this saved outflow was retained in reservoirs for potential additional dry years. At market prices for water south of the Delta (over $\$0.8/m^3$, $1,000/acre-ft), this amounted to approximately $1 billion worth of environmental water made available for water users and storage. Populations of native fish in the Delta continued to decline during the drought. Considerable controversy resulted from the uncompensated reductions in environmental flows to favor other water users (State Water Resource Control Board 2015; Lund et al. 2014; Lund and Moyle 2014). State and federal regulations specify Delta water quality standards, export limitations, and salinity gradient location.

Aquatic Ecosystems

The benefits of organization and preparation for drought are evident in comparing drought management for urban and agricultural uses with fish and waterfowl in the drought (Hanak et al. 2015b; Moyle and Quiñones 2014; Jeffries et al. 2016). From 2013 to 2016,

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drought emergency ecosystem support spending totaled $66 million and $67 million from the state and federal governments. Lack of drought preparation for the environment increased the severity of the effects on ecosystems (Hanak et al. 2015b).

California supports 129 species of freshwater fish. Approximately two-thirds of these species are found only in California. Most of these species are either currently endangered or at risk of becoming endangered (Moyle et al. 2011; Hanak et al. 2015b). Low flows and high temperature from the drought reduced water quality and impaired habitat for native fish species. Additionally, the drought's lower flows, longer water residence times, and higher temperatures supported expansions of some invasive species, particularly aquatic vegetation (Durand et al. 2018). Intervention by the State Water Resources Control Board required some to reduce surface-water diversions or groundwater pumping, which affects flows in some salmon and steelhead streams. However, the State Water Resources Control Board also temporarily voided at least 35 environmental flow regulations during the drought (Hanak et al. 2015b; Mount et al. 2017).

Salmon populations suffered from higher temperatures and reductions of flow during the drought. The hardest-hit was the winter run of Chinook salmon, which historically spawned in cold water, high in the upper Sacramento River watershed. They are now displaced and reduced to habitat below Shasta Dam, where spawning is supported by cold water from the bottom of the reservoir. During the previous long drought (1991), cold water from the reservoir became depleted and caused high egg and juvenile mortality, leading to their official listing as an endangered species, construction of a temperature-mixing control device on Shasta Dam, and regulatory and operational changes for Shasta Dam. During the first years of the 2012–2016 drought, the cold water available behind Shasta Dam was enough to maintain spawning and rearing habitat. However, by 2014, lower reservoir levels, higher temperatures, and various management problems depleted cold water behind Shasta Dam before the outmigration of juveniles, leading to substantial elimination of that year's cohort of winter-run salmon. Despite the attention from this failure, a similar result occurred in 2015, the drought's deepest year. Juvenile salmon populations in these 2 years were supported mostly by refuge hatchery releases (Durand et al. 2018).

Regarding waterfowl, California is a primary stop on the Pacific Flyway (Hanak et al. 2015b; Mount et al. 2017). However, draining of most natural wetlands in California has limited waterfowl to wetlands managed as state and federal refuges, private land, duck hunting clubs, and flooded farmland. Decreased drought water allocations for managed wetlands reduced fall and winter habitats for waterfowl. Wildlife refuges throughout the state collaborated to identify where water supply should be allocated to best support waterfowl habitat (Hanak et al. 2015b; Mount et al. 2017).

Isolated Cities

Cities isolated from California's intertied water system had fewer options to prepare for and adapt to drought. Santa Cruz in 2014 required a 30% mandatory use reduction as local water supplies became depleted without other recourse (City of Santa Cruz Water Dept. 2016). This was the first sizable city forced to mandatory rationing by the absence of water during the drought. Late in the drought, Lake Cachuma, the primary water source for Santa Barbara County, was expected to empty, despite increased supplies acquired from a small connection to the State Water Project. In 2016, the City of Santa Barbara required a 30% water-use reduction and restrictions on residential and commercial water uses (City of Santa Barbara 2017). The city banned all residential lawn irrigation in January 2017 (McPhate and Medina 2016), lifting the ban in March 2017 as Lake Cachuma began to refill.

Cities better connected to other supplies were more able to prepare and adapt to drought. Urban utilities in the San Francisco Bay Area and southern California served by the State Water Project and Central Valley Project faced 80%–95% reductions in water allocations for 2014–2015. These cities responded with sizable voluntary water conservation actions, withdrawals from water stored in reservoirs and banked in local and distant groundwater basins, water purchased from more senior agricultural water users, and purchases or exchanges from neighboring water systems (Alameda Zone 7 2015; SCVWD 2016; ACWD 2016; MWDSC 2015; CCWD 2016). Water banked with agricultural water districts in the Tulare basin provided particularly important replacement urban water supplies. These preparations and interties to neighboring areas greatly reduced drought impacts, largely from agreements and interties developed since the 1988–1992 drought.

Water Accounting and Water Rights Administration

The 2012–2016 drought highlighted California's lack of a coherent water accounting system (Hanak et al. 2014; Escriva-Bou et al. 2016). Although water systems are connected by conveyance networks and hydrologic processes, these water systems are governed and regulated independently with separate water accounting systems. During the drought, legislators and state regulators directed several efforts to incrementally improve water accounting policies (Escriva-Bou et al. 2016).

The 2014–2015 water years were the first since the 1976–1977 drought when junior water rights were formally curtailed by the State Water Board. The 2014–2015 curtailments were made easier by 2009 legislation requiring all water-right holders, not just those holding post-1914 state permits, to report monthly water use. By 2014, the first years of these new data were becoming available. In 2015, Senate Bill 88 required surface-water-right holders to measure and report their monthly diversions annually (Escriva-Bou et al. 2016). The 2014 Sustainable Groundwater Management Act (SGMA) also created a timeline for local groundwater accounting and regulation, with potential state agency enforcement. Similarly, government agencies began expanding environmental flow regulations.

Although some water accounting policy improvements occurred during the drought, further actions are needed to establish broadly effective water accounting in California. These actions include determining water availability, water rights and use quantities, and creating transparent and coherent water balance and information systems (Escriva-Bou et al. 2016).

Some of the biggest impacts of the 2012–2016 California drought were similar to those of the 1976–1977 drought, a shorter drought containing the driest year on record. An excellent assessment of the 1976–1977 drought found that the biggest economic impacts were for agriculture, forests, and hydropower production (DWR 1978). These sectors are inherently water-intensive and can react to water losses almost exclusively by reducing production. In the case of forest impacts, little can be done to substantially manage or compensate for drought impacts (Butsic et al. 2017). Water-based recreational losses are also direct and often difficult to manage. Most problematic areas tended to be less well organized institutionally and less well funded, such as the environment.

Why So Little Economic Impact from Drought in California?

