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STATE OF BAY-DELTA SCIENCE

Drought in the Delta: Socio-ecological Effects, Responses, and Tools

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ABSTRACT

Droughts are frequent events in the western US, and can disrupt water supply and degrade water quality, challenging water management in the Sacramento–San Joaquin Delta. This chapter for the State of Bay–Delta Science report describes what drought means for the Delta, how drought is managed in the Delta, and how drought management has changed over time. Projections of future climate indicate the possibility of increased frequency and severity of droughts, which would increasingly affect California's water system, society, and ecological functions within and beyond the Delta. California has experienced several major droughts in the 20th and 21st centuries, each of which has caused significant social and ecological effects, and has motivated improvements in water management. Droughts decrease native fish populations, increase harmful algal blooms, and promote the spread of many invasive plant and animal species. For people living within the Delta and those that rely on Delta water exports, droughts increase drinking water costs and decrease agricultural production, negatively affecting agricultural economies and labor markets. Tools developed in response to droughts include actions that increase supply (such as building water infrastructure), actions to reduce demand (such as water-conservation campaigns), and mitigation actions (such as monetary relief for drought-affected impacted communities. Improving drought resilience requires development of additional drought responses, increased forecasting accuracy, and increased awareness of effects on vulnerable communities and ecosystems. Even with development of additional management actions, strategies, and regulations, meeting the current levels of demand for water will likely be difficult. Drought conditions already cause conflict between human and environmental uses, and—with more extreme droughts possible in the future and projected increases in demand—providing for all users' needs, even with major changes to water management in the Delta, will be challenging.

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drought, extreme events, climate, socio-ecological systems, water management

INTRODUCTION

Drought is a recurring condition of the western US (Williams et al. 2020), and the effects of droughts are keenly felt in California's Sacramento–San Joaquin Delta (Delta). The Delta provides habitat for hundreds of species of fish and wildlife, supports extensive agricultural production, and supplies water to over 27 million people (DSC 2021a). When winter storms do not come frequently enough, when the snowpack is far below average, and/or when reservoir levels fall, human and environmental demands for water that flows through the Delta conflict. Because of the frequency of droughts, especially over the past 20 years (2003–2023), there have been many scientific studies, essays, and political treatises on how drought affects impact both the ecosystem and the people of the Delta (CNRA 2021; Durand et al. 2020; Lund et al. 2018; Medellín–Azuara et al. 2022). This paper for the State of Bay–Delta Science seeks to build on these studies to convey what drought means for the Delta region, how it is currently being managed, and how management strategies may evolve in the future. Given that projections of future climate indicate an increased frequency and severity of drought (Swain et al. 2018), it is expected that droughts will have major effects on California's water system, people, and ecology. Understanding how drought affects the Delta region and how the socio-ecological system responds is critical to reduce the effects of climate change.

Management actions for responding to droughts have not had as much attention in the literature as the effects of drought. Therefore, this paper describes the effects of drought on the Delta as a socio-ecological system over time, as well as current tools available to support managers as they respond to drought by addressing the following topics:

1. The history of drought in the Delta;
2. Effects on the socio-ecological system, including water quality, fish, wildlife, people, and their interactions;
3. Tools to help manage the effects of drought in the Delta; and
4. Additional research needed to improve management of future droughts.

Defining the Delta: a Socio-ecological System

This paper focuses on how drought affects the legal Delta (as defined in the Delta Plan; DSC 2013), which includes Suisun Bay, and Suisun Marsh. The Delta is the hub of water conveyance in the state, but it is also home to wildlife refuges, natural heritage areas, farmland, and several major cities and towns. Because of the inter-related nature of water conveyances in California, the tools and management actions to address drought in other parts of the state inevitably affect the Delta and vice versa. Freshwater flow in the Delta depends on winter precipitation, snowpack across its watershed, and storage in upstream reservoirs. These reservoirs, though outside the Delta, are key for providing a steady flow of freshwater into the Delta and preventing saline water from intruding (Andrews et al. 2017). Similarly, groundwater sustainability in the San Joaquin Valley may seem unrelated to surface-water flows in the Delta, but decreased availability of Delta water during droughts requires farmers to use more groundwater (DSC 2019). Also, drought in the Colorado River system may cause water users in southern California to rely more heavily on Delta water sources (Lund 2016). Therefore, while we focus on drought in the Delta, we will discuss the effects of drought elsewhere in the state, and tools to manage those effects, if there are clear connections to water management in the Delta.

The people who rely on the Delta—both within its boundaries and beyond—have shaped the land, water, and ecology to their needs, but have also been shaped by it. Indigenous people have long used the Delta watershed for cultural and spiritual practices, with an estimated 10,000 residents once living within what is currently the legal Delta

(Whipple et al. 2012). Indigenous communities continue to rely on the Delta watershed for food, water, basket-making materials, and other ecosystem services (Zedler and Stevens 2018). In particular, for many Indigenous people, salmonids have a fundamental place in their culture and community and are considered part of their family (Hankins 2018; Middleton–Manning et al. 2018).

When European settlers first encountered the Delta, it was a complex network of marshlands seen as merely an impediment to traveling across the Central Valley. However, over time settlers recognized the region as a source of fertile farmland (Whipple et al. 2012). Starting in the 1850s, the involuntary relocation of Indigenous people from the land was concurrent with farmer–settlers draining, enclosing, and “reclaiming” the marshland within the Delta for agriculture (SWRCB 2023c; Whipple et al. 2012). Reclamation activities continued into the early 20th century, and the Delta region is now home to more than 627,000 people (as of 2018) of diverse ethnicities, living in rural agricultural communities, legacy communities, and urban areas including Sacramento, West Sacramento, Stockton, Lathrop, Manteca, and the eastern Bay Area (DSC 2021a). Agriculture remains the dominant land use, with nearly 500,000 acres (out of 730,000 acres total) considered prime farmland or farmland of state or local importance (DSC 2021a). In part because of the importance of agriculture, reduced water quality during droughts is a major concern.

In response to the frequent interannual and intra-annual dry periods inherent in California’s climate, the Delta and its watershed were further modified, beyond the draining of wetlands. Massive dams and water-conveyance facilities were constructed across California to prevent water shortages and control flooding, fundamentally transforming the Delta. The State Water Project (SWP) and Central Valley Project (CVP)—as well as numerous smaller diversions—together form a system of storage and conveyance facilities that is among the largest water-infrastructure systems in the world. Water exported from the Delta via the SWP and CVP amounts to 8% of water used in the state as of 2019 (DSC 2019) and includes drinking water for over 27 million people—who comprised more than half of the state’s population in 2023 (CDWR 2023a). The SWP and CVP convey water south of the Delta to a $32-billion agricultural industry that covers more than 3.7 million irrigated acres (CDWR 2023a; DSC 2021b). Although agriculture is a small percentage of the $4 trillion California economy, California’s agriculture is an important part of the state’s cultural identity, and provides 95% of the processed tomatoes, nearly 100% of almonds, and 70% of lettuce for the entire US (to name just a few examples) (Bruno et al. 2021; Davis and Weber 2024).

The history of modern human settlement of the Delta is one of continuing alteration. In addition to altering the Delta by draining much of the marshland for agriculture and by altering flows, people have introduced many non-native species to the Delta (Dill and Cordone 1997; Moyle 2002), intentionally and unintentionally. Today, fishing for non-native Black Bass (*Micropterus* spp.), Striped Bass (*Morone saxatilis*), and catfish (multiple species from the family Ictaluridae) provides a significant source of livelihood, recreation, and protein for the people of the Delta (Shilling et al. 2010; Mickel et al. 2019). Water diversions that provide drinking water and irrigation water to so many people in the state also negatively affect native fish and invertebrates in the Delta (Perry et al. 2015; Grimaldo 2021). Given the major role of anthropogenic modifications, the Delta is now referred to as a “novel ecosystem,” bearing little to no resemblance to its previous state but still providing habitat for many native and non-native species (Moyle 2014; Conrad et al. 2016). With this context, understanding drought in the Delta relies on understanding how the needs of the humans of California interact and conflict with the needs of the Delta ecosystem during times of water scarcity.

Defining Drought

Broadly defined, drought is when water supplies are unusually low and no longer meet human and environmental needs. How drought is quantitively measured over space and time differs widely. Determining whether a drought is in effect is difficult because its onset is generally gradual, making the start difficult to recognize, except in hindsight. Further difficulty arises because effects accumulate over time and vary across affected human and ecological systems, depending on factors such as available artificial and natural storage and water demand (Wilhite 2000; Wilhite and Buchanan–Smith 2005).

Several commonly used terms describe different categories of drought based on their effects (e.g., Wilhite and Glantz 1985) (Figure 1). **Meteorological drought** results from a deficit of precipitation but can additionally be driven by high temperatures and winds, increased solar radiation, and low relative humidity. These latter factors increase atmospheric "thirst," the capacity of the atmosphere to absorb and hold water vapor. This can lead to increased evapotranspiration and drier soils (Vicente–Serrano et al. 2020). **Hydrological drought** typically results from a sustained meteorological drought and is characterized by reduced streamflow, snowpack, and reservoir and subsurface storage. How hydrological droughts affect humans and the environment depends on the drought's severity and length because longer droughts reduce reservoir year-to-year carry-over storage and groundwater levels. **Agricultural drought**, in which drier soils lead to crop stress and reduced yield, can result from a meteorological drought in non-irrigated regions. In irrigated regions such as the Central Valley, stored water can compensate for a meteorological drought. However, a sufficiently long meteorological drought that leads to hydrological drought and reductions in water storage—and thus supply—can produce an agricultural drought in irrigated regions, as well. Other categories of drought can be defined based on the system being affected, such as **ecological drought**, which is characterized by stress on native plants and wildlife populations. Lastly, **socio-economic drought** occurs when a water supply deficit results in adverse economic effects, particularly related to goods whose demand, production, and/or distribution depend on water supply, with associated effects on communities (Dinar and Mendelsohn 2011; Zseleczky and Yosef 2014; Van Loon 2015). These different descriptions of drought represent how sustained meteorological drought cascades through ecological and social systems.

