

RESEARCH

# Drought and the Sacramento–San Joaquin Delta, 2012–2016: Environmental Review and Lessons

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## ABSTRACT

This paper reviews environmental management and the use of science in the Sacramento–San Joaquin Delta during California’s 2012–2016 drought. The review is based on available reports and data, and guided by discussions with

27 agency staff, stake-holders, and researchers. Key management actions for the drought are discussed relative to four major drought water management priorities stated by water managers: support public health and safety, control saltwater intrusion, preserve cold water in Shasta Reservoir, and maintain minimum protections for endangered species. Despite some success in streamlining communication through interagency task forces, conflicting management mandates sometimes led to confusion about priorities and actions during the drought (i.e., water delivery, the environment, etc.). This report highlights several lessons and offers suggestions to improve management for future droughts. Recommendations include use of pre-drought warnings, timely drought declarations, improved transparency and useful documentation, better scientific preparation, development of a Delta drought management plan (including preparing for salinity barriers), and improved water accounting. Finally, better environmental outcomes occur when resources are applied to improving habitat and bolstering populations of native species during inter-drought periods, well before stressful conditions occur.

SFEWS Volume 18 | Issue 2 | Article 2

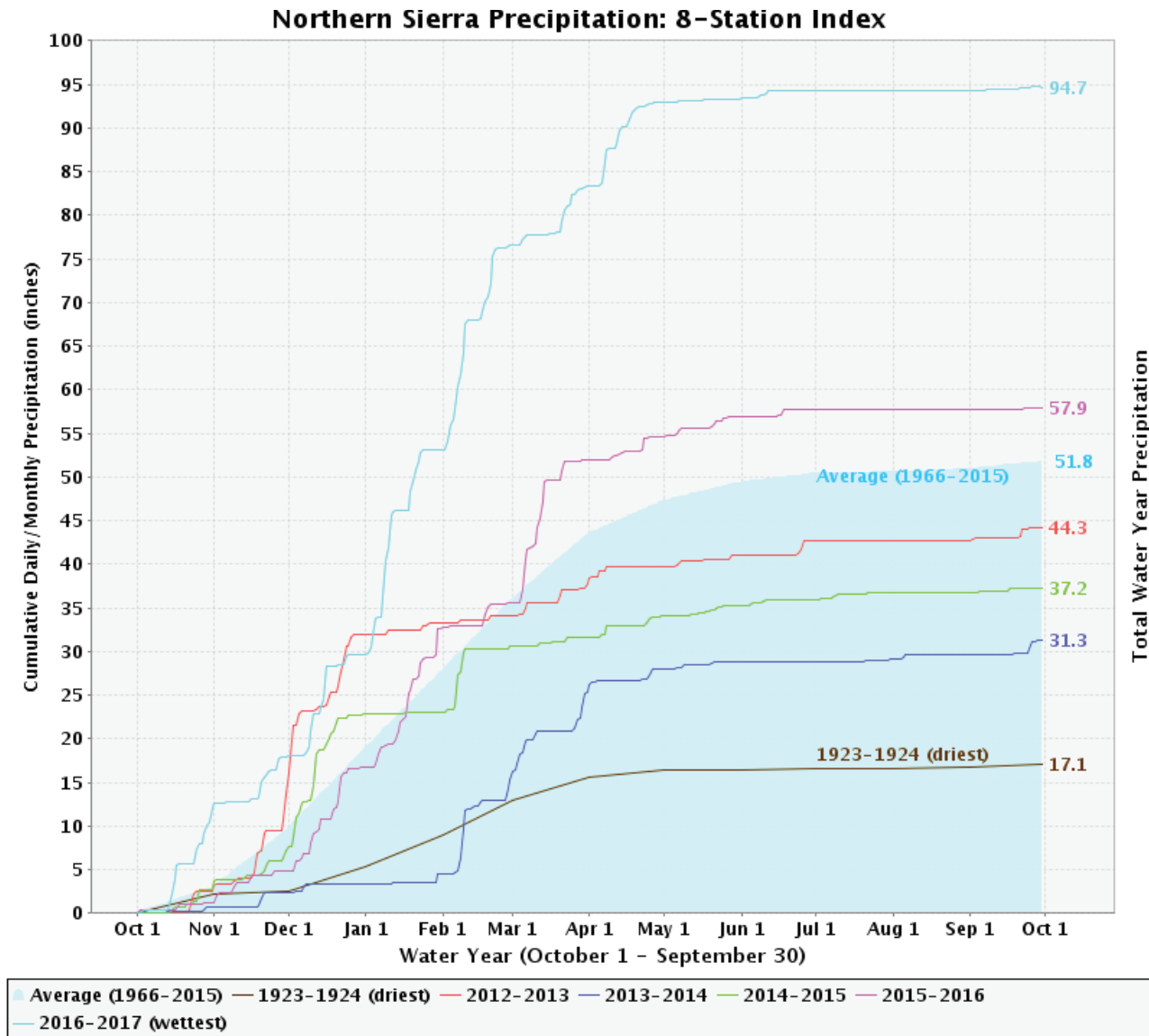
<https://doi.org/10.15447/sfeWS.2020v18iss2art2>

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## KEY WORDS

Sacramento–San Joaquin Delta, drought, California water, water management, scientific monitoring



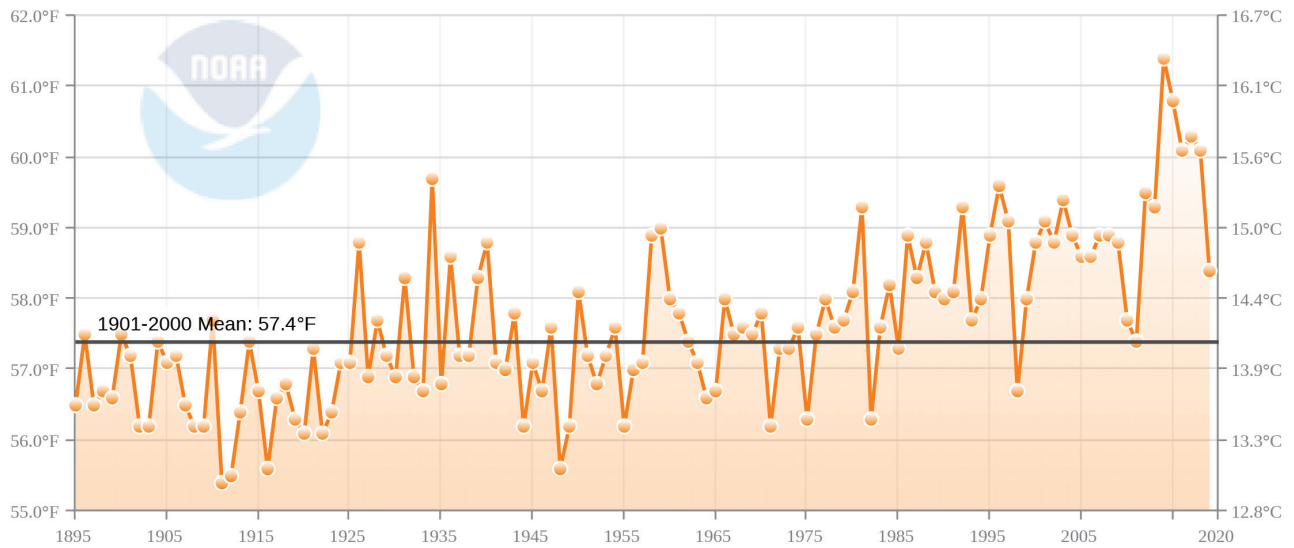
**Figure 1** Cumulative northern Sierra precipitation using an 8-station index for water years 2012–2015, compared with the driest (1923–1924) and wettest (2016–2017) years on record, as well as the 1921–2019 average *Source: CDEC.*