Perhaps the biggest lesson from the drought is how small the economic impacts of drought were relative to the size of the hydrologic event. Total economic losses, on the order of $10 billion over 5 years, were less than 0.09% of the state's $2.3 trillion/year economy. The drought's statewide economic impact was less than the effects from business cycles, federal policies, and international exchange rates. California's statewide economy was substantially adaptable and robust for a temporary loss of approximately one-third of normal water supplies. Modeling studies show substantial economic adaptability and robustness to still longer and deeper droughts (Harou et al. 2010).

Preparation

This was not California's first drought. California's long history of drought has led to the accumulation of infrastructure, institutions, and changes in water demands adapted to droughts (Pisani 1984; Lund 2016c).

Perhaps the best illustration of successful preparation is the contrast of urban drought impacts from California's 1988–1992 drought and the most recent drought. The 1988–1992 drought brought deep widespread impacts to urban areas, often with mandatory cutbacks of 20–30%. Following the 1988–1992 drought, cities individually, regionally, and with state support instituted more effective and permanent water conservation, regional intertie pipelines, local water storage projects, groundwater storage, wastewater reuse, water market arrangements, and contingency plans (Lund 2014b, 2015e, 2016c). As a result, of major cities, only Santa Cruz and Santa Barbara were forced to implement mandatory water conservation by lack of water.

For all other cities and years, urban conservation efforts were voluntary, except for 2015, the drought's fourth and deepest year, when the Governor required 25% urban use reductions, given prospects for additional dry years. These state-required cutbacks varied locally by per-capita water-use rates from 8 to 40%. Given the high proportion of urban water use for landscape irrigation (discussed subsequently), the overall economic impact of this 1-year 25% urban water-use reduction was very small (Lund 2015a, b, c, d).

Groundwater Supplies for Agriculture

Most agriculture in California is blessed with large underlying freshwater aquifers, particularly in the Central Valley, which provides substantial drought water storage. Statewide surface reservoir storage capacity is approximately 52 billion m^3 (42 MAF), but total groundwater storage is approximately 500 billion m^3 (400 MAF), making groundwater the main stored water source for long droughts. Additional groundwater pumping supplied more than 70% of the drought reductions to agriculture's water supply.

However, long-term overdraft of approximately 2.5 billion m^3/year (2 MAF/year) undermines the availability of groundwater for future droughts. In the San Joaquin Valley, groundwater overdraft is about 17% of the total water supply (Arnold et al. 2017). The 2012–2016 drought highlighted groundwater's importance as a long-term and drought source, and the need to protect groundwater availability. This spurred passage of California's Sustainable Groundwater Management Act of 2014, which requires reaching basin groundwater sustainability by 2040. An average net reduction of consumptive use of approximately 2.2 billion m^3/year (1.8 MAF/year) in the San Joaquin Valley will be needed to maintain groundwater for future droughts. Permanent fallowing of some irrigated areas, additional groundwater recharge in wetter years, and pressure to import additional water can be expected (Hanak et al. 2017; Nelson et al. 2016).

Economic Structure

California's economic structure tremendously reduces drought vulnerability. Growth in California's economy has been greatest in less water-consuming sectors for many decades. In the 1920s, agriculture was about 30% of California's employment, and is less than 4% today. Manufacturing has shifted to less water-consuming methods, and the service sector, where most growth has occurred, requires relatively little water. These changes make California's economy overall much less dependent on abundant water supplies and less affected by drought water shortages. This shift has been driven by technological modernization, as well as economic globalization.

Globalization of California's agricultural sector was particularly effective in reducing drought impacts (Lund 2016c; Sumner 2015; York and Sumner 2015; Lund 2015b). Although the drought idled hundreds of thousands of crop acres and markedly reduced farm revenues, the drought's effect on the statewide agricultural economy was relatively small. During the drought, farmers reduced economic losses by allocating water to higher-valued crops, where California has a large share of national and global production (Sumner 2015; York and Sumner 2015). Production and market prices for these specialty crops (particularly almonds) were strong during the drought, which bolstered agricultural revenues and employment (Medellín-Azuara et al. 2015b). California's food staples, which are marketed more globally, saw no higher prices due to drought.

Sizable Lower-Valued Water Uses

Although California has a globalized economy, in which primary agricultural production is a small share of GDP, agriculture is a major source of income and employment in rural areas and the Central Valley. Agricultural water use is approximately 80% of all human water use statewide; the rest goes to cities and towns. Within agriculture, about 85% of employment and gross revenues from crops is from fruits, nuts, and vegetables, which use less than half of all irrigated area and agricultural water use (Fig. 1). The remaining agricultural land and water use support grains and feed crops. Dairy and beef cattle production are about a fourth of all agricultural value and relies on feed from out of state and local silage production. Challenges for agriculture include labor

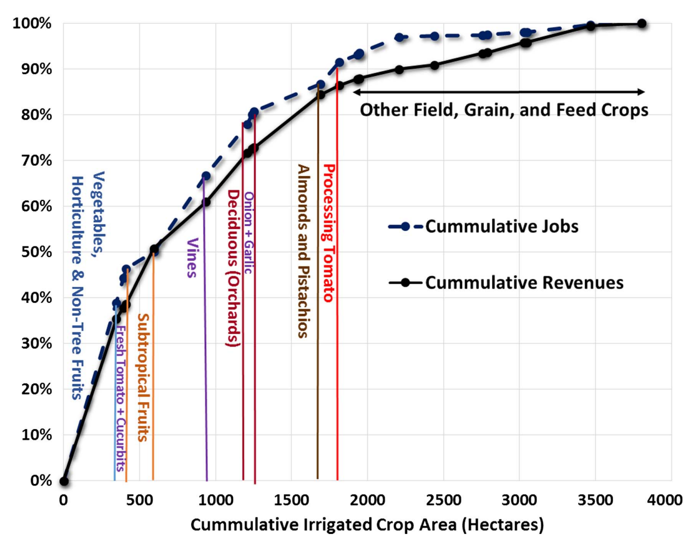

Fig. 1. Crop shares of agricultural crop revenues and employment. (Data from California Employment and Development Department 2018; IMPLAN 2015.)

shortages, droughts, permanent cutbacks to protect groundwater, and competing economic land uses. Another challenge is the continued expansion of permanent crops, orchards and vines, which are more difficult to fallow in dry years, encouraging more attention to groundwater management.

Urban water use has a similar economic structure, with about half of California's urban water use being for landscape irrigation providing relatively little economic contribution. In 2015, the State mandated an average 25% reduction in urban water use, varying from 8% to 36% locally, with cities having higher per-capita water use being required to reduce use more. Reductions were accommodated mostly in landscape irrigation, with little economic impact, despite some inconvenience and loss of urban trees, sometimes referred to as the "war on lawns."

Energy System Flexibility and Market

Hydropower is a highly variable source of California's electricity from year to year, ranging from 7% to 21% of statewide electricity production since 2002 (CEC 2017a, b). Market flexibility, cheap natural gas thermoelectric power, growing electricity production from wind and solar sources, and long-term declining overall electricity use dampened the impact of hydropower losses (CEC 2017a). Still, many power retailers added drought surcharges to cover higher generation costs.