Many attempts have been made to quantify droughts and their effects. The most widely used metric in the US is the Palmer Drought Severity Index (PDSI) (Palmer 1965), which indicates meteorological drought that incorporates a water-balance model to represent cumulative effects on soil moisture. The US Drought Monitor, whose drought maps are widely circulated, combines the PDSI, soil moisture models, US Geological Survey streamflow data, and the Standardized Precipitation Index (SPI, which relates observed precipitation to a probability distribution of expected precipitation) to inform its five different drought classifications: abnormally dry, moderate drought, severe drought, extreme drought, and exceptional drought (Drought Monitor 2023). The California Department of Water Resources (CDWR) also calculates several hydrologic classification indices based on streamflow as measures of water supply, most importantly the Sacramento Valley Index and San Joaquin Valley Index (CDWR 2024b), which represent estimates of total unimpaired flow in the Sacramento and San Joaquin rivers, respectively. These indices are based on estimated unimpaired runoff (the runoff that would have occurred without human alterations such as dams, diversions, exports, and imports) during the current water year (defined as October 1 of the previous year through September 30th) as well as the index from the previous year. Thus, these indices integrate stored water and precipitation to estimate how much water is available for use in the rivers during a given year. These indices are used to classify water years in categories that range from critically dry to wet, and can be considered sequentially as indicators of regional drought.

Generally, a drought is considered to have occurred in the Delta watershed when consecutive years of low precipitation result in water supplies insufficient to meet human and environmental

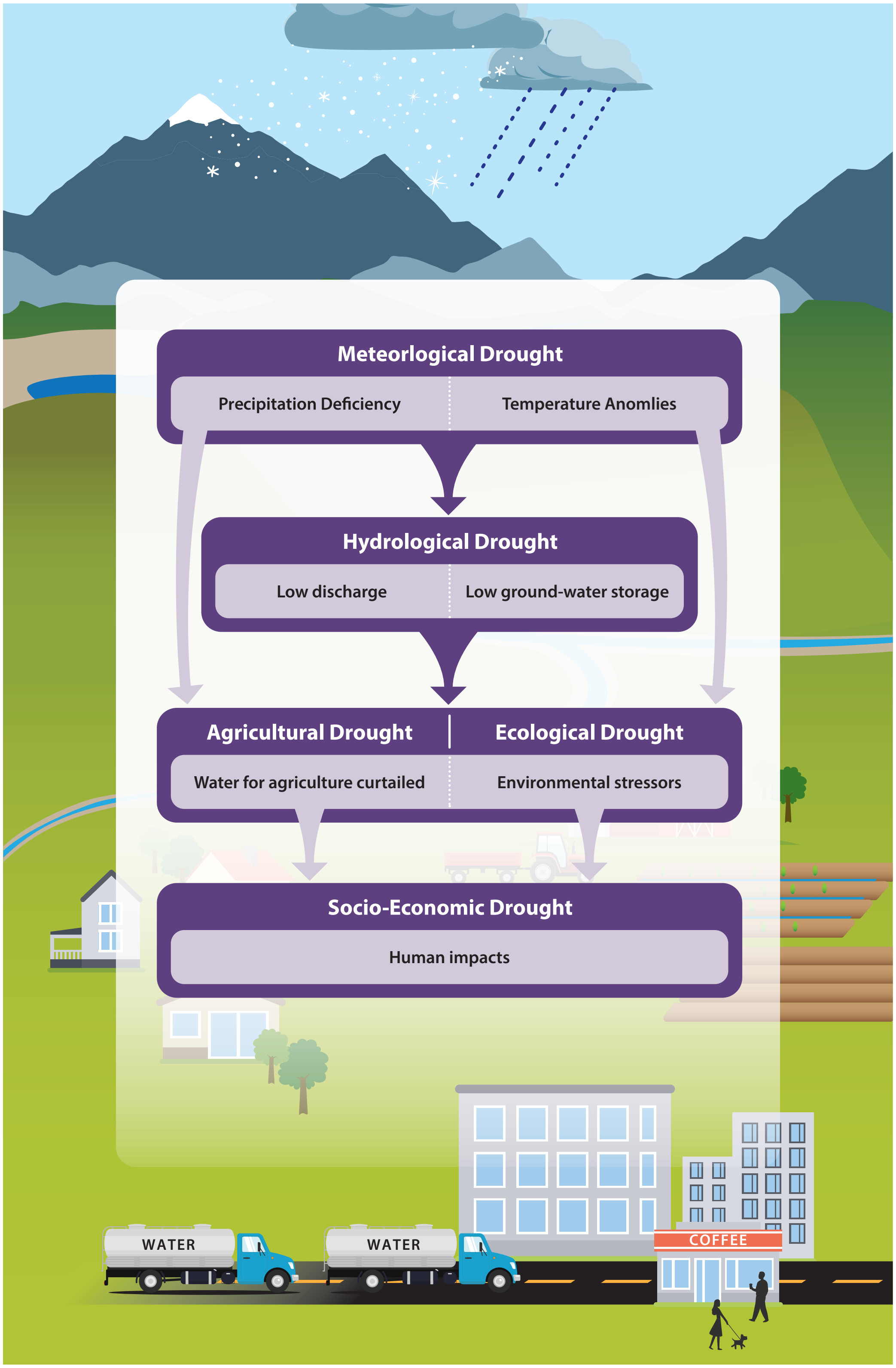


Figure 1 Conceptual model for different types of droughts and their effects on the socio-ecological system. Meteorological drought produces hydrological droughts. The combination of meteorological and hydrological droughts causes agricultural and ecological droughts. The combination of agricultural, hydrological, ecological, and meteorological droughts causes socio-economic droughts and associated effects on the people of the Delta and their environment. Credit: Illustrated by Vincent Pascual with the California Office of State Publishing.

needs (CDWR 2020). From a management perspective, this means that water storage north of the Delta is reduced to a point where water-supply operations can no longer compensate for the reduced flows (CDWR 2020). The Governor's Office issues Drought Emergency Declarations either county by county or statewide (Drought Orders, Proclamations, Notices, and Letters), depending on local conditions and the potential for social and economic effects of water scarcity, but there is no defined standard or trigger for these emergency declarations.

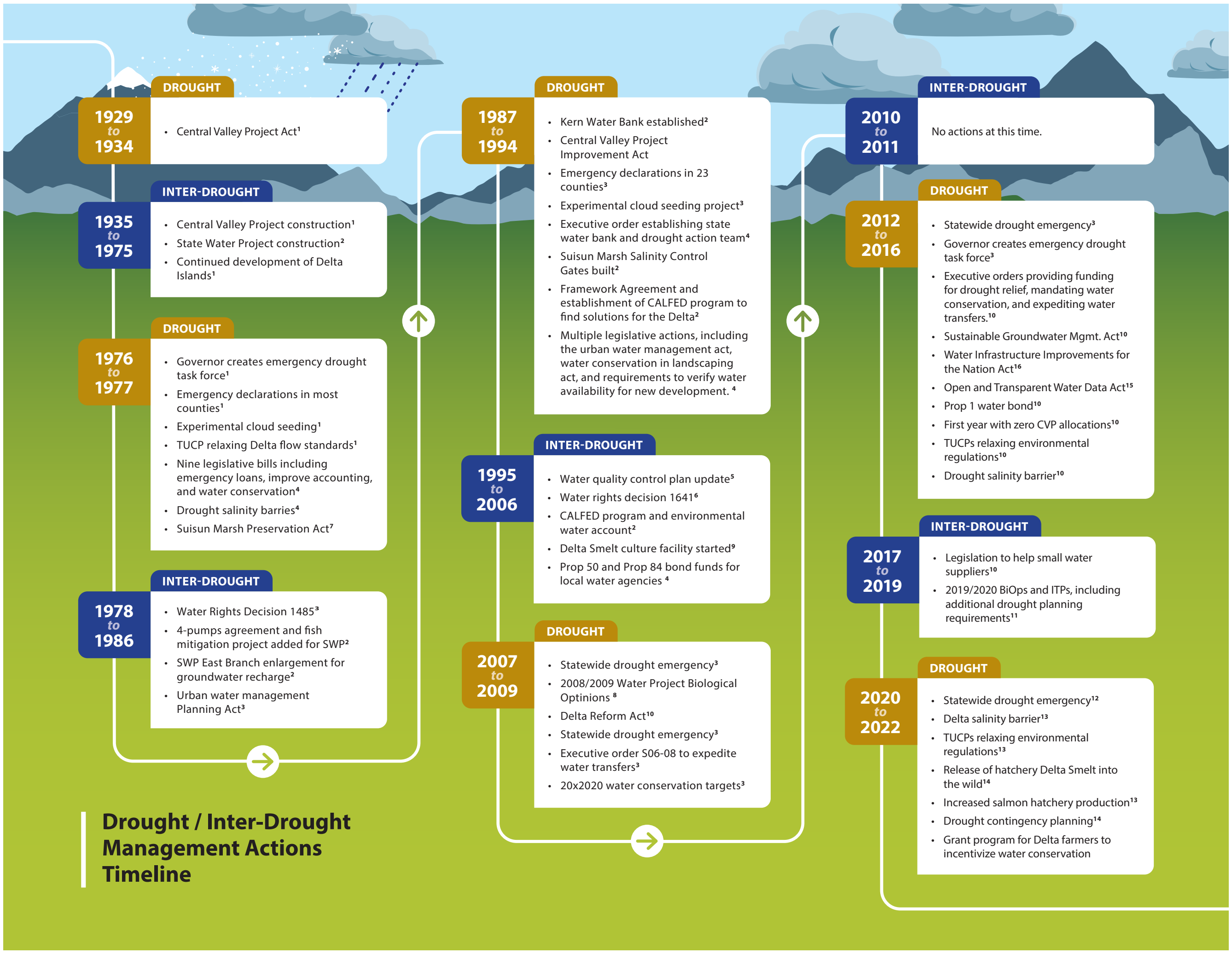
The Delta Watershed's Climate

Although California contains an unusual diversity of climate types, the majority of the Delta's watershed has a Mediterranean climate, with most precipitation occurring in the late fall and winter months, and the remaining months being relatively dry (Kauffman 2003). Generally, a sequence of atmospheric changes over the Pacific Ocean produces this seasonal timing. During the dry months, a high-pressure cell forms over the eastern North Pacific, deflecting storms to the north. During the wet months, this cell migrates south and loses intensity, while the Aleutian Low-pressure center strengthens. As latitudinal temperature and pressure gradients grow, more storms pass across the Pacific (Dettinger et al. 2011; Dettinger and Cayan 2014). However, deviations from this sequence result in differences between years. For example, when the Aleutian Low forms close to the west coast of North America, the storms may move across California and yield significant precipitation. However, if the Low forms farther to the west, a high-pressure cell may develop near the west coast and divert the winter storms to the north, resulting in a drier-than-average year (Swain et al. 2016). A series of such years can result in an extended drought (Dettinger and Cayan 2014).