## I. INTRODUCTION

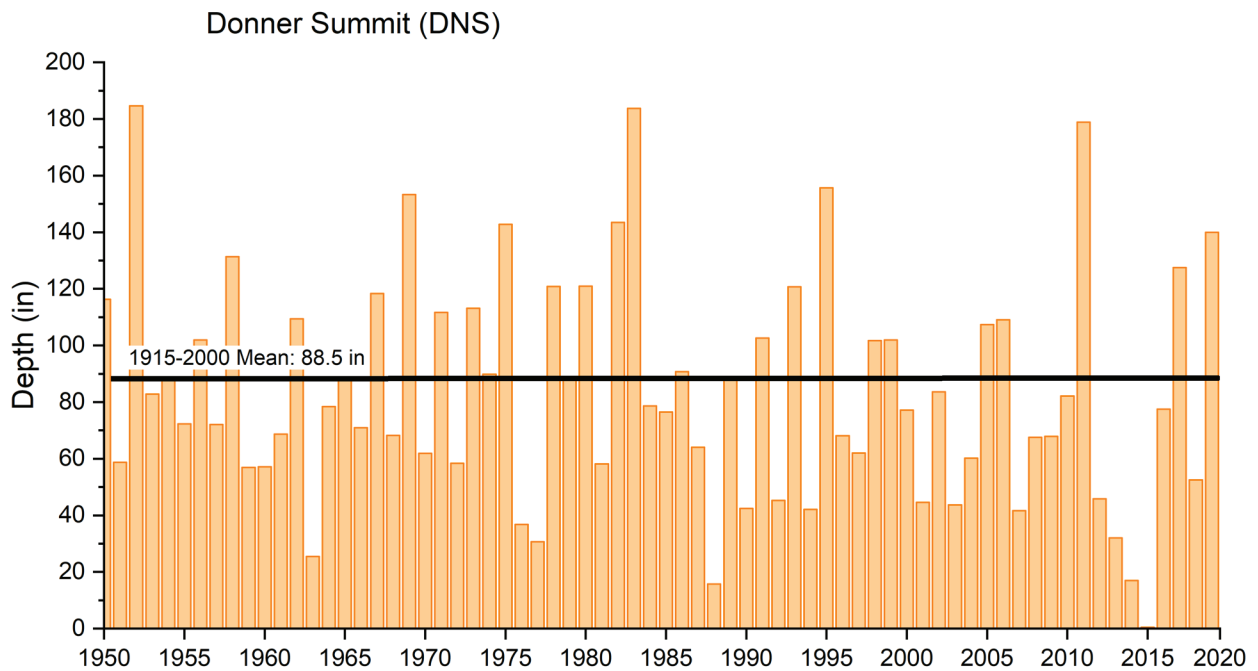
Drought is common in California. The state’s climate has more frequent and extreme dry and wet years than the rest of the country (Dettinger et al. 2016). The recent 2012–2016 drought had similar precipitation and duration as droughts of the previous century (Figure 1), but with higher temperatures (Figure 2) and reduced snowpack (Figure 3) (Griffin and Anchukaitis 2014; Swain 2015; Mount et al. 2017a; Lund et al. 2018). Although the governor did not declare an official

drought emergency until 2014, low precipitation and snowpack marked the true beginning of the drought in 2012, record high temperatures exacerbated the drought in 2014 and 2015, and the slightly above-normal water year of 2016 was insufficient to break the water deficit from the previous 4 years. With record-breaking precipitation in 2017, the governor officially declared the drought over.

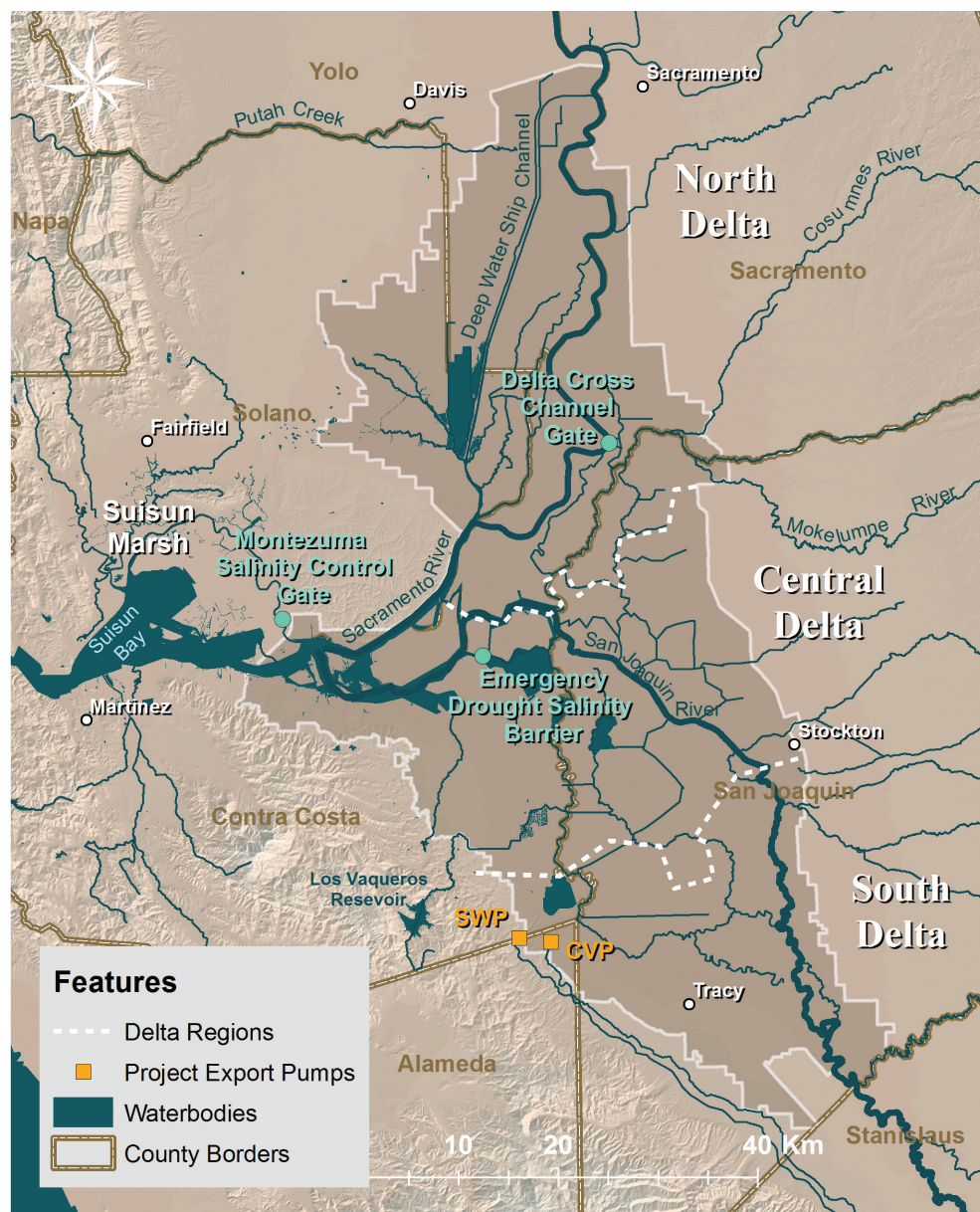
California Average Temperature  
January-December



**Figure 2** California mean annual temperatures relative to 20<sup>th</sup>-Century mean. *Source:* NOAA National Centers for Environmental Information.



**Figure 3** California mean April 1 snowpack at Donner Summit relative to 20<sup>th</sup>-Century mean. *Source:* CDEC.



**Figure 4** Map of the Sacramento–San Joaquin Delta showing major diversion points and infrastructure for managing salinity and flows. *Credit:* Amber Lukk.

This review summarizes and evaluates major water management actions during the 2012–2016 drought in the Sacramento–San Joaquin Delta (Delta), with emphasis on the use of science. Any review of such an extensive event as the 2012–2016 California drought, even narrowed to the Delta, must omit or miss many details, insights, and perspectives. Nevertheless, we have assembled a wide array of information and experiences on drought management and the

Delta, discussed these with a variety of managers and experts, and have findings relevant for preparing for and managing future droughts.