Water System Flexibility and Water Markets

In past droughts, even modest water trading among willing sellers and buyers dampened economic impacts to agriculture and cities (Israel and Lund 1995). Water markets and exchanges were particularly important for shorted agricultural areas lacking access to surface water. Urban water systems in southern California and the San Francisco Bay area activated long-term water market contracts for stored water and agricultural land fallowing. Irrigation districts and farmers lacking sufficient groundwater sought to purchase water from others, driving agricultural water prices as high as $1.7/m^3$ ($2,000/acre-ft), but often over $0.8/m^3$ ($1,000/acre-ft), approximately triple the recent non-drought-water market prices (Hanak et al. 2015b; Hanak et al. 2017).

Cooperative operations, aided by greater availability of interties and anticipatory agreements, further supported water markets and exchanges to make fuller use of available water across California's extensive conveyance and storage network. Institutional flexibility and capability allowed deep and abrupt disruptions in water deliveries to Sacramento Valley farmers from endangered species operations to be rapidly, if inconveniently, accommodated with little economic loss. San Francisco Bay area utilities faced with 80–95% reductions in State Water Project deliveries used markets and system flexibility to accommodate such cuts without severe water rationing.

Water markets face both infrastructure and institutional barriers. Many ideas for improving market effectiveness are discussed (Hanak et al. 2011). Although regulations and agency oversight impede or delay some transfers, within-district resistance due to future water security and other issues is also common. Cooperative agreements among water users, system operators, and government agencies might help smooth low-environmental-impact transfers.

Waterfowl Institutional Preparation and Response

Waterfowl in California benefitted during the drought from a combination of preparation, luck, and creative management (Hanak et al. 2015b). First, waterfowl are more mobile than fish and can therefore better adapt and move with drought conditions. Waterfowl require ponds with a small volume of standing shallow water, in contrast to native fish in streams or the Delta, which require constant fresh water flow. Luckily timed winter storms during the drought helped ease impacts to migrating waterfowl. Beyond this, California has a long-established system of federal, state, and private wetland wildlife refuges, with some coordination. This refuge and institutional infrastructure was well employed to identify and address foreseeable gaps in waterfowl habitat at critical times. Such actions involved many groups. Perhaps the most creative action was the Nature Conservancy's Bird Returns program, in which farmers bid for payments to water fields at particular times and places to support migrating waterfowl (Hallstein and Miller 2014).

The 2012–2016 years were not California's first multiyear drought, and the cumulative lessons of past droughts did much to shape the adaptive capacity and responses for the more recent drought. Although statewide economic impacts were modest, some areas were more acutely and chronically affected. Impacts were mostly in areas least prepared or organized or inherently difficult to organize (forests, fish, and rural water systems).

Benefits from Previous Droughts

The fear, impacts, and controversies of drought bring professional, popular, and political focus needed to make strategic water management improvements. Historically, major droughts have led to major innovations. This is also true for California, as summarized in Table 5. Early droughts alerted immigrants from the humid eastern United States that California's seasonally dry climate could be even drier. As the state's agricultural economy grew, droughts in the 1920s and 1930s led to extensive water infrastructure construction from the 1940s through the 1970s (Pisani 1984). The short, deep 1976–1977 drought surprised many agencies and led to widespread urban conservation programs and early water-market activity (DWR 1978). The prolonged 1988–1992 drought also caught many urban and agricultural areas underprepared, leading to greatly improved urban interties, conjunctive use, and much more extensive water markets. This drought also led to pivotal changes in environmental management with the follow-up listing of several endangered fish species. The short 2007–2009 drought precipitated new institutions for the Delta and improved collection of surface-water-use data.

California's economy, society, and climate are dynamic. Each historical drought has been different hydrologically and impacted a different human economy with a substantially different water management and infrastructure. A region's economic structure drives drought management and impacts. In addition, California's economic structure has always been driven by its changing global economic roles, from shipping hides globally in the early 1800s, gold in the late 1800s, grain in the early 1900s, and markets for higher valued crops, wine, electronics, manufacturing, software, and tourism in the last century.

Changes in California's economic structure drive changes in economic demands for water management (Pisani 1984). Improving technology and changing political institutions and social expectations also change what is possible and desired in water management (Kelley 1989). However, institutional arrangements can be slow to evolve, and droughts (like floods and major lawsuits) provide the attention and sense of urgency often needed for strategic changes. Droughts, floods, and lawsuits help water systems adjust to accumulating historical changes (Hanak et al. 2011).

Adjustments are usually both technological and institutional, and typically build on existing institutions and infrastructure.

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Table 5. Historical droughts in California, their impacts, innovations, and leading innovators

Drought	Impacts	Innovations	Leading innovators
1800s	Herds and crops devastated	Local irrigation, 1873 Federal Central Valley study	Local, private
1924	Crop devastation	Local reservoir projects, major regional/state water project plans	Local, public, and private diverters
1928–1932	Delta salinity, crop losses	Major statewide dam and canal plans and projects (CVP, SWP)	Regional, statewide water agencies and project users
1976–1977	Major urban and agricultural shortages	Urban conservation; early markets	Urban water utilities, water buyers and sellers
1988–1992	Urban and agricultural shortages; endangered fish	Interties, conjunctive use; water markets; conservation; new storage	Local and regional urban water agencies, irrigation districts
2007–2009	Water shortages for agriculture and fish	New water use reporting requirements, Delta planning institutions, and urban water conservation mandates	State agencies, new Delta planning institutions, urban water agencies
2012–2016	Warm drought, little Delta water, major agricultural shortages, damage to fish and forests	Groundwater sustainability legislation; Delta barrier; state urban conservation mandates; more water use reporting; local responsiveness	Local water agencies; water project operators; state agencies

Source: Data from Lund (2014a).

The development of large regional and statewide water projects, responding to droughts in the early twentieth century, did not eliminate local water utilities and irrigation districts. Existing local districts continued to manage local supplies and merely contracted with regional wholesale projects. Existing and new local districts could then benefit from economies of scale with newer regional water management technologies (large dams and aqueducts) and financing institutions (Metropolitan Water District, CVP, SWP), with little loss of local advantages and sovereignty (Maass and Anderson 1978).

In examining the swings of technologies and innovations, often accelerated by droughts, changes in the most economical technological innovations are often accompanied by rebalancing of the portfolio of managing and regulating local, regional, state, and federal institutions. Large-scale regional water infrastructure development shifted initiatives in water management to federal, state, and regional governments. Before this time, water systems were almost entirely local. Now that large reservoir and conveyance systems are largely completed, today's newer water management innovations, such as water conservation, wastewater reuse, conjunctive use of ground and surface waters, and water markets, are often better led and financed locally, requiring adjustments in state and federal regulations and regional system operations. These adjustments challenge routine finance and regulatory structures, and often depend on droughts to accelerate change.