Interannual variability is a defining feature of the Delta watershed's climate. It drives frequent floods and multi-year droughts, resulting in strong year-to-year changes that affect the Delta's aquatic community and challenge the ability of managers to provide water for consumptive use (in which freshwater is diverted but not returned to the system). California's precipitation exhibits greater interannual variability than any other state (Dettinger 2011), with a few major storms typically delivering the majority of the annual precipitation. Variability in the number of these storms can therefore drive year-to-year variance (Dettinger et al. 2016). These major storms are generally associated with atmospheric rivers, which are long, narrow plumes of concentrated water vapor transport in the lower atmosphere. Because so much of California's water supply depends on these few storms, their presence or absence in a given year, or sequence of years, can be the difference between wet periods and droughts. In fact, a relative deficit of atmospheric rivers is the dominant driver of multi-year droughts in California (Dettinger et al. 2016).

When Have Droughts Occurred in the Delta?

California has experienced several significant droughts in its recent recorded history, each of which has caused significant social and ecological effects as well as motivated major changes in how the state government manages water (see CDWR 2020 and Figure 2). The years of 1863–1864 were so dry that the state's cattle industry was decimated, driving a transition from cattle ranching to grain agriculture. The next major California drought was the 6-year drought of 1929–1934. This period, known as the "Dust Bowl" also saw an influx of migrants to California from the middle of the country, which experienced an even more severe drought (CDWR 2020). This drought stoked interest in the utility of building large water export facilities like the SWP and CVP to help sustain irrigation though dry periods. The state legislature passed the Central Valley Project Act in 1933, authorizing bonds to finance large water storage and conveyance infrastructure. The CVP began construction with federal funding in the late 1930s and reshaped how water moves through California, bringing water from areas with higher rainfall to those with lower rainfall, and allowing for storage during wet periods and use during dry periods. In 1960, the legislature passed the California Water Resources Development Bond Act which financed and led to construction of the SWP, increasing the state's resilience to agricultural and socio-economic droughts.



DROUGHT

1929 to 1934

- Central Valley Project Act[1]

INTER-DROUGHT

1935 to 1975

- Central Valley Project construction[1]
- State Water Project construction[2]
- Continued development of Delta Islands[1]

DROUGHT

1976 to 1977

- Governor creates emergency drought task force[1]
- Emergency declarations in most counties[1]
- Experimental cloud seeding[1]
- TUCP relaxing Delta flow standards[1]
- Nine legislative bills including emergency loans, improve accounting, and water conservation[4]
- Drought salinity barries[4]
- Suisun Marsh Preservation Act[7]

INTER-DROUGHT

1978 to 1986

- Water Rights Decision 1485[3]
- 4-pumps agreement and fish mitigation project added for SWP[2]
- SWP East Branch enlargement for groundwater recharge[2]
- Urban water management Planning Act[3]

DROUGHT

1987 to 1994

- Kern Water Bank established[2]
- Central Valley Project Improvement Act
- Emergency declarations in 23 counties[3]
- Experimental cloud seeding project[3]
- Executive order establishing state water bank and drought action team[4]
- Suisun Marsh Salinity Control Gates built[2]
- Framework Agreement and establishment of CALFED program to find solutions for the Delta[2]
- Multiple legislative actions, including the urban water management act, water conservation in landscaping act, and requirements to verify water availability for new development. [4]

INTER-DROUGHT

1995 to 2006

- Water quality control plan update[5]
- Water rights decision 1641[6]
- CALFED program and environmental water account[2]
- Delta Smelt culture facility started[9]
- Prop 50 and Prop 84 bond funds for local water agencies [4]

DROUGHT

2007 to 2009

- Statewide drought emergency[3]
- 2008/2009 Water Project Biological Optinions [8]
- Delta Reform Act[10]
- Statewide drought emergency[3]
- Executive order S06-08 to expedite water transfers[3]
- 20x2020 water conservation targets[3]

INTER-DROUGHT

2010 to 2011

No actions at this time.

DROUGHT

2012 to 2016

- Statewide drought emergency[3]
- Governor creates emergency drought task force[3]
- Executive orders providing funding for drought relief, mandating water conservation, and expediting water transfers.[10]
- Sustainable Groundwater Mgmt. Act[10]
- Water Infrastructure Improvements for the Nation Act[16]
- Open and Transparent Water Data Act[15]
- Prop 1 water bond[10]
- First year with zero CVP allocations[10]
- TUCPs relaxing environmental regulations[10]
- Drought salinity barrier[10]

INTER-DROUGHT

2017 to 2019

- Legislation to help small water suppliers[10]
- 2019/2020 BiOps and ITPs, including additional drought planning requirements[11]

DROUGHT

2020 to 2022

- Statewide drought emergency[12]
- Delta salinity barrier[13]
- TUCPs relaxing environmental regulations[13]
- Release of hatchery Delta Smelt into the wild[14]
- Increased salmon hatchery production[13]
- Drought contingency planning[14]
- Grant program for Delta farmers to incentivize water conservation

Drought / Inter-Drought Management Actions Timeline

Figure 2 Timeline of major drought preparation actions and responses in the Delta over nearly 100 years, 1929–2022. This chart focuses on state-led efforts, but many nationally led efforts also occurred during this timeline. Text notes: 1. CDWR (2020). 2. CDWR (2023d) 3. SWRCB (1978) 4. CDWR (2000) 5. SWRCB (1995). 6. SWRCB (2000) 7. State of California (1977). 8. NMFS (2009); USFWS (2008) 9. Fisch et al. (2013) 10. CNRA (2021). 11. CDFW (2020); USFWS (2019) 12. Newsom (2021). 13. USBR and CDWR (2022) 14. CDFW (2021). 15. Dodd (2016) 16. Cornyn (2016). Credit: Illustration by Vincent Pascual with the California Office of State Publishing.

The two-year 1976-1977 drought was marked by extremely low precipitation, with 1976 being the 12 driest year and 1977 being the driest year in the historical record (1901–2023) (USGS 2024). This drought led to major improvements in water conservation (refer to Box 1—Lessons Learned from Previous Droughts—for details). The 1987–1994 drought was the first that was of a comparable duration to the 1929–1934 drought under modern levels of infrastructure and demand, and it spurred further changes to California's Water Code, incentivizing conservation and allowing water transfers (CDWR 2020). Another drought in 2007–2009, followed by a record-breaking drought in 2012–2016, motivated the passage of the Sustainable Groundwater Management Act (SGMA) in 2014, which established requirements for managing groundwater withdrawals for the first time (Leahy 2015). The latter drought contained the four driest consecutive years in the historical record and the lowest snowpack on record (2015) to date. The most recent 2020–2022 drought was the driest 3-year period on record (CDWR 2022c). See Figure 2 and Box 1 for more information on the last 50 years of major historical droughts.

BOX 1

LESSONS LEARNED FROM PREVIOUS DROUGHTS

Throughout California's history, droughts have negatively affected both the human and ecosystem and uses of the Delta. After each drought, water managers and academics publish "lessons learned" reports on issues that arose during the drought and ways to better respond to future droughts (e.g., CNRA 2021). In some cases, such lessons have led to improvements in drought response, reducing the effects of subsequent droughts. However, some problems reappear in reports after each drought, and lasting solutions have yet to be developed.

1976–1977

During the driest 2-year period on record (CDWR 2020), California water managers (1) learned the importance of urban water conservation (CDWR 1978; Narayanan et al. 1983), (2) saw the need for water markets and greater flexibility for water distribution (CDWR 1978; Matthai 1979), (3) identified inequities in water supply and drought response (Berk et al. 1981), and (4) developed early mechanisms to collect data on water use (Berk et al. 1981). California also identified the need for greater flexibility in water regulations to balance upstream storage and Delta water quality, and highlighted the importance of groundwater in meeting human needs during drought (Comptroller General of the United States 1977; CDWR 1978). The issues that surround balancing upstream storage with water quality and the importance of groundwater are reoccurring themes in water management that became even more apparent in subsequent droughts.

1987–1994

During this drought, the lesson of urban water conservation had been ingrained from the 1976–1977 drought, but the use of mass media for communication about water conservation allowed the message to be shared more effectively (Dziegielewski et al. 1993). Water markets and transfers were implemented at a larger scale, allowing water to be more easily transferred between users for greatest economic mitigation (Zilberman and Dinar 1992; Zilberman et al. 1994). During this period, the state created a "water bank" to facilitate water transfers, and water pricing changed to incentivize conservation. At the end of this drought, there were calls for the state government to develop a computerized system to store water data (Dziegielewski et al. 1993). There were also increased recommendations for statewide and regional drought planning and continued desire for more flexible regulatory mandates and better management of groundwater resources.

2007–2009

The 2007–2009 drought was not as severe as some previous droughts. However, it was the first drought since the Endangered Species Act (ESA) listing of several fishes in the Delta, the Delta Reform Act, and the Water Quality Control Plan update (USFWS 1993; CVRWQCB 2009), all of which demonstrated California's increasing awareness of the need to balance human and environmental uses of water during times of scarcity. The environmental impact effect of drought on the Delta was increasingly apparent as fish populations continued to decline. This was the first drought in which the governor of California declared a statewide drought emergency (Gonzales and Ajami 2017). Urban conservation continued to be a priority, with a bill passed in 2009 to reduce urban water use by 20% by 2020 (Senate Bill X7-7).