The Delta is an important region for water storage and delivery in California, handling about 45% of the state’s runoff, before water is diverted, exported, or released as outflow to the Pacific Ocean (Lund et al. 2010). Water moving through the Delta (Figure 4) supports California cities,

agriculture, and ecosystems, which are at risk during droughts. The Delta consists largely of built water conveyance networks that also serve as critical habitat for threatened and endangered species (USFWS 2008; NMFS 2009). Diverse resource managers must therefore make decisions while considering input from numerous agencies with overlapping jurisdictions and conflicting mandates (i.e., supply vs. environment) (Hanak et al. 2011, 2013; Lund et al. 2018).

During the 2012–16 drought, key drought water management priorities for the Delta and its tributaries were established by US Bureau of Reclamation (USBR) and the California Department of Water Resources (CDWR) (USBR et al. 2014a, 2014b, 2015, 2016):

1. Provide essential human health and safety needs, and expand water management flexibilities
2. Control saltwater intrusion into the Delta
3. Maintain reservoir storage: cold-water pool and carryover capacity
4. Maintain protections for endangered species and other fish and wildlife

Supporting the priorities were multiple management actions, which included reducing and storing Delta inflows and outflows; changing operation of water gates, diversions, and export pumps; installing salinity barriers; facilitating water market exchanges; increasing salmon hatchery production and trucking juvenile salmon; conserving urban water; and increasing efforts to control invasive aquatic weeds (USBR et al. 2014b).

In Section II, we summarize the water management structure for the Delta, and how accommodations were made to handle the drought. Section III examines each of the four drought management priorities, evaluates the

environmental outcomes of priority actions, and considers the role of science in decision-making. Section IV discusses scientific lessons from the drought, and Section V provides recommendations to improve California's readiness for the next drought, followed by some concluding thoughts.

An appendix provides a more detailed catalogue of the priority actions in Section III. It reviews the background of the actions, data used for decision-making, and major remaining scientific uncertainties.

## II. WATER MANAGEMENT

The modern Delta (Figure 4) is very different from the inland tidal freshwater wetland that developed with post-Ice Age sea level rise (Moyle et al. 2010; Lund et al. 2010). More than 90% of the original wetlands have been claimed for agriculture and urban uses, while water courses were dredged, straightened, and hardened to manage floods and water transport. As California's water storage and conveyance capacities increased in the 20th century, the Delta became a conduit for water from wetter northern California to its drier central and southern regions, changing hydrodynamic patterns within the Delta (Lund et al. 2008, 2010). Water storage and conveyance is managed largely by the USBR (operating the Central Valley Project, CVP) and the CDWR (operating the State Water Project, SWP), in conjunction with numerous local and regional water agencies (Lund et al. 2007). Delta diversions export water to about 25 million urban users and 3 million acres of irrigated farmland, accounting for about 15% of the state's total water supply (Lund et al. 2008; Mount et al. 2017b). The CVP and SWP (together, "the Projects") operate large pumps in the South Delta (Figure 4) that draw water for transport to central and southern California agriculture and cities. Contra Costa County, Solano County, the City of Stockton, and numerous local farmers operate smaller intakes from the Delta to supply water to their constituents. Delta Cross Channel gates (Figure 4) are operated by CDWR to control the timing and direction of flows from the north Delta to south, helping to improve water quality, species needs,

and water project diversions. Various temporary barriers are installed seasonally to help manage water level and quality in the south Delta (Lund et al. 2008).

Water agencies (the USBR and CDWR) operate under permits issued by state and federal regulatory agencies that evaluate whether permit conditions are followed, make recommendations, and modify permit terms accordingly. They also establish mitigations for water use, including habitat restoration. Key regulatory agencies that oversee Delta water management and provide operating permits include:

- California State Water Resources Control Board (SWRCB), regulating water rights for upstream and in-Delta water diversions, and water quality (mainly salinity and nutrients) in the Delta through Water Rights Decision 1641 (D-1641)
- California Department of Fish and Wildlife (CDFW), requiring project operators to maintain below-dam populations of fish “in good condition” (California Fish and Game Code § 5937), and provide protections for threatened and endangered species under the 1970 California Endangered Species Act (CESA; California Fish and Game Code §2050-2100)
- US Fish and Wildlife Service (USFWS), enforcing the 1973 US Endangered Species Act (ESA; 16 USC §1531 et seq.) for terrestrial and freshwater species
- National Marine Fisheries Service (NMFS), enforcing the ESA for marine and anadromous species (Salmon and Steelhead)
- Federal Energy Regulatory Commission (FERC), which regulates flows in rivers upstream for hydropower production

The complexity of water operations and regulatory requirements has led to creation of

numerous interagency management teams to evaluate data and make recommendations. The Water Operations Management Team (WOMT, consisting of the CDWR, USBR, USFWS, NMFS, and the CDFW) provides the CDWR and USBR with operations guidance. This group receives technical support from the Smelt Working Group (SWG), the Delta Operation for Salmon and Sturgeon (DOSS), the Sacramento River Temperature Task Group (SRTTG), and teams for several major tributaries (Clear Creek, American, Stanislaus, and Feather rivers) (USFWS 2008). These teams formally consist of scientific experts from the various regulatory agencies.

In response to conditions like drought, management decisions often must be made iteratively, based upon supply, demand, environmental conditions, species’ needs, and legal requirements. Water operations also must balance carryover water supply with flood management, creating additional uncertainty about whether to manage for drought by holding water, or for potential floods and immediate needs by releasing water from reservoirs.

The variability of California’s hydrology and climate often causes regional differences in drought onset (Steinemann et al. 2015; Mount et al. 2017b). The governor’s Proclamation of a State Emergency in 2014 brought a unified statewide drought response (Brown 2014). It ordered statewide urban water conservation, eased California Environmental Quality Act (CEQA) requirements to support management flexibility, notified water-rights holders of potential restrictions on water diversions, released additional funding to address developing problems from drought conditions, and convened an advisory Drought Task Force (Hanak et al. 2015; Mount et al. 2017b).

The Declaration provided more flexibility for the SWRCB to respond to Temporary Urgency Change

Petitions (TUCPs) when the USBR and CDWR were unable to meet the requirements of their operating permits (SWRCB 2019). Petitions during the drought convened a Real-Time Drought Operations Management Team (RTDOMT) of representatives from the USBR, CDWR, USFWS, NMFS, CDFW, and SWRCB, which met weekly (RTDOMT 2014); reduced Project exports; and relaxed D-1641 Delta water-quality requirements (SWRCB 2014). The TUCP process was invoked regularly throughout the drought in public hearings, with supporting evidence from operators, statements from fisheries agencies, and objections or support from various stakeholders (Nylen et al. 2018).

### III. PRIORITY ACTIONS AND ENVIRONMENTAL RESPONSE

Because the Delta is a focal point for demands and conflicts among diverse agricultural, urban, and environmental interests, tensions exist even in wet years (Hanak et al. 2011), and are exacerbated by extreme events such as the 2012–2016 drought (Mount et al. 2017a). Federal, state, and local agencies sought to balance watershed storage with Project exports, senior water rights diversions, municipal and agricultural diversions, water quality conditions, and environmental flows. At the same time, they struggled to resolve differences in their individual mandates as well as uncertainties in data, analysis, and interpretation. Statewide emergency actions designed to address convergent drought management priorities (USBR et al. 2014a, 2014b, 2015, 2016) are briefly summarized below and elaborated on in the Appendix.