Environmental Susceptibility

The general drought robustness of California's urban, agricultural, energy, and recreation sectors contrast starkly with weaknesses seen in environmental and ecosystem management. In part, the drought management successes of California's economic sectors come from water delivery systems, levees, storage and conveyance infrastructure, management, and water allocations that disrupt conditions for native ecosystems in droughts and in wetter years. Drought buffering for the economy in part has been paid for by native ecosystems.

Many of California's aquatic ecosystems remain chronically starved for habitat and water in all years, but especially in droughts. Therefore, native species enter droughts with diminished and geographically limited populations, only to encounter greater stresses during drought (Moyle et al. 2017). Chronic problems of water development for aquatic ecosystems include dams that block fish migration to upper watershed habitats, elimination of wetland and floodplain spawning and rearing habitat by levees, entrainment of juvenile fish by water export pumping, and poor water quality. Most of California's endemic species' populations were at historical lows at the 2012–2016 drought onset. By entering the drought with such low stocks, several species were pushed to the brink of extinction by higher water temperatures and lower flows.

As species approach extinction, federal and state agencies charged with species protection have become more deeply involved. Droughts have often accelerated the listing of endangered species and regulatory agency involvement due to rapid reductions in native fish populations. For winter-run salmon and Delta smelt, this process began after the 1988–1992 drought, after long declines.

Droughts have long-term environmental effects that may take many years and management changes to repair. Without the time, water, and habitat needed to rebuild fish stocks, droughts ratchet down native fish populations, with little recovery between droughts. The Delta smelt was listed as threatened in 1993, state endangered in 2010, and nearly disappeared from detection by 2016. Droughts also facilitate invasive organisms, beginning in the early 1900s with the invasive teredo's spread into the Delta in drier years (Means 1928). More recently, invasive clams and vegetation have been aided by drought, disrupting food webs, stressing native populations, and disturbing infrastructure and passage (Jeffries et al. 2016; Lehman et al. 2017).

Successful environmental and ecosystem management will require a more proactive approach, involving planning, organization, and financing of effective actions, including drought planning. Proactive drought-management approach has been effective for urban and agricultural sectors, and for managing wetlands for waterfowl.

Innovations and Future Benefits from This Drought

The 2012–2016 California drought brought a range of innovations likely to improve preparations for future droughts.

The 2014 SGMA, the first forceful state effort to make groundwater use sustainable, passed because of the drought, approximately 100 years after California legislation first regulated surface water. A thoughtfully implemented SMGA will not only improve

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prospects for dealing with future droughts by improving groundwater reserves but will also foster broader coordination, accounting, and tighter water management at local and regional scales (Hanak et al. 2017).

The drought brought local and state government pressure to reduce per-capita urban water use, which remains higher that most of the country and most other developed economies in dry regions (Cahill and Lund 2013). Urban areas face long-term state pressure to reduce per-capita, mostly outdoor, water use from drought-driven legislation in 2009 and more recent drought legislation, executive orders, and regulations.

In 2014 and 2015, low inflows and depleted upstream storage raised concerns about seawater intrusion into the Delta and led to consideration of several temporary flow barriers to reduce salinity intrusion and the construction in 2015 of a temporary salinity barrier in the western Delta. Future droughts will also likely use salinity barriers, perhaps with greater planning and preparation.

Another benefit of the drought was additional state and federal spending on drought-related water problems in California (Hanak et al. 2015a). Much of these funds were merely redirected or retitled from other water and environmental programs, and some helped to directly relieve drought impacts to small communities and farmers, but some also led to longer-term infrastructure improvements and other long-lasting benefits.

The drought did not immediately result in broad improvements to environmental management. Some notable innovations occurred for coordinating water-bird management (Hallstein and Miller 2014). California's WaterFix and EcoRestore mandate over 8,000 acres of tidal habitat restoration in the Delta, which may help buffer some threatened populations. Much attention was paid to potential innovations from Australia (Mount et al. 2016). Perhaps the difficulties of managing forest and aquatic ecosystems from drought will motivate more effective efforts to come. Discussion of an environmental water right has begun, which may be one way to allow environmental flows to support postdrought recovery of vulnerable fish species and end drought ratcheting of ecosystems (Mount et al. 2017).

One of the most important benefits of the drought is the reminder to the broader society and political discourse that California is a dry place overall, where water must be carefully managed. This lesson is particularly poignant for the southern Central Valley, which has extensive and high-valued agricultural water demands in one of California's drier regions, prone to groundwater overdraft, and particularly vulnerable to shortages of Delta water imports.

A final optimistic lesson is that if water is well managed, damages from drought (and floods) will usually be quite modest in the context of California's overall society and economy. The combination of California's global economy, urban and substantial agricultural preparation for drought, relatively abundant groundwater reserves, and substantial institutional flexibility greatly dampened the impacts of one of history's most severe and lengthy droughts in California (Lund 2016b). Important problems and opportunities are also pointed out that should be addressed to both prepare for future droughts and improve the water system overall.

Having demonstrated substantial economic robustness to severe drought allows California the opportunity to more aggressively counter environmental damages. California has considerable wealth and flexibility to solve its environmental and water quality crises. Much of the resources needed to effectively manage the environment (e.g., water, money, habitat restoration) are needed during interdrought periods, when resources should be more available. Investments in environmental preparation for drought could be as successful as they are for economic sectors.

Use and Organization of Science

The behavior of systems under unusual stress is an important opportunity to learn and improve, despite undesired impacts. The drought provided opportunities for "natural" ecological and institutional experiments that would otherwise be impossible to permit or be impractically expensive. Drought-related reductions in flows and rises in temperatures were widespread. Major emergency changes to infrastructure, such as the Delta emergency salinity barrier, provided opportunities to examine effects of major Delta changes on water quality, flow, and ecological conditions.

State and federal agencies and science programs were largely unprepared to take advantage of these scientific opportunities. Some important scientific work did occur (Durand et al. 2018; Jeffries et al. 2016; Lehman et al. 2017; Medellín-Azuara et al. 2018; Lord et al. 2018), although often less systematically. Scientific syntheses that assemble data, analyses, and lessons from the drought likely have great value.

Historically, major droughts in California have occurred at a rate of each generation experiencing approximately one major drought in a career. This often means that each drought is greeted by a new generation of professionals, lacking direct drought management experience. This infrequency of drought dampens personal incentives for institutions to learn from past droughts and prepare for the next drought. If climate warming and tighter water demands make drought more frequent, with two or more droughts expected in a career, agencies might make deeper drought preparations. More frequent droughts appear likely to affect environmental protection agencies especially, with noted weaknesses in drought preparation.

The development and use of water-use data and estimates saw particular advances during the drought. Drought legislation in 2009 required all surface-water right holders to report monthly use to the State Water Board every 3 years—for the first time applying to riparian and pre-1914 appropriative water right holders. The 2010–2013 water-right use data became available in 2013. Although these data were often incomplete, they greatly improved water-use estimates for declarations of water unavailability by the state.