2012–2016

There was only a 2-year break between the 2007–2009 drought and the 2012–2016 drought, so although reservoirs refilled, aquifers had still not recovered. This drought led to the first ever absence of agricultural allocations of surface water for the CVP (CDWR 2021a). This was also a much warmer drought period than previous droughts: statewide average temperatures in 2014 and 2015 were the warmest on record at the time (CDWR 2021a). It was also the first drought to be linked to longer-term changes in climate (Diffenbaugh et al. 2015; Swain 2015), leading to important lessons on planning for droughts, which were projected to have greater frequency and severity in the future (CNRA 2021). An emergency drought salinity barrier was built in the Delta

BOX 1 *(continued)*

for the first time since 1977 to prevent saltwater from intruding into the Central Delta (CDWR 2019; Kimmerer et al. 2019). The state created its first domestic well-outage tracking system as thousands of self-supplying households struggled with water reliability; local and state agencies started building a tool kit of responses for small water systems (Ekstrom et al. 2017, 2018; Pauloo et al. 2020). An important lesson learned was the need to codify groundwater protection with state regulatory oversight. While the importance of groundwater management was theoretically a "lesson learned" in previously, it was not until 2014 that the Sustainable Groundwater Management Act was enacted to regulate groundwater (Leahy 2015).

This drought also led to increasing awareness of the environmental cost of droughts and the need to provide for environmental flows to mitigate how drought affected the environment (Mount et al. 2017). Calls for environmental water rights increased (Escriva–Bou et al. 2016). At the federal level, the Water Infrastructure Improvement for the Nation Act (WIIN) was passed, increasing operational flexibility and increasing research into tools to mitigate environmental effects of drought (Cornyn 2016). Water resource managers at the state-agency level also started planning for drought more seriously (CNRA 2021). Updates to the Biological Opinions and Incidental Take Permit for the SWP and CVP that occurred in 2019 and 2020 included specific requirements for advanced drought planning (USFWS 2019; CDFW 2020). Awareness of the increasing importance of managing water data for these kinds of advanced planning requirements led to the passing of Assembly Bill 1755 (Dodd 2016), which coincided with the broader "open data" and "open science" movements, and the increasing data literacy amongst water management and the public (Baerwald et al. 2020). Greater, faster data accessibility also made possible more real-time decision-making in response to rapidly changing conditions. As social media and internet searches increased the public's access to information about these subjects, this new technology also helped communicate drought effects and the importance of drought conservation measures. (Gonzales and Ajami 2017).

2020–2022

The most recent drought has ended statewide, yet lessons have still not been fully collated, and the state quickly shifted to responding to disastrous flooding in early 2023. Although statewide drought resilience has increased, vulnerable communities are still disproportionately affected (Sugg 2018; Wikstrom et al. 2019), which challenges the state's commitment to the human right to water (Bostic et al. 2023; Méndez–Barrientos et al. 2023). The passage of the Safe and Affordable Funding for Equity and Resilience Program (SAFER) in 2019 established baseline and annual funding to help address underlying structural and climate vulnerabilities in small systems that, leading into this drought, had been failing. Legislation like Senate Bill 552 "Drought Planning for Small Water Suppliers and Rural Communities" was enacted in fall 2021, which codified joint local–state responsibility to proactively assess, plan, and provide public assistance for the most drought-vulnerable drinking-water users in the state. As was done in 1977 and 2015, an emergency drought salinity barrier in the Delta at West False River was reinstalled in 2021 and left in place during 2022 (CDWR 2022b). Reinstalling this barrier only 6 years after the last installation prompted CDWR to begin permitting processes to streamline installation during future droughts (CDWR 2022d), as was recommended after the 2012–2016 drought (Durand et al. 2020). Emergency curtailment orders (restrictions on water use; see "What Tools are Available" section, p. 23) in several Delta watersheds issued in 2021 remained in place into early 2023. Processes and regulations put in place by the 2020 Incidental Take Permit for the SWP (USBR 2022) were implemented for the first time. However, there are still calls for improved drought planning, improved predictive modeling, and improved integration of climate-change projections into drought planning (Shimabuku and Kammeryer 2022; Auditor for the State of California 2023). During drought and inter-drought periods over the recent decade, state and federal agencies have invested in tools to improve drought preparedness, particularly improved forecasting of meteorological conditions to inform reservoir operations (Forecast Informed Reservoir Operations, or FIRO [Brodeur et al. 2024]), as well as managed aquifer recharge to improve replenishment of groundwater supply during inter-drought periods (see "Tools" section).

Paleoclimatic Context

Placing the 20th century into a paleoclimatic context can provide insight into what types of natural climate variability the future may hold, and whether that variability may exceed the infrastructure's capacity for mitigation. We can reconstruct the paleoclimate using tree rings, sediment cores, and other natural records in the region (see Malamud–Roam et al. 2007 for a review). However, reconciling multiple characterizations of the 20th century as a whole, relative to the longer paleoclimatic context, can be complicated by differing reconstruction periods, locations, and reconstructed quantities (e.g., precipitation versus streamflow). For example, Earle (1993) found that the historical period 1850–1980 was wetter than the few centuries preceding it. In a longer-term context, Meko et al. (2014) found that whether the historical period 1906–2011 was wetter than the last 1,000 years was uncertain, and depended on the metric used. Some paleoclimatic studies support the characterization of the period during which California's water management infrastructure was developed (the last 150 years or so) as relatively stable (e.g., Malamud–Roam et al. 2007), especially considering the occurrence of drought. Hughes and Brown (1992) found that the period 1850–1950 had "one of the lowest frequencies of drought of any one-hundred-year period" in the 2,089-year, tree-ring-based record they analyzed for occurrence of extreme droughts. They also found that most of the 20th century (1900 through 1989) had a slightly-below-average frequency of extreme droughts. However, Zamora–Reyes et al. (2022) found that northern California, which sources most of the Delta's annual inflow via the Sacramento River, experienced a rapid increase in interannual hydroclimatic variability during the 20th century, reaching the highest values of precipitation and streamflow variability in 600 years. They found that this increase resulted from an increase in the occurrence of wet extremes, with no increase in dry extremes, consistent with the findings of Hughes and Brown (1992). Similarly, Meko et al. (2014) found that the recent historical period exhibited high variability in annual total flow in the Sacramento and San Joaquin river basins of the Delta watershed, compared to the last 1,100 years.

One feature that is consistent across all reconstructions is the recurrence of prolonged deviations from the mean, including multi-decade "mega-droughts" (e.g., Ault et al. 2014; Meko et al. 2014). Given the relatively brief period in which California and its settlers developed and operated the current freshwater monitoring and management infrastructure, the Delta is likely to eventually experience deviations that exceed those in the recorded history in terms of magnitude and/or duration. The climatic behavior of the 21st century to date supports this inference. Williams et al. (2022) found, using tree-ring reconstructions and a water-balance model, that summer soil moisture in the greater American Southwest (California, Nevada, Arizona, New Mexico) "was below the 800–2021 average in 18 of the 22 years from 2000–2021," and that this 22-year period was the driest since at least 800 AD. Due to its length and intensity, this period has been labeled a mega-drought. And with the driest wet season on record, 2022 extended it another year.

How are Droughts Likely to Change in the Future?

The frequency and intensity of dry years and droughts are projected to increase (Diffenbaugh et al. 2015; Knowles et al. 2018), and individual droughts are projected to intensify more rapidly (Yuan et al. 2023). Further, based on a combined analysis of paleoclimatic evidence and projections from global climate models, the results of Ault et al. (2014) indicate that the future likelihood of decadal or longer drought in California may be much greater than projected by global climate models alone.

Climate models project increases in evaporative demand in California as a result of warming (McEvoy et al. 2020). This would result in increased evaporation from waterbodies, though the magnitude of the change is a subject of debate (McEvoy et al. 2020; Vicente–Serrano et al. 2020). Williams et al. (2022) also found that anthropogenic climate change was responsible for 42% of the 2000–2021 mean soil moisture anomaly, primarily from warming, which has increased evaporative demand (Albano et al. 2022). Williams et al. (2022) concluded that without the contribution of anthropogenic climate change, this period would not have been considered a mega-drought. Potential increases in transpiration from vegetation are being debated, with large differences between modeling techniques (Dewes et al. 2017; Vicente–Serrano et al. 2020). Rising temperatures and decreased dormancy periods can both increase evapotranspiration. Alternatively, some models suggest that increasing CO_2 levels in the atmosphere could reduce stomatal conductance, causing transpiration to remain more or less constant (Vahmani et al. 2022).

Regardless of the potential increase in evaporative demand, increased frequency and intensity of droughts is consistent with projected changes in precipitation. Though projected trends in California's total annual precipitation are inconclusive, models suggest that an increasing portion of California's annual precipitation will come from atmospheric rivers, enhancing year-to-year volatility (Dettinger et al. 2016; Gershunov et al. 2019). Atmospheric rivers are also projected to increase in frequency and intensity (e.g., Dettinger et al. 2016; Hagos et al. 2016). As these changes progress, the frequency of climate "whiplash" events (extreme dry-to-wet transitions) is projected to increase (Swain et al. 2018). Because it may take multiple years for baseflow in streams to recover from a meteorological drought (Lee and Ajami 2023), these rapid year-to-year swings in precipitation—coupled with other anthropogenic stressors—may leave the ecosystem little time to recover.

Warming would also reduce snowpack and cause earlier snowmelt (e.g., Huang et al. 2018; Knowles and Cayan 2002), increasing winter runoff and reducing dry season flows. Left unmitigated, these changes would result in effective drought conditions throughout the dry season, even in relatively wet years (i.e., "warm snow drought," Harpold et al. 2017; Hatchett and McEvoy 2018). Increased surface and groundwater storage would be needed to capture the increased wet-season runoff to help maintain the dry-season flows necessary, for example, to meet salinity standards in the Delta. These reductions in runoff could lead to reductions in water supply for all users of water in the Delta (Persad et al. 2020; Ray et al. 2020).