Maintaining water supply for essential human health and safety (Priority 1) was supported by

1. Project export reductions (Appendix A, p. 1)
2. mandatory urban conservation (Appendix A, p. 4)
3. voluntary water use reduction on Delta farmland (Appendix A, p. 5), and

4. interties, operations, and markets to move water among districts (Appendix A, p. 6)

While these actions were intended to preserve water and water quality in the Delta, they had important environmental implications, especially the reduction in Project exports, which reduced entrainment risk for vulnerable species (Polansky et al. 2014) and helped control water-quality conditions (especially salinity) in the south Delta.

Water export reductions can have dual effects on Delta water quality. A minimum level of export is thought to be necessary to maintain water quality in the south Delta (Monsen et al. 2007), by removing brackish agricultural runoff from the San Joaquin River and drawing in fresher water from the Sacramento River (Monsen et al. 2007). At the same time, large south Delta exports can cause salinity from Central and Suisun bays to encroach into the Delta. Reducing exports helped leverage reservoir releases from the Sacramento River watershed to reduce saltwater intrusion. The resulting outflow resulted in mutual benefits for in-Delta agriculture, drinking water, and environmental protections, although current water accounting often obscures the benefits and losses of water conservation actions (Appendix A, p. 3) (Gartrell et al. 2017; Reis et al. 2019).

In response to increasingly poor water-quality conditions, urban users developed alternative strategies, including use of off-stream storage and water market transfers to maintain supply, and conservation to reduce water demands (Lund et al. 2018). Agricultural users fallowed and employed other conservation measures to reduce demand (George 2016), but otherwise had no other options for supply but to irrigate crops with poorer-quality water.

Nonetheless, water scarcity decreased control over saltwater intrusion and water quality in the Delta (Priority 2). Actions supporting water quality included

1. installing an emergency drought salinity barrier in 2015 (Figure 4; Appendix A, p. 7),

2. re-operating the Delta Cross Channel gates to allow Sacramento River water to freshen the south Delta as necessary (Figure 4; Appendix A, p. 9), and
3. monitoring harmful algal blooms (Appendix A p. 9)

The emergency drought salinity barrier was installed at West False River in the central Delta to help reduce the volume of outflow needed to maintain salinity standards, saving approximately 90 taf in reservoir storage (2015 presentation by E. Ateljevich, unreferenced, see “Notes”; 2016 presentation by P. Marshall, unreferenced, see “Notes”). With the \$37 million cost of the barrier (Maven’s Notebook c2015), the approximate unit water cost of saved water was \$411 per af. A formal post-hoc analysis of the benefits versus cost of implementation has not appeared. Despite the barrier, parts of the western, central and south Delta (Figure 4) had violations of water quality objectives in 2015 (SWRCB 2015; USBR et al. 2016; CDEC 2018).

Delta Cross Channel gate re-operation was rarely employed (USBR 2019), and monitoring harmful algal blooms was not a mitigation strategy per se, but allowed for early warnings if levels became hazardous—which did not happen (Kurobe et al. 2018; Lehman et al. 2018).

In response to increasingly poor water-quality conditions, urban users developed alternative strategies, including use of off-stream storage and water market transfers to maintain supply, and conservation to reduce water demands (Lund et al. 2018). Agricultural users followed and employed other conservation measures to reduce demand (George 2016), but otherwise had no other options for supply but to irrigate crops using with poorer quality water.

Strategies to maintain reservoir storage for cold-water pool and carryover capacity (Priority 3) included reducing:

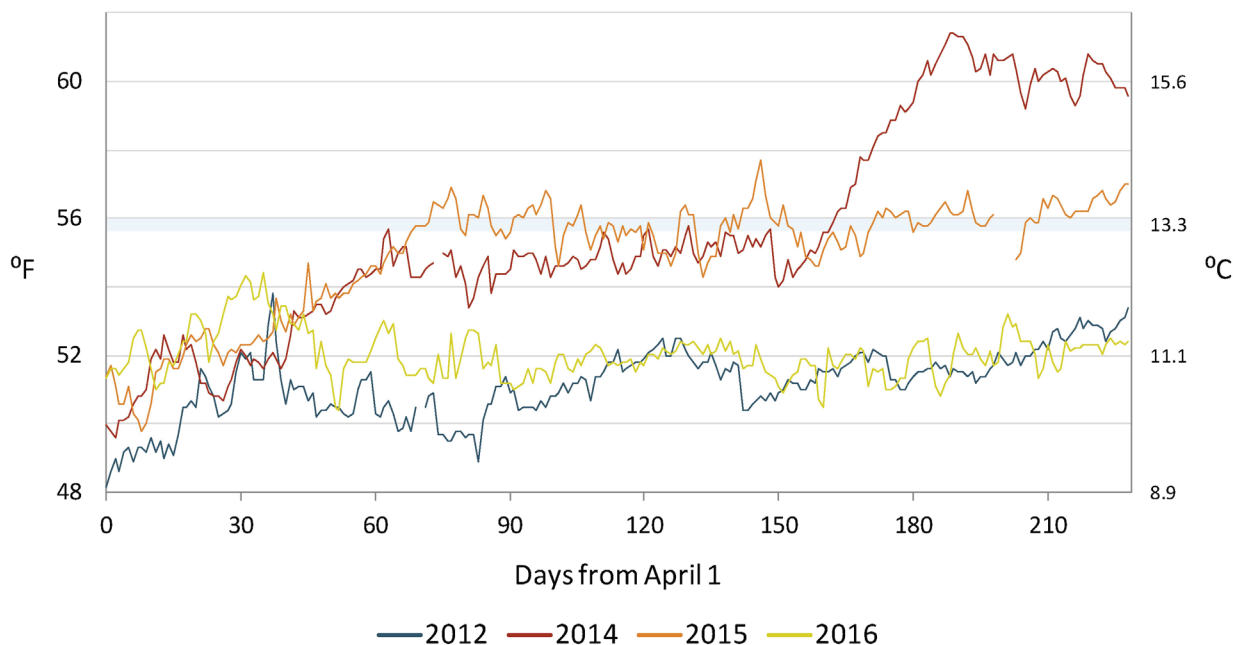
1. Delta inflow and outflow (Appendix A, p. 11) and

2. releases from Shasta Reservoir (Appendix A, p. 13)

Water releases from the major upstream Sacramento Valley reservoirs largely determine Delta inflow during dry periods. Outflow can be controlled by changing Delta inflow, consumptive use (mostly agriculture and urban), and water export (precipitation and snowpack are more important, but not subject to direct management) (Enright and Culberson 2009; Hutton et al. 2017). During the drought, inflow was reduced to preserve water in reservoir storage (both for later use and to supply cold water in streams). Corresponding reductions in water export diversions, and the installation of the emergency salinity barrier, were needed to maintain outflow to prevent salinity intrusion from San Francisco Bay.

However, by 2014 and 2015, surface reservoirs were significantly depleted (Dettinger and Anderson 2015; Xiao et al. 2017), leading to concerns that cold-water storage in Shasta would be insufficient to protect winter-run Chinook Salmon larvae. Winter-run Chinook became endangered as a result of Shasta Dam, which cut off access to cold water habitat in high mountain streams. Ironically, the sole remaining spawning habitat for winter-run is now below Shasta Dam in the Sacramento River, which depends on cold water stored in Shasta Reservoir (Yates et al 2008). In an effort to hold Shasta Reservoir water for late summer use, water temperature thresholds were increased by the Sacramento River Temperature Task Group, and efforts were made to improve the temperature control device on the dam designed to maintain cold water releases (USBR et al. 2014b, 2016). Water releases from Lake Oroville, which lacks cold-water regulations, were prioritized by inter-agency agreements between the CVP and the SWP (USBR et al. 2014b, 2016; Mount et al. 2017b). But in 2014, measurement and modeling errors led to depletion of cold water behind Shasta Dam and high temperatures below Keswick Dam (Figure 5), killing 95% of larval winter-run Chinook Salmon (USBR et al. 2016a, 2016b; Rea 2017, unferenced, see “Notes;” Shaffer 2018). These problems were fixed, but similar mortality

### Sacramento River Daily Average Temperature at Keswick



**Figure 5** Sacramento River daily average temperature at Keswick Dam. Note that temperatures began climbing in late 2014, after the cold-water pool became depleted. *Data source:* CDEC.

occurred in 2015, when the cold-water pool again became depleted because of lack of water in the reservoir. Precipitation increased to slightly above normal in 2016, resulting in better management of the cold-water pool, and less in-river larvae mortality.