Errors in models and field data also became apparent during the drought. Models of stream and reservoir temperatures were forced to operate outside their normal and calibrated ranges. Field measurements of reservoir temperature took on new significance and were sometimes found to be gravely inaccurate for the salmon they were intended to protect (Durand et al. 2018).

Droughts always heighten public, political, and agency interest in drought forecasting. This drought greatly increased funding and publicity for real-time predictions of drought and floods (often based on El Nino conditions). Such efforts have improved insights into atmospheric processes, but long-term forecasting remains substantially unsuccessful (Cayan and Mount 2015; Schonher and Nicholson 1989).

Conclusions

Water management in California was unusually effective for the 2012–2016 drought, with the exception of ecosystems and rural drinking water supplies. However, the drought highlighted several moderate to severe problems, and helped bring attention and innovations—following a common pattern of droughts bringing innovation.

Success in water management for California has always been dynamic. California's semi-arid Mediterranean climate and ever-changing economy, society, and ecosystems require that water management constantly adapt, as it has for over 150 years. Such adaptations are always imperfect and controversial, involving a messy awkward mix of convenient past practices, present exigencies, and preparing for an imagined future.

Several overall conclusions arise from California's most recent drought:

1. Droughts focus attention and encourage improvements in water management. Each major drought in California's history has motivated improvements in water management, often responding to long-term problems and opportunities. The current drought highlighted the dependence of California's agriculture on groundwater in dry periods, and led to substantial legislation requiring more effective local groundwater management. Some improvements in water accounting, urban water conservation, and other areas were accelerated by the drought;
2. A diversified economy with deep global connections significantly buffers economic effects of drought. California and most modern economies depend less on abundant water supplies than in the past. Agriculture is California's most water-dependent industry, about 80% of human water use, but despite its growth and prosperity, provides less than 4% of California's jobs. High values for major export crops greatly reduced the impacts of fallowing about 6% of the least-profitable irrigated land during this drought. Despite local problems, the effect of major drought on California's statewide economy was quite small (Howitt et al. 2014, 2015a, b). Urban areas, supporting most of the people and economic activity, have developed diversified portfolios of water supply and conservation activities that were quite successful during the California drought;
3. Major drought and climate change have much less impact on irrigated water systems with diversified supply sources, particularly groundwater, and flexibility in operations with water networks and markets. California's extensive and diverse water infrastructure allowed more than 70% of lost water supplies to be replaced by pumped groundwater for agriculture, requiring greater recharge of groundwater in the long term. Although costly compared with dryland agriculture, California's irrigation infrastructure and network of reservoirs and canals greatly mute the effects of drought, and are particularly effective for protecting the most economically valuable crops and economic activities. With reductions in the least-profitable irrigated area, this system can be sustainable for many decades if properly managed;
4. Ecosystems were most affected by the drought, given the weak condition of many native species, even in wet years, due to decades of losses of habitat and water and the growing abundance of invasive species. With each drought, humans become better at weathering drought, but effective institutions and funding are lacking to improve ecosystem management and preparation for drought. Forests are particularly vulnerable and difficult to protect from droughts. Dedicated environmental water rights and restoration and migration programs can help support ecosystems. Such actions are needed to break the cycle of cumulative drought impacts to ecosystems and the environment;
5. Small rural water systems are especially vulnerable to drought. Small systems often struggle in normal years, lack economies of scale, typically have only a single vulnerable water source, and commonly lack sufficient organization and finance; and
6. Every drought is different. Droughts are hydrologically unique events that occur under different historical, economic, and ecosystem conditions, and increasingly with different climate conditions. But all droughts provide opportunities and incentives to improve and adjust water management to changing economic and environmental conditions and priorities. In well-managed systems, each drought is greeted with improved preparations from previous droughts.

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References

ACWD (Alameda County Water District). 2016. *Urban water management plan 2015–2020*. Fremont, CA: ACWD.

Alameda Zone 7. 2015. *Annual report 2015 corrected*. Livermore, CA: Alameda Zone 7 Water Agency.

Arnold, B., A. Escriva-Bou, and J. Lund. 2017. "San Joaquin valley water supplies: Unavoidable variability and uncertainty." Accessed July 2, 2017. https://californiawaterblog.com.

Barber, M. 2015. "Inside the high-dollar fight to save California skiing." Curbed Ski. Accessed March 11, 2015. https://ski.curbed.com/2015/3/11/9981892/california-drought-ski-resorts.

Belmecheri, S., F. Babst, E. R. Wahl, D. W. Stahle, and V. Trouet. 2016. "Multi-century evaluation of Sierra Nevada snowpack." *Nat. Clim. Change* 6 (1): 2–3. https://doi.org/10.1038/nclimate2809.

Borchers, J. W., V. Kretsinger Grabert, M. Carpenter, B. Dalgish, and D. Cannon. 2014. *Land subsidence from groundwater use in California*. Rep. for the California Water Foundation. Sacramento, CA: Water Foundation.

Butsic, V., H. McCann, J. Axelson, B. Gray, Y. Jin, J. Mount, S. Stephens, and W. Stewart. 2017. *Improving the health of California's headwater forests*. San Francisco: Public Policy Institute of California.

Cahill, R., and J. R. Lund. 2013. "Residential water conservation in Australia." *J. Water Resour. Plann. Manage.* 139 (1): 117–121. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000225.

California Department of Water Resources. 2009. "Delta emergency drought barriers, administrative draft." Accessed July 2, 2018. http://www.water.ca.gov/waterconditions/docs/DWR-EmergencyBarriersDraftReport-Apr2009.pdf.

California Department of Water Resources. 2018a. "Bulletin 132 management of the California State water project." Accessed July 2, 2018. https://www.water.ca.gov/Programs/State-Water-Project/Management/Bulletin-132.

California Department of Water Resources. 2018b. "California data exchange center (CDEC)." Accessed July 2, 2018. http://cdec.water.ca.gov.

California Department of Water Resources and US Bureau of Reclamation. 2016. "Final environmental impact report/environmental impact statement for the Bay Delta conservation plan/California WaterFix. Accessed July 2, 2018. https://www.californiawaterfix.com/resources/planning-process/eir-eis/.

California Employment and Development Department. 2018. "Agricultural employment in California. Detailed agricultural employment and earnings data tables." Accessed December 1, 2017. http://www.labormarketinfo.edd.ca.gov/data/ca-agriculture.html.

Cayan, D., and J. Mount. 2015. "Don't count on El Niño to end the drought." Accessed July 9, 2015. http://www.ppic.org/blog/dont-count-on-el-nino-to-end-the-drought/.

Cayan, D. R., E. P. Maurer, M. D. Dettinger, M. Tyree, and K. Hayhoe 2008. "Climate change scenarios for the California region." Supplement, *Climatic Change* 87 (S1): S21–S42. https://doi.org/10.1007/s10584-007-9377-6.