Cascading and Compounding Climate Effects

Increases in drought frequency and severity are projected to occur in conjunction with increased frequency and severity of other extreme events (Dahm et al., this issue; Mahardja et al., this issue; Rudnick et al., this issue). Meteorological droughts are frequently accompanied by increased wildfires, and changes in climate are projected to increase the likelihood of extreme wildfires across California (Goss et al. 2020). Wildfires result in massive social and economic consequences, increased sediment runoff (Reale et al. 2015), changes to water chemistry (Bixby et al. 2015; Dahm et al. 2015), and changes to light availability (McKendry et al. 2019; Scordo et al. 2021), though additional research is required to determine how these changes affect the Delta. While most of these changes adversely affect water supply and water quality, smoke from wildfires can lower water temperatures (David et al. 2018), temporarily mitigating some effects of projected warming on aquatic organisms.

Climate change may be making droughts more frequent, but droughts can also create a feedback mechanism that would exacerbate projected changes in climate. As flows decrease, hydropower generation also decreases, increasing reliance on alternative sources of power, frequently fossil fuels (Hardin et al. 2017; Turner et al. 2022). During the 2012–2014 drought, power generation in California resulted in an estimated 33% increase in annual CO_2 emissions (Hardin et al. 2017). Hydropower currently serves as a back-up for intermittent renewables such as power and wind, but this is not possible when reservoir levels become very low, such as in 2021 when the Hyatt Power Plant at Oroville was taken offline as a result of low lake levels (CDWR 2021b). With projected changes in climate, greater energy may be required to pump water longer distances, extract water from increasingly depleted reservoirs, drill new wells, cool buildings, and maintain temperatures in fish hatcheries (Alam et al. 2019; Kern et al. 2020; Qin and Horvath 2020). Increased frequency and severity of wildfires would also contribute to higher CO_2 emissions (Jerrett et al. 2022).

Projected increases in the water levels of the Delta's channels as sea level rise propagates from the coastal ocean would be associated with a greater tendency for saline waters to move upstream (Fleenor and Bombardelli 2013; Ghalambor et al. 2021), requiring higher freshwater flows to meet Delta water-quality standards and exacerbating water shortages for other needs. Increasing salinity may cause increasing stress on Delta Smelt (*Hypomesus transpacificus*) because low-salinity-zone habitat (less than 6 psu) would be upstream in the clear water of the Sacramento River instead of the turbid water of Suisun Bay (Feyrer et al. 2007), and increasing salinity may also limit waterfowl nesting habitat in Suisun Marsh (Schacter et al. 2021). Increasing salinity would also limit agricultural production in the Delta (Rahman et al. 2019). Water diversions, both large and small, would have increasing difficulty meeting drinking-water quality standards (Ray et al. 2020). Increased releases from reservoirs to meet Delta water-quality standards are seen as one of the primary factors in future water shortages (DSC 2021b), and significant management actions—such as drought salinity barrier installations—are likely to become more frequent in response (Durand et al. 2020).

HOW DROUGHT AFFECTS THE DELTA

Reduced freshwater inflow to the Delta causes changes to water quality that negatively affect both humans and wildlife, thus affecting the socio-ecological system of the Delta (Bosworth et al. 2024; Hartman, Stumpner et al. 2024). Furthermore, reduced freshwater flow is often accompanied by restrictions on how much water can be withdrawn and diverted for use by humans (Reis et al. 2019). Droughts thus not only affect the availability and quality of water within the Delta itself, but the resulting reductions in Delta water exports can have far-ranging consequences for municipal, industrial, and agricultural water users throughout the state (Wikstrom et al. 2019). Together, reduction in water quantity and quality in the Delta can cause major changes to primary productivity, invertebrate abundance, fish populations, and human economies.

Ecosystem Effects

The influence of annual freshwater flow (or lack of flow) on water quality, primary productivity, and fishes of the Delta is well studied, though many responses remain difficult to predict. Multi-year droughts have received less study than seasonal or annual outflow, but the 2012–2016 drought yielded several important studies on the influence of drought on the Delta ecosystem (Lehman et al. 2017; Jabusch et al. 2018; Singer et al. 2020; Mahardja et al. 2021). Also, a recent collection of Interagency Ecological Program (IEP) Drought Synthesis papers provides an overview of how multi-year droughts affect broad-scale, multiple components of the ecosystem, and these papers are included in the literature review below (Barros et al. 2024; Bosworth et al. 2024; Bouma–Gregson et al. 2024; Hartman, Stumpner et al. 2024; Hartman, Twardochleb et al. 2024).

Freshwater Inflow

Reduced precipitation and the associated decrease in freshwater inputs to the Delta is an obvious indicator of a drought. Flows in the Delta are regulated through upstream dam releases, diversions, gates, and barriers to meet the demands of legal water users, in-stream water-quality regulations, federal- and state-listed endangered species, and to enhance other beneficial water uses. As a consequence of management, water-quality conditions in the Delta vary less than they would naturally, and the altered hydrograph has lower spring outflow and higher summer flows than under unimpaired conditions (Knowles 2002).

During droughts, lower annual precipitation results in lower instream flows in all of the major rivers that enter the Delta (Durand et al. 2020). Meeting all conflicting water demands in the system can often exacerbate meteorological droughts by reducing streamflow further (He et al. 2017; Van Loon et al. 2022). The decreased inflow directly affects water quality in several ways. Within the Delta, the salinity gradient moves inland as a result of greater relative oceanic and tidal influence under decreased outflow conditions (Ghalambor et al. 2021; Bosworth et al. 2024). Water management stabilizes salinity in the Delta because water withdrawals from the Delta require fresh conditions for agricultural and drinking water supplies. Before extensive water infrastructure development, Delta salinity varied more (Hutton and Roy 2019). Drought-driven salinity encroachment often requires trade-offs between upstream water needs (e.g., management of cold water for salmon habitat below dams [Yates et al. 2008] and Delta water quality [Ghalambor et al. 2021]).

Water residence times in the Delta generally increase under low flows, allowing more time for biogeochemical processes to affect water quality, as well as more time for biota (e.g., phytoplankton and zooplankton) to grow (Hammock et al. 2019; Bergamaschi et al. 2020; Hartman, Stumpner et al. 2024). Lower freshwater flows with lower sediment loading reduce turbidity in the spring (Livsey et al. 2021; Bosworth et al. 2024). Lower turbidity may (1) decrease growth and survival of pelagic fishes that use turbidity as a refuge from predation (Gregory and Levings 1998; Hasenbein et al. 2013), (2) increase potential for algal blooms (Kudela et al. 2023; Bouma–Gregson et al. 2024), and (3) reduce sediment accretion in tidal wetlands (Stern et al. 2020). All these changes—and the ways in which managers respond and adapt to them—have profound ecological effects.

Water temperature in the Delta is driven primarily by air temperature; an increase of 10 °C in air temperature will lead to up to a 7 °C increase in water temperature, whereas a 33% decrease in flow results in only a 1 °C increase in water temperature (Vroom et al. 2017). Therefore, reduced flow during droughts is unlikely to significantly affect water temperatures, except during certain large-flow events (Wagner et al. 2011). However, water temperatures during droughts tend to be warmer, on average, than wet periods because of the combination of decreased flow and increased air temperature (Nobriga et al. 2021; Bashevkin and Mahardja 2022; Bosworth et al. 2024), though this flow–temperature relationship varies spatially and seasonally (Bashevkin and Mahardja 2022).

Decreased inflow to the Delta decreases loading of nutrients from upstream sources, but also decreases dilution of nutrients from point sources. Discharges from wastewater treatment plants have historically provided the bulk of the nitrogen influx into the system during summer, with agricultural sources providing a greater percentage of nitrogen during winter and spring (Wankel et al. 2006; Novick et al. 2015; Saleh and Domagalski 2015). Treatment plant upgrades have reduced wastewater nutrient loading over time (Thompson et al. 2023). Even with effective urban conservation, drought may not significantly influence loading from wastewater treatment plants because urban use is expected to remain roughly constant. However, decreased river flow reduces dilution, potentially leading to increases in nutrient concentrations observed in certain areas (Jabusch et al. 2018). Bosworth et al. (2024) found that concentrations of nutrients increased during droughts in most regions and seasons of the Delta, which is important because most biological processes are more responsive to changes in concentrations than loads.

Phytoplankton

Phytoplankton (photosynthetic algae and cyanobacteria) convert raw materials (sunlight and inorganic material in the water) into biomass that fuels the base of the aquatic food web (Durand 2015). The relationship between flow and chlorophyll concentration (used as a proxy for phytoplankton biomass) varies highly over space and time, so drought effects are difficult to predict. Kimmerer et al. (2002) found no relationship at the Delta-wide level, but Lehman (1992) and Jassby et al. (2008) found a negative relationship between Delta chlorophyll concentration and flow. Cloern et al. (1983) found a positive relationship between chlorophyll concentration in Suisun Bay and outflow. Lehman (1996) found chlorophyll concentration was lower during critically dry years than during wet years; however, the highest chlorophyll concentration commonly occurred during years with intermediate streamflow. Drought years in the past were characterized by a decrease in diatoms and an increase in cryptophytes and cyanobacteria (Lehman 1996, 2000, 2004). Since the 1990s, spring diatom blooms have been rare, but relatively large diatom blooms in 2014 and 2016 were probably the result of long residence times during the drought (Glibert et al. 2014; Jungbluth et al. 2021). Bosworth et al. (2024) found seasonally and regionally variable relationships between droughts and chlorophyll. There were increases in chlorophyll in the South Delta and the confluence (of the Sacramento and San Joaquin rivers) during droughts, with decreases in Suisun Bay. There were greater increases in chlorophyll during winter and spring of droughts than summer or fall. The lack of increases in chlorophyll in Suisun Bay during droughts may result from increases in grazing from invasive clams (Crauder et al. 2016; Hartman, Twardochleb et al. 2024).