Efforts to protect species of special status (Priority 4) are included in some actions discussed above, such as export reductions, maintenance of minimum outflow standards, and efforts to preserve in-river cold water temperatures. Additional actions included

1. Hatchery improvements (Appendix A, p. 15),
2. Trucking salmon around the Delta (Appendix A, p. 17), and
3. Aquatic vegetation management (Appendix A, p. 18).

Hatchery re-operation provided fall-run Chinook for the commercial fishery and offset significant

natural-origin losses of wild-spawning winter-run Chinook (USBR 2008; USBR et al. 2014b). The wild run of winter-run Chinook Salmon has been supplemented with hatchery stock from the Livingston Stone National Fish Hatchery since 1998, and supplementation increased greatly in 2014 and 2015 (NMFS 2016). Chinook Salmon typically return to natal streams from the sea after 2 to 3 years, so 2017 and 2018 returns comprised cohorts born during the drought. In 2017, only about 147 wild fish returned (~15% of total returns), the lowest number on record (Figure 6). In 2018, 528 wild fish returned (~20% of the run), the lowest number since hatchery supplementation began in 1998 (Azat 2019). In this case, hatchery supplementation may have prevented extirpation of at least one of the annual cohorts, but did so by increasing genetic dominance of hatchery stock, with potential long-term decreases in fitness (Myers et al. 1998; USBR 2008; Hanak et al. 2015; Willmes et al. 2018).

Trucking from hatchery to the lower estuary bolstered fall-run Chinook Salmon populations

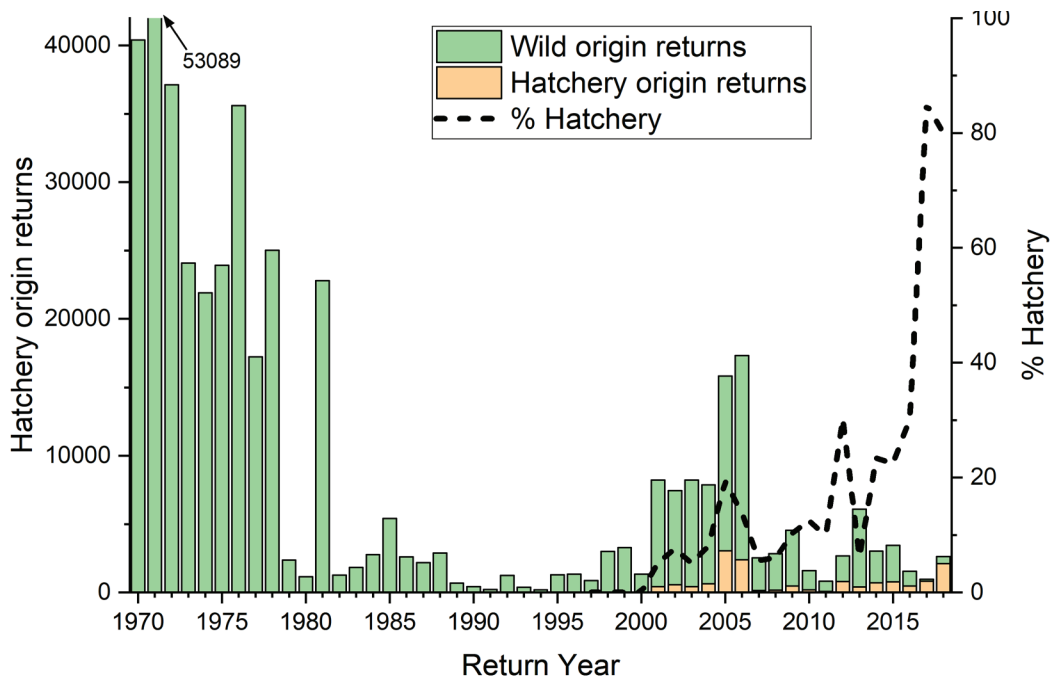


Figure 6 Annual winter-run Chinook Salmon returns to Sacramento River *Data source: NMFS.*

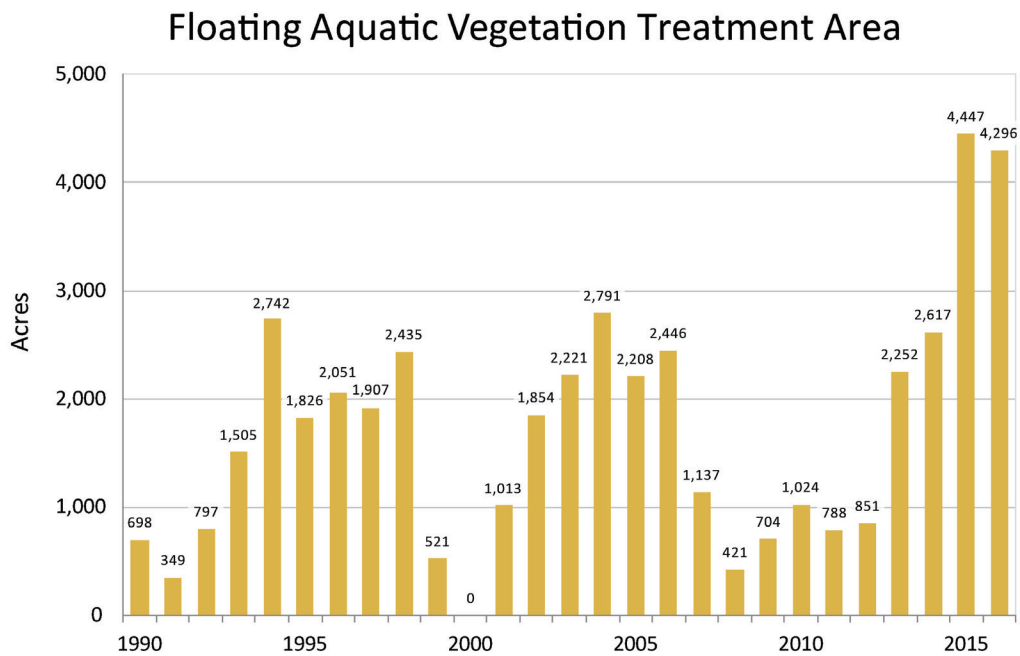


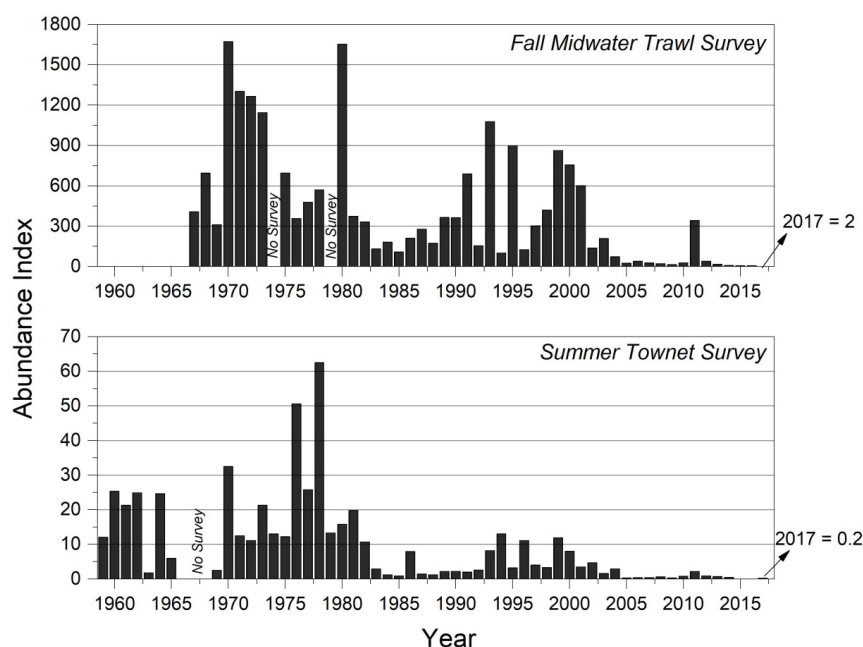
Figure 7 Annual acreage of herbicidal treatments for floating aquatic vegetation 1990–2016. *Source: Division of Boating and Waterways (2017b).*

against high temperatures and slow-moving water in the Delta, which can increase outmigration mortality (CDFW 2014; USFWS 2014, 2015a, 2015b). Trucking was the main tool used to boost ocean fisheries harvest, but with increased risk of straying when spawners return. Straying can disrupt the genetic integrity of individual runs, re-establish lost runs, and reduce the number of hatchery returns, which brings both opportunities and risks in the inter-drought period (USBR 2008; Satterthwaite and Carlson 2015; Dedrick and Baskett 2018).