CCWD (Contra Costa Water District). 2016. *2015 urban water management plan for the Contra Costa water district*. Concord, CA: Contra Costa Water District.

CEC (California Energy Commission). 2017a. "California hydroelectric statistics & data." Accessed July 2, 2018. http://www.energy.ca.gov/almanac/renewables_data/hydro/index.php.

J. Water Resour. Plann. Manage., 2018, 144(10): 04018067

CEC (California Energy Commission). 2017b. "Total system electric generation, California Energy Commission." Accessed August 25, 2017. http://www.energy.ca.gov/almanac/electricity_data/total_system_power.html.

City of Santa Barbara. 2017. "Stage 3 drought regulations." Accessed August 8, 2017. http://www.santabarbaraca.gov/gov/depts/pw/resources/system/docs/stage3regulations.asp.

City of Santa Cruz Water Dept. 2016. *2015 urban water management plan*. Santa Cruz, CA: City of Santa Cruz Water Dept.

Dettinger, M. D. 2005. "From climate change spaghetti to climate-change distributions for 21st Century California." *San Francisco Estuary and Watershed Science* 3 (1): 1–14.

Diffenbaugh, N. S., D. L. Swain, and D. Touma. 2015. "Anthropogenic warming has increased drought risk in California." *PNAS* 112 (13): 3931–3936. https://doi.org/10.1073/pnas.1422385112.

Douglas, P. M. J., M. Pagani, M. A. Canuto, M. Brenner, D. A. Hodell, T. I. Eglinton, and J. H. Curtis. 2015. "Drought, agricultural adaptation, and sociopolitical collapse in the Maya Lowlands." *PNAS* 112 (18): 5607–5612. https://doi.org/10.1073/pnas.1419133112.

Drysdale, R., G. Zanchetta, J. Hellstrom, R. Maas, A. Fallick, M. Pickett, I. Cartwright, and L. Piccini. 2005. "Late Holocene drought responsible for the collapse of old world civilizations is recorded in an Italian cave flowstone." *Geol.* 34 (2): 101–104. https://doi.org/10.1130/G22103.1.

Durand, J., et al. 2018. *Drought and the Sacramento-San Joaquin Delta, 2012–2016: Synthesis review and lessons*. Davis, CA: Univ. of California.

DWR (Department of Water Resources). 1978. *The 1976–1977 California drought: A review.* Sacramento, CA: California Dept. of Water Resources.

Escriva-Bou, A., H. McCann, E. Hanak, J. Lund, and B. Gray. 2016. *Accounting for California's water (Rep.)*. San Francisco: Public Policy Institute of California.

Fagan, B. M. 2009. *Floods, famines, and emperors: El Niño and the fate of civilizations*. New York: Basic Books.

Farr, T. G., C. E. Jones, and Z. Liu. 2017. *Progress report: Subsidence in California, March 2015–September 2016*. Pasadena, CA: Jet Propulsion Laboratory.

Faunt, C. C., and M. Sneed. 2015. "Water availability and subsidence in California's Central Valley." *San Francisco Estuary Watershed Sci.* 13 (3), in press.

Fencl, A., and M. Klasic. 2017. "Small self-sufficient water systems continue to battle a hidden drought." Accessed August 6, 2017. https://californiawaterblog.com/2017/08/06/small-self-sufficient-water-systems-continue-to-battle-a-hidden-drought.

Fleck, J. 2016. *Water is for fighting over: And other myths about water in the west*. Washington, DC: Island Press.

Friant Water Authority. 2017. *Subsidence: A critical challenge to Friant-Kern canal water deliveries*. Lindsay, CA: Friant Water Authority.

Gailey, R. M. 2018. "Approaches for groundwater management in times of depletion and regulatory change." Ph.D. dissertation, Univ. of California.

Gartrell, G., J. Mount, E. Hanak, A. Escriva-Bou, and B. Grey. 2017a. *Appendix B: Water assigned to meeting environmental standards in the Delta from 1980–2016*. San Francisco: Public Policy Institute of California.

Gartrell, G., J. Mount, E. Hanak, and B. Grey. 2017b. *A new approach to accounting for environmental water, insights from the Sacramento-San Joaquin Delta*. San Francisco: Public Policy Institute of California.

Gleick, P. 2016. *Impacts of California's ongoing drought: Hydroelectricity generation 2015 update*. Oakland, CA: Pacific Institute.

Griffin, D., and K. J. Anchukaitis. 2014. "How unusual is the 2012–2014 California drought?" *Geophys. Res. Lett.* 41 (24): 9017–9023. https://doi.org/10.1002/2014GL062433.

Grossi, M. 2017. "California's biggest drought success story came with a high cost." Water Deeply. Accessed August 3, 2018. https://www.newsdeeply.com/water/articles/2017/08/03/californias-biggest-drought-success-story-came-with-a-high-cost.

Hallstein, E., and M. Miller. 2014. "A renter's market: BirdReturns offers innovative conservation, cool green science blog, the nature conservancy." Accessed August 06, 2014. https://blog.nature.org/science.

Hanak, E., et al. 2017. "Water stress and a changing San Joaquin valley." PPIC Water Policy Center. Accessed August 31, 2017. http://www.ppic.org/main/publication.asp?i=1224.

Hanak, E., J. Lund, A. Dinar, B. Gray, R. Howitt, J. Mount, P. Moyle, and B. Thompson. 2011. *Managing California's water: From conflict to reconciliation*, 500. San Francisco: Public Policy Institute of California.

Hanak, E., J. Mount, C. Chappelle, R. Frank, J. Lund, P. Moyle, G. Gartrell, B. Gray, and B. Thompson. 2015a. "Ten ways US agencies and congress can help ease the drought in California and other western states." Accessed May 27, 2015. https://californiawaterblog.com.

Hanak, E., J. Mount, C. Chappelle, J. Lund, J. Medellín-Azuara, P. Moyle, and N. Seavy. 2015b. *What if California's drought continues?* San Francisco: PPIC Water Policy Center.

Hanak, E., J. Mount, J. Lund, G. Gartrell, B. Gray, R. Frank, and P. Moyle. 2014. "Modernizing drought water allocations." Accessed October 16, 2014. https://californiawaterblog.com.

Harou, J. J., J. Medellin-Azuara, T. Zhu, S. K. Tanaka, J. Lund, S. Stine, M. A. Olivares, and M. A. Jenkins. 2010. "Economic consequences of optimized water management for a prolonged, severe drought in California." *Water Resour. Res.* 46 (5): W05522. https://doi.org/10.1029/2008WR007681.

Howitt, R., J. MacEwan, J. Medellín-Azuara, and J. Lund. 2015a. "Drought bites harder, but agriculture remains robust." Accessed August 18, 2015. https://californiawaterblog.com.

Howitt, R., J. Medellín-Azuara, D. MacEwan, J. Lund, and D. Sumner. 2015b. *Economic analysis of the 2015 drought for California agriculture*. Davis, CA: Center for Watershed Sciences.