While the patterns of chlorophyll as a measure of phytoplankton biomass are difficult to tie to flow, the species that dominate the phytoplankton pool show clearer relationships to drought. For example, harmful cyanobacterial blooms—commonly known as harmful algal blooms (HABs), including toxic strains of *Microcystis*—clearly increase during droughts. *Microcystis* and other harmful cyanobacteria increase during low outflow conditions (Lehman et al. 2017, 2022), though the severity and distribution of *Microcystis* blooms changes depending on water-management actions and weather conditions (Lehman et al. 2018). This increase has been directly linked to the increase in water residence time during droughts and is exacerbated by increased temperature and water clarity (Kudela et al. 2023; Bouma–Gregson et al. 2024). Increases in HABs have been linked to changes in the composition of zooplankton communities, and many harmful algal toxins negatively affect the health, growth, and survival of fish in the Delta (Acuna et al. 2012; Ger et al. 2018; Acuña et al. 2020; Lehman et al. 2021). HABs can also affect human health (Preece et al. 2017; Kudela et al. 2023) and negatively influence recreation in the Delta when major blooms necessitate the closure of popular recreation sites, such as Big Break Regional Shoreline (Hartman et al. 2022).

Vegetation

Both submerged aquatic vegetation and floating aquatic vegetation establish more readily in slower-moving water, so there is some evidence that submerged and floating vegetation may increase during droughts (Kimmerer et al. 2019). However, an analysis of vegetation coverage in the Delta from 2004 to 2020 did not find a relationship between freshwater flow and vegetation coverage (Hartman et al. 2022). Further research could enhance understanding of the drivers behind the establishment of aquatic weeds. Tidal action, not outflow (Bosworth et al. 2024), primarily drives maximum current speed in the Delta during the summer growing season, whether there is a drought or not, so this mechanism may not apply to aquatic weeds in the Delta. Increases in nutrient concentrations observed in the Delta during droughts may also facilitate expansion of aquatic vegetation, though this effect is less conclusive and more complicated since many—but not all—submerged species obtain nutrients through roots in the sediment (Boyer and Sutula 2015; Dahm et al. 2016). The drought salinity barriers installed in Franks Tract in 2015, 2021, and 2022 altered the distribution—though not the overall coverage—of submerged vegetation there (Kimmerer et al. 2019; Hartman et al. 2022).

A complicating factor to understanding the relationship between drought and aquatic weeds is variable levels of herbicide treatment of both submerged and floating vegetation, and different levels of treatment efficacy between submerged and floating plant forms (Caudill et al. 2021; Rasmussen et al. 2022; Khanna et al. 2023). For example, water hyacinth (*Pontederia crassipes*), a floating invasive aquatic plant, reached high coverage levels in 2014 during drought conditions, but declined through the remaining period of drought because it was extensively treated with herbicide. Submerged vegetation, in contrast, steadily increased during this same period, despite increases in herbicide treatment, and continued to expand during the wet year of 2017 (FLOAT–MAST 2021).

Drought conditions also affect wetland and terrestrial vegetation in the Delta. Increases in salinity that result from lower freshwater flows may reduce growth of wetland vegetation, slowing wetland restoration (Chapple and Dronova 2017), or drive community shifts toward more salt-tolerant species (Watson and Byrne 2012). Even when salinization does not kill plants, more saline conditions may reduce their productivity (Chamberlain et al. 2020; Russell et al. 2023). Changes to wetland plant cover may have cascading effects on birds and wildlife that use those wetlands, reducing habitat resources, food resources, and migration resting areas (Barbaree et al. 2020; Schacter et al. 2021; Kahara et al. 2022).

Invertebrates

Zooplankton responses to droughts are also regionally variable and species-specific. During droughts, overall zooplankton biomass tends to increase in the South Delta and decrease in Suisun Bay (Barros et al. 2024). This may result partially from decreasing transport of freshwater zooplankton into Suisun Bay, resulting in decreased abundance of certain taxa (particularly the calanoid copepod *Pseudodiaptomus forbesi*) in this region (Kimmerer, Ignoffo, Kayfetz et al. 2018), as well as the expansion and increased consumption rates of the overbite clam (*Potamocorbula amurensis*, see below) (Crauder et al. 2016). The drought-induced change in phytoplankton communities discussed earlier may also have bottom-up effects on the zooplankton community, but these effects are difficult to predict. *Microcystis* and other toxigenic cyanobacteria may directly harm copepods in the Delta (Ger et al. 2009). However, other cyanobacteria, usually considered "poor-quality" food for zooplankton, may comprise a larger proportion of zooplankton diet than previously thought (Kimmerer, Ignoffo, Bemowski et al. 2018). Additionally, though diatoms are usually considered high-quality food for zooplankton, the *Aulacoseira* sp. blooms that formed during the 2012–2016 drought did not aid in zooplankton growth (Jungbluth et al. 2021).

Non-native species dominate the zooplankton community in the Delta, particularly non-native copepods in brackish and low-salinity waters. It has been hypothesized that droughts may have facilitated invasion and establishment of non-native zooplankton in the Delta (Winder et al. 2011). The non-native cyclopoid copepod, *Limnoithona tetraspina*, in particular, has become the dominant zooplankter in Suisun Bay, where it increases in abundance during droughts (Barros et al. 2024) but is considered relatively poor food for pelagic fishes because of its small size (Slater and Baxter 2014; Sullivan et al. 2016). Non-native gelatinous zooplankton (jellyfish) compete with pelagic fishes for zooplankton prey (Wintzer et al. 2011), and the most dominant jellyfish in the Delta (*Maeotias marginata*) shifts its distribution upstream during droughts, where it may have greater overlap with Delta Smelt (*Hypomesus transpacificus*), Longfin Smelt (*Spirinchus thaleichthys*), and other native fishes (Hartman, Twardochleb et al. 2024).

Drought may also exacerbate the effects of invasive benthic invertebrates. The overbite clam (*P. amurensis*) can filter large amounts of phytoplankton and zooplankton out of the water column, disrupting the foundation of the food web. The introduction of *P. amurensis* in 1986 has been linked to declines in chlorophyll, zooplankton, and fishes, particularly in Suisun Bay (Feyrer et al. 2003; Greene et al. 2011; Kimmerer and Thompson 2014). Growth and reproductive rates in the clam are strongly linked to outflow, with larger population sizes and greater upstream distribution in years following dry years (Parchaso and Thompson 2002; Crauder et al. 2016; Hartman, Twardochleb et al. 2024). Increased grazing pressure from clams may be why chlorophyll decreases during droughts in regions with increased clam abundance (Hartman, Stumpner et al. 2024).

Native Fish

The native fish community of the Delta evolved in response to regular cycles of floods and droughts, but the changing characteristics of recent droughts combined with anthropogenic influences in the system have resulted in stress to native fish assemblages. Droughts result in an increase in invasive fishes, particularly those associated with aquatic vegetation, and a decrease in floodplain spawners and pelagic fishes (Mahardja et al. 2021). The highly-managed hydrograph already varies less than the historical hydrograph, allowing introduced fishes from areas with lower variation in flow—such as Mississippi Silversides (*Menidia audens*), catfish (Ictiluridae), and sunfish (Centrarchidae)—to thrive (Hanak et al. 2012). During droughts, stream currents are slower, and water is warmer, making habitat more suitable for fish from the southeastern US. Salinity intrusion during low flow periods would be expected to reduce abundance of invasive freshwater centrarchids (such as Largemouth Bass, *Micropterus salmoides*), but during the 2012–2016 drought there was no decline in these fishes detected (Mahardja et al. 2021).

Mahardja et al. (2021) found that pelagic fish tended to decline during drought conditions, and Longfin Smelt have a particularly strong flow–abundance relationship. Longfin Smelt populations experience large increases during high-outflow years and decreases during droughts (Kimmerer 2002; Nobriga and Rosenfield 2016). American Shad (*Alosa sapidissima*) and young-of-the-year Striped Bass also decline during dry years (Mahardja et al. 2021), but Delta Smelt do not show direct flow–abundance relationships. Some high-outflow years have been particularly good for population growth; others have not (IEP–MAST et al. 2015; FLOAT–MAST 2021). However, during drought conditions Delta Smelt female reproductive output declines (Kurobe et al. 2022). Littoral fishes are more resistant to drought. In particular, the invasive Mississippi Silverside markedly increased in abundance during droughts (Mahardja et al. 2016).

Salmonids may be affected by drought at multiple life stages. Higher water temperatures in the rivers may cause lower survival of adults returning to their spawning habitats (CDFW 2017), as well as lower egg survival, particularly if cold-water pool resources in upstream reservoirs become limited during multi-year droughts. Once fry have left their spawning habitat to begin their out-migration, juvenile salmon are known to have low survival during low-outflow years (Michel et al. 2015), with reductions in survival as great as 95% during severe drought conditions (Stewart et al. 2020). Salmon generally initiate migration during flow pulses, so their out-migration may be delayed in dry years (del Rosario et al. 2013; Morita 2019). The importance of floodplains for juvenile salmon rearing habitat is increasingly recognized (Sommer et al. 2020; Sturrock et al. 2022; Holmes 2022), but floodplains—where growth rates may be much higher than in-channel habitat (Katz et al. 2017; Takata et al. 2017)—are not inundated during droughts, cutting off this critical habitat (Hance et al. 2022)..

In the Delta, higher temperatures and lower flow result in more activity by non-native predators (Henderson et al. 2019; Nobriga et al. 2021; Hance et al. 2022) and higher juvenile salmon metabolic stress (Farrell 2009; Del Rio et al. 2019), culminating in salmon's higher vulnerability to predation and pathogens (Marine and Cech 2004). Lower flows may also result in juveniles rearing for a shorter time and entering the ocean at a smaller size, reducing their survival in the ocean (Hassrick et al. 2016; Munsch et al. 2019). Reduced outflows also influence the routes of migrating salmon migration (Melnychuk et al. 2010; Perry et al. 2018; Nobriga et al. 2021), increasing the risk of salmon migrating into the Central and South Delta, where survival rates are known to be low relative to Steamboat Slough and the mainstem Sacramento River (Singer et al. 2020; Pope et al. 2021; Hance et al. 2022). Because of this risk, the CDWR is currently testing a non-physical barrier using bubbles, lights, and sound to guide out-migrating salmon to stay in the Sacramento River, avoiding the Central Delta at Georgiana Slough[1] (Perry et al. 2014; Swyers et al. 2024).