The other major action in support of native fishes was the effort to reduce the extent of invasive aquatic weeds (also intended to support navigation, recreation, and water diversions). Slow-moving warm-water conditions expanded, favoring non-native aquatic species, including plants. Aquatic weed management could not stop the steady expansion of *Egeria densa* and other submersed aquatic macrophytes throughout the Delta (Ta et al. 2017; Hard 2018). The expansion of submersed aquatic vegetation likely aided Largemouth Bass and sunfish populations, which use it for habitat (Brown 2003; Nobriga and Feyrer 2007; Ferrari et al. 2014).

Both submersed and floating weeds can slow water movement, reduce turbidity in the water column, increase temperature, and provide habitat for non-native piscivores (Nobriga et al. 2005; Conrad et al. 2016; Hestir et al. 2016). By applying large quantities of herbicides across targeted locations in the Delta, the Division of Boating and Waterways (DBW) of the California Department of Parks and Recreation, might have slowed the spread of weeds across the Delta (Figure 7) (DBW 2017a; 2017b). The wet winter of 2017 may have temporarily cleared some vegetation (Hard 2018), probably because the vegetation appears to advance less rapidly with cool temperatures and high flows (Ustin et al. 2015, 2017; Durand et al. 2016). There is considerable uncertainty about the efficacy of aquatic weed management to enhance habitat for native fishes. Although the weeds degrade native habitat quality, and offer opportunities for alien species colonization, there is no clear evidence that their suppression opens habitat for native fishes.

Native fishes entered the drought with already-depleted populations, making them more vulnerable to extinction (Moyle et al. 2015, 2017). Over the past 30 years, habitat loss, alien species, high temperatures, export pumping and decreased



**Figure 8** Abundance of Delta Smelt in the Fall Midwater Trawl index and Summer Towntnet index. *Data source:* CDFW.

outflow have contributed to declines in many native species, including Delta Smelt, Sacramento Splittail, White and Green Sturgeon, and Tule Perch (Moyle et al. 2016; Lund et al. 2018).

Actions to protect native species (reduced export, minimum outflows, weed removal) may have helped prevent extinction, but failed to promote recovery, during or after the drought. For Delta Smelt, reduced water exports, early-warning fish sampling, and maintaining Delta outflow at 3,000 cfs did not avert historic declines or support post-drought population recovery (Figure 8). In fact, they became so rare during the drought that it was effectively impossible to estimate population size in spite of extensive sampling efforts (Gore et al. 2018; CDFW 2018). Cold-water storage at Shasta Reservoir, combined with reduced water deliveries and relaxed water-quality provisions, was insufficient to prevent 95% egg and fry mortality of winter-run Chinook Salmon from high temperatures in 2014 and 2015 (Rea 2017, unreferenced, see “Notes;” Shaffer 2018; USBR et al. 2016a, 2016b)—again with no apparent post-drought recovery. Because winter-run Chinook Salmon entered the drought with historically low numbers, another year of similar conditions could have resulted in extirpation of the wild winter run (Figure 6; Hanak et al. 2015).

#### IV. SCIENTIFIC STUDIES OF THE DROUGHT

The events and uncertainties of the 2012–2016 drought highlighted several critical risks for water management, water quality, Delta farming, invasive species spread, wild salmon, and other native fishes (Lund et al. 2018). Many uncertainties remain, especially given the high temperatures and low snowpack that distinguished this drought from previous recorded droughts. The extreme conditions created new uncertainties around the long-term effects of brackish irrigation water on Delta soil conditions (Aegerter and Leinfelder–Miles 2016); maintaining the Shasta cold-water pool to support winter-run Chinook Salmon (Mount et al. 2017b); the effect of hatchery supplementation on winter-run Chinook Salmon (NMFS 2016); the effects of increased straying of fall-run Chinook Salmon

from trucking (Dedrick and Baskett 2018); the control of long-term expansion of some aquatic weeds (Ta et al. 2017); and the response of *Microcystis* to drought and water quality (Lehman et al. 2018).

Studies that extend across extremes, such as periods of drought and flood, provide powerful opportunities for understanding ecosystems (Katz et al. 2005). Departures from average conditions create data that increase analytical power in hard-to-replicate systems (Thomson et al. 2010). The extensive network of water-quality stations and fisheries surveys in the San Francisco Estuary are important data resources (Myers and Mertz 1998; Wagner et al. 2013). Most agencies collect large amounts of data before, during, and after a drought, overlapping the initiation and conclusion of management actions, as well as shifts in conditions. These monitoring data can aid in understanding the effects of drought and management responses, and help prepare for the inevitable trade-offs that will be required to navigate a changing environment

Much of our understanding of the effects of management actions come from long-term, continuous surveys. A post-drought, ecosystem-wide study of Montezuma Salinity Control Gates re-operation relied on long-term survey data to compare fish and water-quality response within and between years (Beakes 2019, unreferenced, see “Notes”). Such studies become more powerful when extended across variable environmental conditions.

The effect of reduced Project export on entrainment of vulnerable species has been studied extensively (Kimmerer 2008; Grimaldo et al. 2009; Castillo et al. 2012). Export reduction was ordered during the drought mostly because of reduced water availability, but export reductions also may have benefited vulnerable fish species like Delta Smelt, although Delta Smelt mostly disappeared during and after the drought.

Unfortunately, it is difficult to separate the effects of environmental conditions from those of management actions. A more powerful (but

expensive) experiment might be made by holding exports steady across variable conditions—that is, reducing exports during wet years.

Post-hoc, comparative analysis is critical to understanding the system across droughts and floods, and it means that most scientific insight about droughts will occur in the inter-drought period (CDWR 1978; Wilhite 1993, 1997; Brumbaugh et al. 1994; CDWR 2010, 2015; Dettinger et al. 2016). For example, shifts in hatchery management were made in response to difficult choices with limited options (NMFS 2016). Hatchery supplementation of winter-run Chinook Salmon and trucking of fall-run Chinook were begun when stocks were in imminent danger of collapse. Hatchery managers must wait 2 to 4 years after the actions to know if the actions worked, after surviving tagged adults return (to their natal streams and other locations).

However, scientific attention and management policy often focuses on other matters during inter-drought periods, making monitoring programs vulnerable to funding contractions. Such waxing and waning of interest and funding can be seen in long-term data sets (CDEC 2018; Stompe et al., this issue), which have notable data gaps in collection effort at critical times—often just before drought.

Drought-based studies are somewhat rare, possibly because droughts usually end by the time the opportunity is recognized, and a study is designed, funded, and implemented. For example, the Delta Smelt Resiliency Strategy only began in the last year of the drought with enhanced monitoring of Delta Smelt (CNRA 2016, 2017). This was in response to both the drought and the apparent spiral to extinction.