Howitt, R. E., J. Medellin-Azuara, D. MacEwan, J. R. Lund, and D. A. Sumner. 2014. *Economic analysis of the 2014 drought for California agriculture*. Davis, CA: Univ. of California.

IMPLAN. 2015. IMPLAN Professional, Version 3.0. Stillwater, Minnesota: Minnesota IMPLAN Group, Inc.

Israel, M., and J. R. Lund. 1995. "Recent California water transfers: Implications for water management." *Nat. Resour. J.* 35 (1): 1–32.

Jeffries, K. M., R. E. Connon, B. E. Davis, L. M. Komoroske, M. T. Britton, T. Sommer, A. E. Todgham, and N. A. Fangue. 2016. "Effects of high temperatures on threatened estuarine fishes during periods of extreme drought." *J. Exp. Biol.* 219 (11): 1705–1716. https://doi.org/10.1242/jeb.134528.

Kelley, R. 1989. *Battling the Inland Sea*. Berkeley, CA: University of California Press.

Kirkpatrick, N. 2015. "These snowless ski resorts show just how bad California's drought really is." *Washington Post*, March 24, 2015.

Krieger, L. M. 2014. "What the west's ancient droughts say about its future." *National Geographic*, February 15, 2014.

Kwon, A. 2017. "Declining groundwater level effects on supply well operations." M.S. thesis, Univ. of California.

Lehman, P. W., T. Kurobe, S. Lesmeister, D. Baxa, A. Tung, and S. J. Teh. 2017. "Impacts of the 2014 severe drought on the Microcystis bloom in San Francisco Estuary." *Harmful Algae* 63 (Mar): 94–108. https://doi.org/10.1016/j.hal.2017.01.011.

Lord, B., B. Magnuson-Skeels, A. Tweet, C. Whittington, L. Adams, R. Thayer, and J. Lund. 2018. "Drought water right curtailment analysis for California's Eel river." *J. Water Resour. Plann. Manage.* 144 (2): 04017082. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000820.

Lund, J. 2014a. "California droughts precipitate innovation." Accessed January 21, 2014. https://californiawaterblog.com/2014/01/21/california-droughts-precipitate-innovation.

Lund, J. 2014b. "Why utilities shy from mandatory water saving during a drought." Accessed July 30, 2014. https://californiawaterblog.com/2014/07/30/why-utilities-shy-from-mandatory-water-saving-during-a-drought.

Lund, J. 2015b. "California drought: Virtual water vs. real water." Accessed July 5, 2015. https://californiawaterblog.com/2015/07/05/virtual-water-vs-real-water-in-california-2.

Lund, J. 2015c. "Improving mandatory State cutbacks of urban water use for a 5th year of drought." Accessed December 13, 2015. https://californiawaterblog.com/2015/12/13/improving-mandatory-state-cutbacks-of-urban-water-use-for-a-5th-year-of-drought.

Lund, J. 2015a. "The banality of California's '1,200-year' drought." Accessed September 23, 2015. https://californiawaterblog.com/2015/09/23/the-banality-of-californias-1200-year-drought.

Lund, J. 2015d. "Urban water conservation for the birds." Accessed October 6, 2015. https://californiawaterblog.com/2015/10/06/water-conservation-could-be-for-the-birds.

Lund, J. 2015e. "Water rationing and California's drought." Accessed May 3, 2015. https://californiawaterblog.com.

Lund, J. 2016b. "How bad is water management in California?" Accessed June 26, 2016. https://californiawaterblog.com/2016/06/26/how-bad-is-water-management-in-california.

Lund, J. 2016c. "You can't always get what you want: A Mick Jagger theory of drought management." Accessed February 21, 2016. https://californiawaterblog.com/2016/02/21/you-cant-always-get-what-you-want-a-mick-jagger-theory-of-drought-management.

Lund, J., E. Hanak, W. Fleenor, W. Bennett, R. Howitt, J. Mount, and P. Moyle. 2010. *Comparing futures for the Sacramento-San Joaquin Delta*. Berkeley, CA: University of California Press.

Lund, J., E. Hanak, B. Thompson, B. Gray, J. Mount, and K. Jessoe. 2014. "Why give fish flows away for free during a drought?" Accessed February 11, 2014. https://californiawaterblog.com.

Lund, J., and P Moyle. 2014. "Is shorting fish of water during drought good for water users?" Accessed June 3, 2014. https://californiawaterblog.com.

Lund, J. R. 2016a. "Droughts and the global economy: Lessons from California: Harvard College Review of Environment and Society: Running dry, weathering the great California drought." Accessed July 2, 2018. https://issuu.com/harvarduniversityreviewofenvironmen/docs/hcres_2016.

Maass, A., and R. L. Anderson. 1978. *… And the desert shall rejoice*. Cambridge, MA: MIT Press.

MacEwan, D., M. Cayar, A. Taghavi, D. Mitchell, S. Hatchett, and R. Howitt. 2017. "Hydroeconomic modeling of sustainable groundwater management." *Water Resour. Res.* 53 (3): 2384–2403. https://doi.org/10.1002/2016WR019639.

Madani, K., and J. R. Lund. 2009. "Modeling California's high-elevation hydropower systems in energy units." *Water Resour. Res.* 45 (9): W09413. https://doi.org/10.1029/2008WR007206.

McPhate, M., and J. Medina. 2016. "California today: A water crisis on the central coast." *New York Times*, August 8, 2017.

Means, T. H. 1928. *Saltwater problem: San Francisco bay and delta of Sacramento and San Joaquin rivers*. Consultant Report for the Association of Industrial Water Users of Contra Costa and Solano Counties. Contra Costa, CA: Association of Industrial Water Users of Contra Costa and Solano Counties.

Medellín-Azuara, J., R. Howitt, D. MacEwan, D. Sumner, and J. Lund. 2015a. "Drought killing farm jobs even as they grow." Accessed June 8, 2015. https://californiawaterblog.com.

Medellín-Azuara, J., D. MacEwan, R. E. Howitt, G. Koruakos, E. C. Dogrul, C. F. Brush, T. N. Kadir, T. Harter, F. Melton, and J. R. Lund. 2015b. "Hydro-economic analysis of groundwater pumping for irrigated agriculture in California's Central Valley, USA." *Hydrogeol. J.* 23 (6): 1205–1216. https://doi.org/10.1007/s10040-015-1283-9.

Medellín-Azuara, J., et al. 2018. "A comparative study for estimating crop evapotranspiration in the Sacramento-San Joaquin delta-final report, appendix set, and project datasets." Center for Watershed Sciences, University of California, Davis. https://watershed.ucdavis.edu/project/delta-et.

Medellín-Azuara, J., D. MacEwan, R. E. Howitt, D. A. Sumner, and J. R. Lund. 2016. *Economic analysis of the 2016 California drought on agriculture*. A Report for the California Department of Food and Agriculture. Davis, CA: Univ. of California.