Droughts also negatively affect other migratory fishes. Green Sturgeon (*Acipenser medirostris*) have

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[1] *https://water.ca.gov/Programs/State-Water-Project/Operations-and-Maintenance/Georgiana-Slough-Salmonid-Migratory-Barrier-Project*

reduced spawning habitat along the Sacramento River during drought years (Klimley et al. 2020), and White Sturgeon (*Acipenser transmontanus*) recruitment is strongly related to flow, so year classes often fail during droughts (Blackburn et al. 2019; Ulaski et al. 2022). Adults of both species are long-lived (20+ years), so a few years with no recruitment may not be problematic, but droughts can also contribute to HABs, and a particularly severe *Heterosigma akashiwo* bloom in the summer of 2022 is estimated to have killed hundreds of adult sturgeon (Schreier et al. 2022; Kudela et al. 2024). Losing large adults in events like this is much more detrimental than losing recruits (Blackburn et al. 2019), and the population may take decades to recover.

Droughts may lead to conflict between native fishes. For example, salmon spawning habitat is frequently restricted to the area below the major dams, so water is released from the dam during summer to control temperatures. However, cold-water releases may be detrimental for the native Green Sturgeon which relies on warm river water for juvenile rearing (Zarri et al. 2019). Maintaining the cold-water pool in spring and summer for rearing winter-run Chinook Salmon (*Oncorhynchus tshawytscha*) during droughts can mean there is not enough cold water left to provide habitat for fall-run Chinook Salmon later in the year (Michel et al. 2023).

Birds and Other Wildlife

Birds are somewhat more resilient to drought than fishes because of their greater ability to move with changing habitat conditions, their ability to access a coordinated network of wildlife refuges, and the existence of the Nature Conservancy's Bird Returns program, which works to provide bird habitat across the landscape (Lund et al. 2018). However, wetlands in the Delta and Suisun Marsh provide critical habitat for waterfowl and shorebirds, and droughts can reduce habitat availability and food supply. This is particularly true when less rice is cultivated, because winter-flooded rice fields may provide up to 45% of food resources for ducks in the Central Valley (Petrie et al. 2016). Also, some wildlife refuges rely on the SWP and CVP for water supplies, and they may be subject to cuts in allocations during extreme droughts (Hanak et al. 2015). Some birds find alternative habitats, such as shorebirds who increase their use of coastal habitat (Barbaree et al. 2020), but drought significantly reduces mallard populations in Suisun Marsh and all waterfowl in the Delta (Kahara et al. 2022). This is presumably because of reductions in acreage of rice and riparian wetland habitat, which have been shown to significantly increase waterfowl populations (Kahara et al. 2022). Increased salinity in areas such as Suisun Marsh may decrease waterfowl nesting and survival of hatchlings (Schacter et al. 2021).

How drought affects other native terrestrial wildlife has not been extensively studied. Prolonged drought may reduce food availability for the salt marsh harvest mouse as a result of decreased wetland vegetation (Smith et al. 2018). Similarly, populations of the giant garter snake (*Thamnophis gigas*) may decline with reduced rice cultivation during droughts (Reyes et al. 2017; Rose et al. 2018). Additional research is needed to study how drought affects other native mammals, reptiles, and amphibians.

Human Dimensions of Drought in the Delta

The ecology of the Delta is inherently connected to the people of the Delta, and these connections become even more apparent during droughts. Human effects on the environment—such as contaminants, invasive species, and altered flow regimes—become more pronounced during periods of water scarcity. Ecosystem services upon which humans rely—such as clean drinking water, irrigation water, and recreation—also become impaired or limited. Thus, droughts have had widespread effects on people throughout time, including pre- and post-modern day infrastructure. To help identify appropriate tools for future droughts, here we document three key effects on humans: (1) effects to Native American's cultural practices, (2) water allocation for agriculture within and beyond the Delta, and (3) drinking water reliability.

Effects on Native American Cultural Practices

Before European settlers modified the hydrology of California, Native American Tribes that relied on the Delta had to cope with more extreme winter and spring floods and very low flows during the summer because of the lack of major flood-control and water-storage infrastructure (Whipple et al. 2012). Flows became particularly low during droughts, but extensive agricultural withdrawals did not further reduce these flows. Although there are no available studies (to our knowledge) on how the Indigenous people of the Delta respond to drought, pre-colonization, other Native Americans in the American Southwest had varied responses to drought. Some migrated with shifting climates, some experienced increased conflict over scarce resources, and many abandoned settlements—whereas other Native Americans developed sophisticated water infrastructure to better store and use scarce water (MacDonald 2007). Resource use changed during droughts, and trade frequently increased (Jones and Schwitalla 2008).

For today's Native Americans, droughts affect many cultural practices. The Vice Chair of the Shingle Springs Band of Miwok Indians, Malissa Tayaba, explained to *The Los Angeles Times*, "[The drought has] had a huge impact on tribes... It's been really, really hard for us... Every part of our culture is embedded in the watershed, and so everything that we need and traditionally use comes from there" (Smith 2022). In many cases, drought's effect on salmonids is felt the most, because salmon are such an important part of their culture (Yoshiyama 1999; Zacky 2024). Droughts severely reduce the number of juvenile salmon migrating out of rivers as a result of the reduced cold-water pool habitat below rim dams, increased temperatures, and increased predation (see "Native Fish" section). As a result, Native Americans in California have experienced curtailment of their cultural practices and threats to their livelihoods because of drought.

Water Availability Within and Beyond the Delta

Within the Delta, summer water levels seldom decrease substantially during droughts, but water quality degrades when freshwater flow decreases (Reis et al. 2019). Increased salinity during droughts has caused some farmers to let land lie fallow, modify their choice of crops, or continue with reduced yields (Medellín–Azuara et al. 2014; Gebremichael et al. 2021). Increased salinization in the future may expose more acreage to saline intrusion than has occurred historically (DSC 2021a).

Droughts also reduce water available for export, with far-ranging consequences for municipal, industrial, and agricultural water users throughout the state. Water exports from the Delta amount to 8% of water used in the state (DSC 2019). As Figure 3 shows, Delta outflow and exports generally decline during drought years (grey bars). During periods of shortage, the SWRCB may issue curtailments to water-rights holders to limit the amount of water they can use (Green Nylen et al. 2023), causing them to let land lie fallow or increase groundwater pumping (Liu et al. 2022). Fallowing land has many severe economic consequences, particularly if the land has been planted with perennial crops that take several years to establish (Howitt et al. 2015; Gebremichael et al. 2021).

When Project water contractors do not receive Delta surface-water allocations, many of them switch to local groundwater, and there can be negative consequences. These include increased salinization of groundwater, accumulation of contaminants in groundwater, increased energy costs from pumping, and land subsidence (Hansen et al. 2018; Kern et al. 2020; Liu et al. 2022). Groundwater basins are still used at unsustainable levels in much of the state, despite the roll-out of SGMA, causing many wells to run dry during precipitation scarcity (Pauloo et al. 2020; Bostic et al. 2023). Modeling of future conditions suggests that more aggressive groundwater pumping restrictions will need to be put in place for groundwater basins to recharge and recover between droughts (Langridge and Daniels 2017; Alam, Gebremichael et al. 2021) but doing so equitably—to maintain sources of drinking water and livelihoods for *all* Californians—will be difficult (Dobbin 2020; Chappelle et al. 2023).

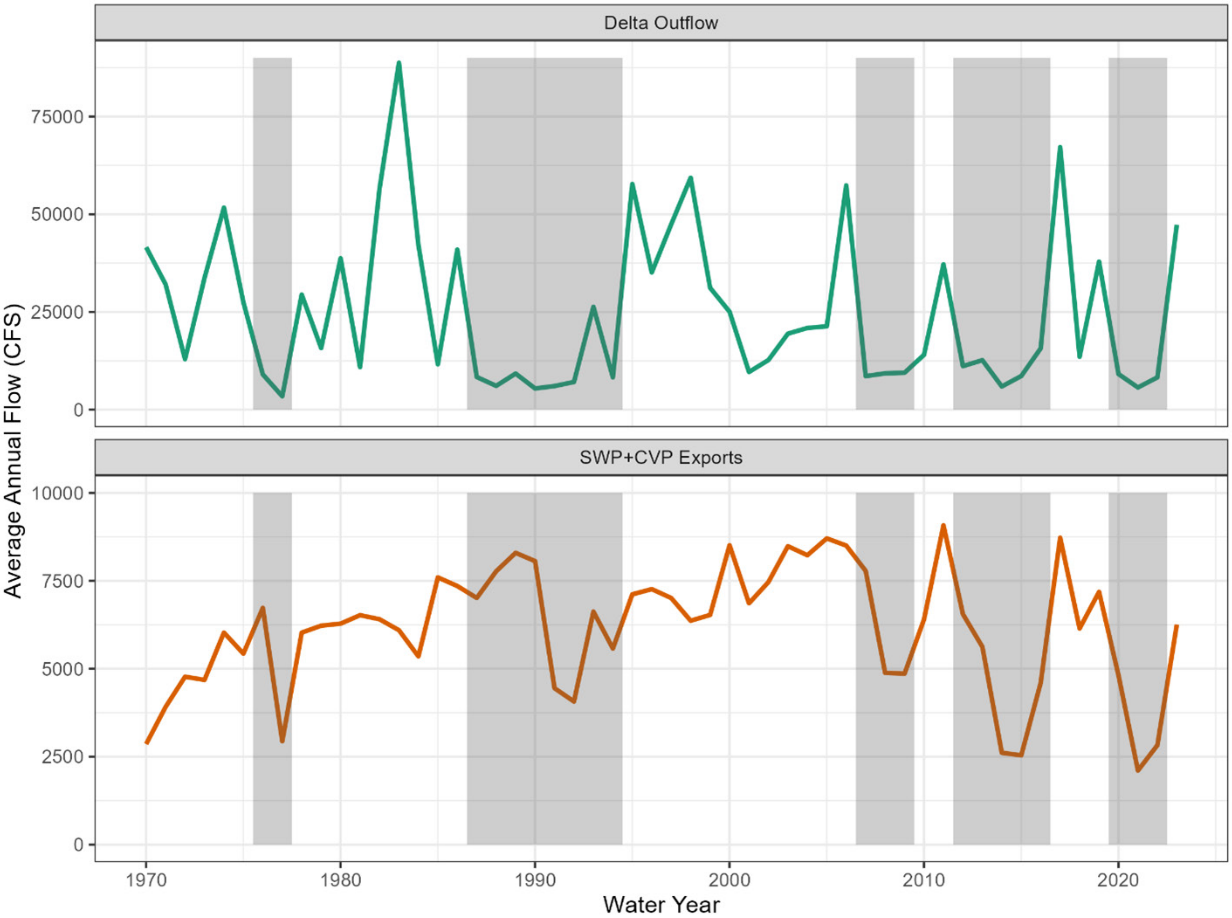

Figure 3 Average annual Net Delta Outflow Index (*top plot*) and average annual Central Valley Project and State Water Project export rates by water year from 1970–2022. *Grey bars* indicate drought periods. Data are from CDWR's Dayflow model (CDWR 2022a).