An exception to the paucity of drought-based studies is research implemented with the 2015 emergency drought salinity barrier (Figure 4). This was one of the most important drought management actions to successfully incorporate science. Salinity barriers had been considered during and after the 1976–1977 drought (CDWR 1978), and again during the 2007–2009

drought (CDWR 2009, 2010). The extreme 2012–2016 drought again brought attention to salinity barriers, although the required studies, permitting, and vetting were not in place until 2015 (AECOM 2015). However, several thoughtful studies were implemented to examine barrier effects on changes in the salinity field, water quality, food web dynamics, and invasive clam distribution (2015 presentation by E. Ateljevich, unreferenced, see “Notes”; CDWR 2017; Kimmerer et al. 2019). These studies provide reasonably good evidence for the effectiveness of the drought barrier, and provide a model of rapid implementation of hypothesis-driven drought science.

Several research and monitoring programs coincided with the drought by luck rather than design. These studies included agricultural soil salinity studies (Aegerter and Leinfelder–Miles 2016), spectral imagery surveys of submersed aquatic vegetation (Ustin et al. 2017), *Microcystis* studies (Lehman et al. 2018); Delta and Longfin Smelt studies (Polansky et al. 2014; Hammock et al. 2015), and Chinook Salmon otolith microchemistry studies (Ogaz 2019, unreferenced, see “Notes;” Sturrock 2019, unreferenced, see “Notes”). These studies are less effective in isolation than if they can be used as one extreme of an environmental gradient. For example, acoustic tagging studies or stable isotope otolith habitat-use studies become more powerful when comparative results from wet, dry, and intermediate years can be used.

A study of in-Delta crop consumptive use (Medellín–Azuares et al. 2018) followed the Delta agricultural diversion reduction program (George 2016), but additional studies on soil salinity effects from the program would be useful. Studies of the harmful algae *Microcystis* spp. during peak drought years of 2014–2015 were inconclusive (Lehman et al. 2015; Kurobe et al. 2018), but should be useful in understanding the effect of

future droughts, as well as planned reductions in ammonium in Sacramento Regional Wastewater Treatment Plant discharges.

However, for most management actions and scientific studies, it was difficult to assemble reliable information. An effort in California to make information and data transparent (Dodd 2016) has resulted in the accumulation of large quantities of outdated or incorrect information that is haphazardly stored online. We found that these data and reports occasionally moved, so published internet links were no longer valid. Publishing large quantities of documents and data online without curation can increase opacity and confusion for policy-makers, stake-holders, and scientists.

## V. DISCUSSION AND RECOMMENDATIONS

### Discussion

Each drought in recent history has led to changes in water management and policy, either during the drought itself or by influencing management of future droughts (Lund et al. 2018; Pinter et al. 2019). The droughts of the 1920s and 1930s spurred development of water-management infrastructure (including the CVP and SWP) from the 1940s through the 1970s (Pisani 1984). The short, deep 1976–1977 drought led to the first water shortages following completion of the CVP and SWP, instigating early water-conservation programs and water market activity (CDWR 1978; Gilbert et al. 1990), as well as the first installation of Delta salinity barriers. The 1987–1992 drought, which was less intense but longer than the previous drought, spurred improvements in urban interties, municipal conservation, recycling, conjunctive use, and water markets (Lund 1991; Brumbaugh et al. 1994; Lund and Israel 1995; Hanak et al. 2011). That drought also initiated a cascade of changes in environmental management over the subsequent 2 decades, following declines and ESA listings of native fishes. These included winter-run Chinook Salmon (originally listed 1989), Delta Smelt (1993), spring-run Chinook Salmon (1999), Central Valley Steelhead (2006), Green Sturgeon (2006), and Longfin Smelt (2009). The short 2007–2009

drought precipitated new institutions for the Delta, in particular the Delta Stewardship Council (Delta Reform Act 2009) and improved collection of surface water use data (CDWR 2010).

The 2012–2016 drought was consistent with predictions of climate change for California, and differed significantly from previous recorded droughts. Although precipitation was well below average, droughts during the 1920s and 1970s were worse. This drought was unique in having record-breaking high temperatures and low snowpacks, and probably represents the sorts of droughts we can expect in coming decades. Science and management need to prepare for these new types of droughts, driven by a changing climate. In particular, we need to understand the effect of reduced snowpack and increased evaporative demands for Sacramento River and Delta water management and timing. In addition, rising sea levels will complicate water-quality management in periods of freshwater scarcity. Finally, extreme variation in precipitation, such as the record-breaking rebound year of 2017, will change the timing of water hold and release decisions across California's reservoirs, and these decisions must be coordinated with Delta operations, groundwater management allocations, and water-user allotments via water contractors. (Griffin and Anchukaitis 2014; Mann and Gleick 2015; Diffenbaugh et al. 2015).

In 2012–2016, water-demand conflicts also increased, because of the need to accommodate increased regulatory requirements, which were implemented since previous droughts in response to deteriorating environmental conditions but did not consider extreme heat and precipitation variation, since these conditions were outside historical experience. Directives such as D-1641 and the 2008–2009 Biological Opinions—which require managers to balance Sacramento River temperatures, Delta water quality, Delta outflow, diversions, and exports—may become outdated (USFWS 2008; NMFS 2009).

Ultimately, competing demands for Delta water and ecosystem services under changing

conditions will increase pressure to manage trade-offs among outcomes and uncertainties. Concessions to support one demand often increase uncertainty for other sectors. Improving scientific understanding of emerging conditions could help make decisions and compromises more robust.

For example, maintaining outflow and water quality in the Delta comes at the direct expense of water stored, as water is released from upstream reservoirs to repel salinity in the Delta (Enright and Culberson 2009; Hutton et al. 2017). Likewise, diversions from the CVP and SWP project pumps can reduce outflow and water quality, putting Delta urban, agriculture, and ecosystem users in opposition to agricultural San Joaquin Valley exchange contractors, junior water-rights holders, and southern California and Bay Area urban users. The emergency salinity barrier attempted to reduce these conflicts, and to some extent it worked. Although the actual water savings were small (see Appendix A, p. 8), its chief benefit may have been to secure more reliability for stake-holders in a period of uncertainty.

Trade-offs occur with ecosystem decisions as well. For example, winter-run Chinook Salmon, fall-run Chinook Salmon, and sturgeon directly competed for water in the Sacramento River. Sufficient releases from Shasta Reservoir were needed to immerse wild fall-run Chinook redds, and to create flow pulses to assist outmigration of juveniles (Stacey et al. 2015; CDFW 2016). These came at the expense of preserving cold water for developing juvenile winter-run Chinook later in the year, and potentially for future years (NMFS 2016). The Shasta Dam Temperature Control Device (Appendix A, p. 10) is an attempt to reduce this and other conflicts, but was ultimately ineffective with the extended dry conditions in 2014–2015 (USBR et al. 2016).

Because California's water infrastructure was built to manage both floods and droughts for human uses, trade-offs are increased, although much of the ecology of the system is based on "natural" seasonal floods and droughts (Sommer et al. 2004; Feyrer et al. 2006; Opperman 2012).

However, as the climate changes, drought effects will become more severe because of increasing temperatures. There is more uncertainty on how ecosystems respond to droughts because drought effects tend to be slow and chronic, with vague beginning and end points, whereas floods begin and end more discretely and quickly. Collaborative teams such as the RTDOMT offer opportunities for collaborative approaches that can resolve conflicts through trade-offs. Other interagency collaborative scientific teams such as the Interagency Ecological Program (IEP; consisting of the CDWR, CDFW, SWRCB, NMFS, USBR, US Environmental Protection Agency, USFWS, and the US Geological Survey) are poised to assemble interdisciplinary teams of experts to resolve scientific uncertainties.