Mount, J., B. Gray, C. Chappelle, J. Doolan, T. Grantham, and N. Seavy. 2016. *Managing water for the environment during drought: Lessons from Victoria, Australia*. San Francisco: Public Policy Institute of California.

Mount, J., B. Gray, C. Chappelle, G. Gartrell, T. Grantham, P. Moyle, N. Seavy, L. Szeptycki, and B. Thompson. 2017. *Managing California's freshwater ecosystems—Lessons from the 2012–16 drought*. San Francisco: Public Policy Institute of California.

Moyle, P., R. Lusardi, P. Samuel, and J. Katz. 2017. "State of the Salmonids: Status of California's emblematic fishes 2017." Accessed July 2, 2018. https://watershed.ucdavis.edu/files/content/news/SOS%20II_Final.pdf.

Moyle, P., and R. M. Quiñones. 2014. "Drought journal: Hope springs eternal." Accessed September 21, 2014. https://californiawaterblog.com/2014/09/21/drought-journal-hope-springs-eternal.

Moyle, P. B., J. Katz, and R. M. Quiñones. 2011. "Rapid decline of California's native inland fishes: a status assessment." *Biol. Conserv.* 144 (10): 2414–2423. https://doi.org/10.1016/j.biocon.2011.06.002.

MWDSC (Metropolitan Water District of Southern California). 2015. *Urban water management plan*. Los Angeles: Metropolitan Water District of Southern California.

Nelson, T., H. Chou, P. Zikalala, J. Lund, R. Hui, and J. Medellin-Azuara. 2016. "Economic and water supply effects of ending groundwater overdraft in California's Central Valley." *San Francisco Estuary Watershed Sci.* 14 (1): 19. https://doi.org/10.15447/sfews.2016v14iss1art7.

Pisani, D. 1984. *From the family farm to agribusiness: The irrigation crusade in California*, 1850–1931. Berkeley, CA: University of California Press.

Sanchez, N. 2017. *Changes in evapotranspiration of agricultural crops in Kern County during the 2014-2015 drought years*. MS Rep. Davis, CA: Univ. of California.

Schonher, T., and S. E. Nicholson. 1989. "The relationship between California rainfall and ENSO events." *J. Clim.* 2 (11): 1258–1269. https://doi.org/10.1175/1520-0442(1989)002<1258:TRBCRA>2.0.CO;2.

SCVWD (Santa Clara Valley Water District). 2016. *2015 urban water management plan*. San Jose, CA: Santa Clara Valley Water District.

Shimada, I., L. Schaff, L. G. Thompson, and E. Moseley-Thompson. 1991. "Cultural impacts of severe drought in the prehistoric Andes: Application of a 1500-year ice core precipitation record." *World Archaeology* 22 (3): 247–270. https://doi.org/10.1080/00438243.1991.9980145.

Singh, D., D. L. Swain, J. S. Mankin, D. E. Horton, L. N. Thomas, B. Rajaratnam, and N. S. Diffenbaugh. 2016. "Recent amplification of the North American winter temperature dipole." *J. Geophys. Res. Atmos.* 121 (17): 9911–9928. https://doi.org/10.1002/2016JD025116.

Sneed, M., J. Brandt, and M. Solt. 2013. *Land subsidence along the Delta-Mendota Canal in the northern part of the San Joaquin Valley, California, 2003–10*. Reston, VA: US Dept. of the Interior, US Geological Survey.

State Water Resource Control Board. 2015. "Comments/objections/protests regarding January 23, 2015 temporary urgency change petition and petitions for reconsideration of order approving temporary urgency change for the Central Valley and state water projects, Sacramento, CA." Accessed July 2, 2018. https://www.waterboards.ca.gov/waterrights/water_issues/programs/drought/comments_tucp2015.

Staubwasser, M., F. Sirocko, P. M. Grootes, and M. Segl. 2003. "Climate change at the 4.2 ka BP termination of the Indus valley civilization and Holocene south Asian monsoon variability." *Geophys. Res. Lett.* 30 (8): 1425. https://doi.org/10.1029/2002GL016822.

Stevens, M. 2016. "102 million dead California trees 'unprecedented in our modern history,' officials say." Accessed July 2, 2018. http://www.latimes.com/local/lanow/la-me-dead-trees-20161118-story.html.

Stine, S. 1994. "Extreme and persistent drought in California and Patagonia during medieval time." *Nature* 369 (6481): 546–549. https://doi.org/10.1038/369546a0.

Sumner, D. A. 2015. "California's severe drought has only marginal impacts on food prices." *Agric. Resour. Econ. Update* 18 (5): 12–15.

Swain, D. L. 2015. "A tale of two California droughts: Lessons amidst record warmth and dryness in a region of complex physical and human geography." *Geophys. Res. Lett.* 42 (22): 9999–10003. https://doi.org/10.1002/2015GL066628.

Swain, D. L., D. Singh, D. E. Horton, J. S. Mankin, T. C. Ballard, and N. S. Diffenbaugh. 2017. "Remote linkages to anomalous winter atmospheric ridging over the Northeastern Pacific." *J. Geophys. Res. Atmos.* 122 (22): 12194–12209. https://doi.org/10.1002/2017JD026575.

Teng, H., and G. Branstator. 2017. "Causes of extreme ridges that induce California droughts." *J. Clim.*, in press. https://doi.org/10.1175/JCLI-D-16-0524.1.

Tulare County. 2017. “Drought effects status updates.” Accessed July 2, 2018. http://tularecounty.ca.gov/emergencies/index.cfm/drought/drought-effects-status-updates/.
US Bureau of Reclamation. 2018. “Summary of water supply allocations.” Accessed July 2, 2018. https://www.usbr.gov/mp/cvo/vungvari/water_allocations_historical.pdf.
US Forest Service. 2016. “New aerial survey identifies more than 100 million dead trees in California.” Accessed July 2, 2018. https://www.fs.fed.us/news/releases/new-aerial-survey-identifies-more-100-million-dead-trees-california.
Weiss, H. 1997. “Late third millennium abrupt climate change and social collapse in West Asia and Egypt.” Vol. 49 of *Third millennium BC climate change and old world collapse: NATO ASI series*. Edited by H. N Dalfes, G. Kukla, and H. Weiss, 711–723. Berlin: Springer.
Winder, M., A. D. Jassby, and R. Mac Nally. 2011. “Synergies between climate anomalies and hydrological modifications facilitate estuarine biotic invasions.” *Ecol. Lett.* 14 (8): 749–757. https://doi.org/10.1111/j.1461-0248.2011.01635.x.
York, T., and D. A. Sumner. 2015. “Why food prices are drought-resistant.” *Wall Street J.* 12.
Young, D., J. Stevens, J. M. Earles, J. Moore, A. Ellis, A. L. Jirka, and A. M. Latimer. 2016. “Long-term climate and competition explain forest mortality patterns under extreme drought.” *Ecol. Lett.* 20 (1): 78–86. https://doi.org/10.1111/ele.12711.