## Recommendations

Our survey of management actions (Section III, Appendix A) and science (Section IV) implemented during the 2012–2016 drought provided us with useful insights about how to better prepare for the next drought. Managers and scientists will require dedicated resources and organization, much as California has dedicated resources and organization anticipating floods, fires, and earthquakes. Drought preparation should include reliable funding, interagency plans, regular drought exercises, an emergency authority mechanism, and monitoring and oversight that can be mobilized within a few months. An integrated drought program to support Delta science would improve emergency response, and improve overall understanding of the Delta ecosystem and its management. Below is our summary of lessons and recommendations that will help California prepare for the future.

- 1. Pre-Drought Warning Declarations.** Drought-related actions were slow to begin until the official drought declaration. State and federal employees were delayed until the governor's drought emergency order (Brown 2014), even though regional drought effects were already apparent and anticipated (Steinemann et al. 2015; Mount et al. 2017b). Earlier drought preparation and management would help managers respond effectively and organize

scientific responses (Hanak et al. 2015). State pre-drought declarations might help prepare drought managers and scientists in early years of drought, with a statewide drought emergency initiated when conditions worsen.

## **2. Accountability and Independent Evaluation.**

Effective management requires independent data and analysis, and learning from experience. The RTDOMT streamlined interagency communication and decision-making (RTDOMT 2014). However, agencies have conflicting mandates at times, driven by conflicts about how water should be distributed and their role as regulators or permittees. To support decisions broadly in the public interest, scientific and technical decisions must be transparent and supported by data, analysis, results, and recommendations, with independent expert evaluation of conflicting data and management implications. The interdisciplinary IEP should be tasked with creating a drought project work team that will be prepared to make unbiased, scientifically sound recommendations to managers. Water management would benefit from more independent scrutiny of data collection practices, data, analyses, and conclusions. Another year of drought would have required substantially greater cuts, including for municipalities, environmental uses, senior water right holders—including riparian right holders—and water contractors (Hanak et al. 2015). To prepare for such events, a clear accounting of Delta water use and availability is needed (Gartrell et al. 2017; Reis et al. 2019), and water allocations should be arranged earlier so users and operators can begin contingency planning.

**3. Transparency and Documentation.** The loss of institutional knowledge from a surge of post-drought retirements by senior managers is a challenge to future drought management. To prepare for future droughts, efforts are needed to ensure that lessons from previous droughts are recorded and made available to new managers, policy-makers, and the public.

Drought actions should be documented with background information and justifications, and resulting outcomes (when possible) and reflections. Data should be published in archived and accessible reports in a timely fashion. The current mandate for policy and data transparency (Dodd 2016) has resulted in archiving of web pages, reports, memos, and data, but the information is disorganized, redundant, difficult to use, and varies by institution and/or regulatory agency. Links to information change and become invalid. A group of researchers and archivists should be charged with information- and knowledge-management across agencies.

- 4. Scientific Preparation.** Drought response often overrode scientific opportunities. Agencies responded to enormous technical, operational, communication, and scientific demands during the drought (USBR et al. 2014a, 2014b, 2015, 2016). Surveys to monitor fish, wildlife, and water quality conditions were increased by the CDFW and CDWR (California Drought Portal c2017; CDFW 2019), but few resources were available to produce research in response to management actions that would help in managing future droughts and climate change. Agencies struggled to assess drought conditions and provide needed information in real-time. Little time and few resources have been devoted to inform management and scientific responses for future droughts that can be expected to be the “new normal” for California: hot, dry and protracted.
- 5. Planning.** A multi-agency Delta drought plan should be developed to support management and scientific preparation for the next drought. The governor’s drought declaration was intended to put forward such preparations on an emergency basis (Brown 2014). Advance preparation of such a plan can support deeper Delta scientific organization and management syntheses, and accelerate effective drought responses. Such a plan should include
- a. major lessons from past droughts, including collection and analyses of data

on how wildlife, water quality, agriculture, recreation and municipalities are affected;

- b. mechanisms and protocols for interagency communication, preparation, and action, including pre-drought and early drought (pre-Declaration) actions;
- c. resource deployment plans, including funding and flexible staffing preparations and deployment of additional planned scientific efforts that take advantage of drought opportunities, coordinated by the IEP;
- d. scientific advisors and preparations for major management options and actions; and
- e. advance planning and permitting for major actions, including salinity and other flow barriers, and post-installation assessments.

**6. Salinity Barriers.** The temporary salinity barrier at False River was effectively implemented with supporting analysis and hypothesis-based monitoring, and was perhaps the best example of pairing management action and scientific study during the 2012–2016 drought (CDWR 2017; Kimmerer et al. 2019). The barrier helped stabilize water quality in the southern Delta and was combined with scientific inquiries. Effects on water quality, zooplankton, and local hydrodynamics were evaluated, with public reports. Effects on fish were less well-studied. Because future drought barriers are likely to be considered and deployed, having some studies and permitting in advance seems prudent.

**7. Ecosystem Resilience.** When vulnerable populations cannot recover sufficiently during inter-drought periods, they become more vulnerable to extirpation. Vulnerable fish stocks should be rebuilt between droughts, when stocks—under more favorable conditions—should be easier to increase, study, and manage. Droughts stress already

weakened native fish populations and cause population declines, while favoring non-native fishes. Larger and more diverse populations can better recover from droughts. During inter-drought periods, interventions should be more effective, and more management tools readily available, including flow releases, water control gate re-operations, export reductions, habitat restoration, and hatchery supplementation.

**8. Hatcheries.** Salmon management, including hatchery augmentation and trucking, involves trade-offs between commercial fisheries and the genetic integrity of wild stocks. These conflicts may be exacerbated during droughts, when stocks are depleted with outsized and unintended genetic effects on populations (Willmes et al. 2018). Trucking and hatchery production of Chinook Salmon juveniles for release in the lower estuary likely improved outmigrant survival and supported commercial fishery, but probably decreased returns to natal tributaries (Dedrick and Baskett 2018). Stray rates appeared to increase in the first returning cohort in 2017, supporting some novel runs (e.g., Putah Creek), but also increasing interbreeding between hatchery and wild fish stocks (Austing and Niemela 2018). The genetic management of hatchery fish and trade-offs between hatchery production and promotion of naturally spawning individuals is a concern for policy and organized research. More research on the likely effects of disasters and drought-based hatchery management should be helpful.

**9. Climate Change.** The recent (2012–2016) and unusually warm drought and the flood year of 2017 that followed are likely harbingers of changes predicted by climate models (Griffin and Anchukaitis 2014; Dettinger et al. 2016). California will become warmer, lose much of its seasonal snowpack storage, and see more extremes in precipitation—patterns consistent with this drought and its wet conclusion. Droughts and floods are opportunities to

learn and to prepare for the new breed of hot droughts to come.

California and the Delta will have more droughts, some more severe than the 2012–2016 drought. Effective preparation of organizations, plans, resources, and organized science greatly reduces drought effects and improves management for the next drought. Every drought has resulted in improvements to water systems and their preparedness for the next drought, especially for urban and agricultural water supplies and users (Lund et al. 2018). At the same time, each drought has brought environmental declines in the watersheds and Delta. The trend toward a warmer and more extreme climate reinforces ecological regime shifts that fundamentally disadvantage many native species and will accelerate their decline (Moyle and Bennett 2008). Organized science offers opportunities to understand these changes and prepare for future droughts and climate change. The insights and preparedness resulting from such organized science should come at relatively little cost, compared to their benefits.

## ACKNOWLEDGMENTS

Thanks to the many public employees, consultants, writers, and scientists willing to discuss the drought with us, and to the Delta Science Program for commissioning and supporting the work. Also, thanks to many pre-submission reviewers from numerous agencies who commented and corrected our early manuscripts, and three anonymous reviewers who provided excellent comments for this journal version. Finally, many thanks to Scout Carlson

for providing research support and Amber Lukk for mapping. This research was funded by the Delta Science Program through Delta Stewardship Council Grant Agreement No. 4473 for Drought Management and Science Synthesis.

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