Drought affects not only farm-owners, but also the labor and economies that rely on agriculture. Experts estimated that the 2020–2022 drought cost the state $3.9 billion in total gross revenue loss and more than 14,000 jobs (Medellín–Azuara et al. 2022). While these effects pertain to the state of California generally, and are not specific to the Delta and its water users, they show how droughts affects agricultural communities such as the Delta. Declining employment opportunities during droughts result from shorter harvest seasons and closures of food-processing plants, among other factors. Generally, the loss of agricultural jobs disproportionately affects disadvantaged and migrant communities (Greene 2018, 2021).

Drinking Water Reliability

The most direct interaction many Californians have with Delta water is through their drinking water. Many communities in and around the Delta rely on its water to meet 100% of their drinking-water needs (SWRCB 2024). Water suppliers that have been classified as high-risk (as assessed by the 2023 Needs Assessment and SWRCB's SAFER program, SWRCB 2023a, 2023b, c2023d) have ongoing performance issues that reduce their ability to mitigate the effects of drought. Among the SWRQCB's three drinking water districts that regulate the safety of drinking water in the region (Districts 4, 9, 10), several water systems are at

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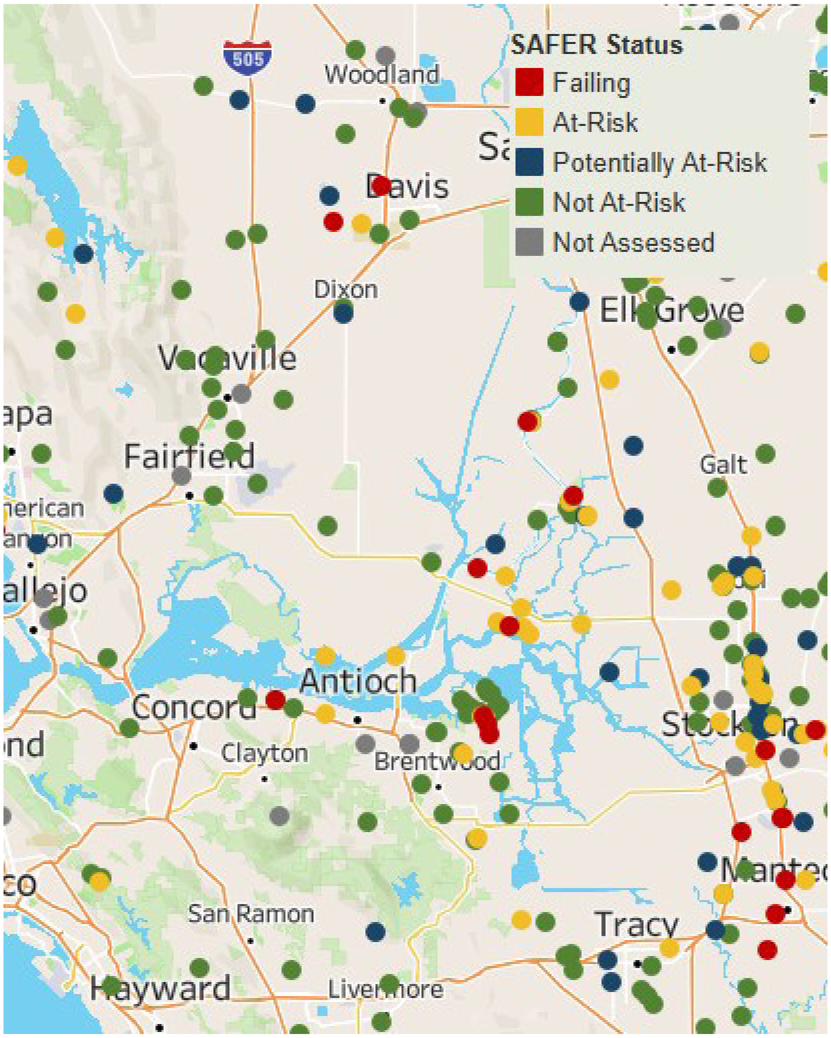

Figure 4 Snapshot of small public water system's Safe and Affordable Funding for Equity and Resilience (SAFER) status in the Delta Region (SWRCB 2023a), see *https://www.waterboards.ca.gov/drinking_water/certlic/drinkingwater/saferdashboard.html*. *Points* indicate centroids of service areas with fewer than 500 connections. Status is based on water quality; accessibility; affordability; and technical, managerial, and financial capacity.

risk (yellow) or already failing[2] to meet (red) the state's "human right to water" goal (Figure 4). Many of the region's at-risk and failing regulated water systems are quite small—from as few as 15 to fewer than 500 service connections—and are thus particularly vulnerable to drought (CDWR 2021c; SWRCB 2023d). The CDWR assessed the vulnerability to drought of small suppliers in 2021 and found that six of the Delta's 129 small water systems, which provide water to approximately 580 people, scored "relatively high vulnerability" to drought and water supply shortages (CDWR 2021c). In general, smaller systems and self-supplying communities will need substantial investment and support to continue adapting to droughts while also coming into compliance with drinking-water standards and delivering on the state's "human right to water" law (West 2012).

Even large water providers can be negatively affected by water-quality issues during droughts. As discussed above, drought years typically lead to higher salinity in the Delta, which can negatively affect drinking-water treatment costs (Medellín–Azuara et al. 2012). Higher incidences of HABs in the Delta can also increase surface-water treatment costs (Ekstrom et al. 2017; Klasic et al. 2022). Larger water systems—typically more equipped to prepare for and adapt to drought conditions—that rely directly on surface water

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[2] A "failing" system is one that is actively out of compliance or "consistently failing to meet" primary drinking water standards, as outlined by the Safe Drinking Water Act (*https://www.waterboards.ca.gov/water_issues/programs/hr2w/docs/hr2w_expanded_criteria.pdf*)

intakes in the Delta have started to invest in costly alternative strategies. For example, the Bay Area's largest water agencies (Contra Costa Water District, East Bay Municipal Utility District, Santa Clara Valley Water District, San Francisco Public Utilities Commission, Zone 7 Water Agency) have been considering a regional desalination plant to ensure sufficient water is available during droughts (Brown and Caldwell et al. 2017). In 2021, the City of Antioch broke ground on the Delta's first brackish-water desalination plant to have more operational flexibility and supply reliability during droughts (City of Antioch 2023). In other parts of the state, providers reliant on importing Delta water are pursuing expensive supply-augmentation strategies to increase their self-sufficiency through projects such as groundwater recharge and potable reuse. Water managers in central and southern California consider this shift from reliance on imported water to self-sufficiency to be an important drought-resilience strategy as changes in climate are projected to render imported surface water supplies and increasingly unreliable option (Ekstrom et al. 2017; Klasic et al. 2022). Reductions in Delta water exports as a result of drought can have cascading consequences. Water systems that normally import Delta water will have to find more expensive water sources, increase treatment costs, or invest in expensive potable reuse and desalination facilities that may render water more unaffordable for low-income communities (Feinstein et al. 2017).

Drought and Equity

Fair and equitable distribution of water amongst all beneficial uses—human and environmental—has been a point of contention throughout the Delta's history, even in the wettest periods. During periods of scarcity, reaching an agreement on equitable water allocation becomes even more difficult. When water rights are curtailed or the SWP and CVP reduce allocations, cuts are applied first to "junior" water-rights holders (those that claimed their water rights later in time). Many scholars, politicians, and activists have criticized this water rights system as unfair, saying it is inherently inequitable because of its origin during a period of historic dispossession and disenfranchisement in the 19th century (Curley 2019). History aside, enforcement of the current water-rights priority system may leave junior water-rights holders without any water during droughts, while senior water-rights holders have their full share (Sugg 2018; Green Nylen et al. 2023). Urban users and high-income areas are frequently the least affected because they have been able to secure the most senior water rights—either in time or through purchasing them—or have been able to invest in drought resilience (Ekstrom et al. 2018). Rural and low-income areas experience more curtailments, especially in the Central Valley (Stewart et al. 2020), and/or rely more on over-allocated groundwater resources and thus can have their wells run completely dry (Feinstein et al. 2017; Pauloo et al. 2020). Awareness of these problems is growing, and initiatives such as the University of California-led Collaboratory for Equity in Water Allocation[3] are working to increase equity in water policy.

During droughts, drinking water availability frequently affects marginalized communities first (Feinstein et al. 2017). A DSC study identified areas with high social vulnerability to climate hazards like drought. These vulnerable areas include parts of Delta cities such as Antioch, Pittsburg, Tracy, Sacramento, Stockton, West Sacramento as well as unincorporated areas of San Joaquin County (DSC 2021a) (Figure 5). Social vulnerability indicators included the presence of low-income communities, farmworker communities, and communities that either self-supply their household water (i.e., rely on private domestic wells) or rely on small water systems. These communities are typically the first affected and the least able to adapt to extreme events, including droughts (Feinstein et al. 2017; Ekstrom et al. 2018; Klasic et al. 2022).

Outside the Delta, many disadvantaged communities rely on the CVP or SWP for their water, with over six million people living in disadvantaged communities in the SWP service area (25% of the total population in the area), according to the CalEnviroScreen definition of disadvantage (Sunding et al. 2023). The California

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[3] *https://coeqwal.berkeley.edu/*

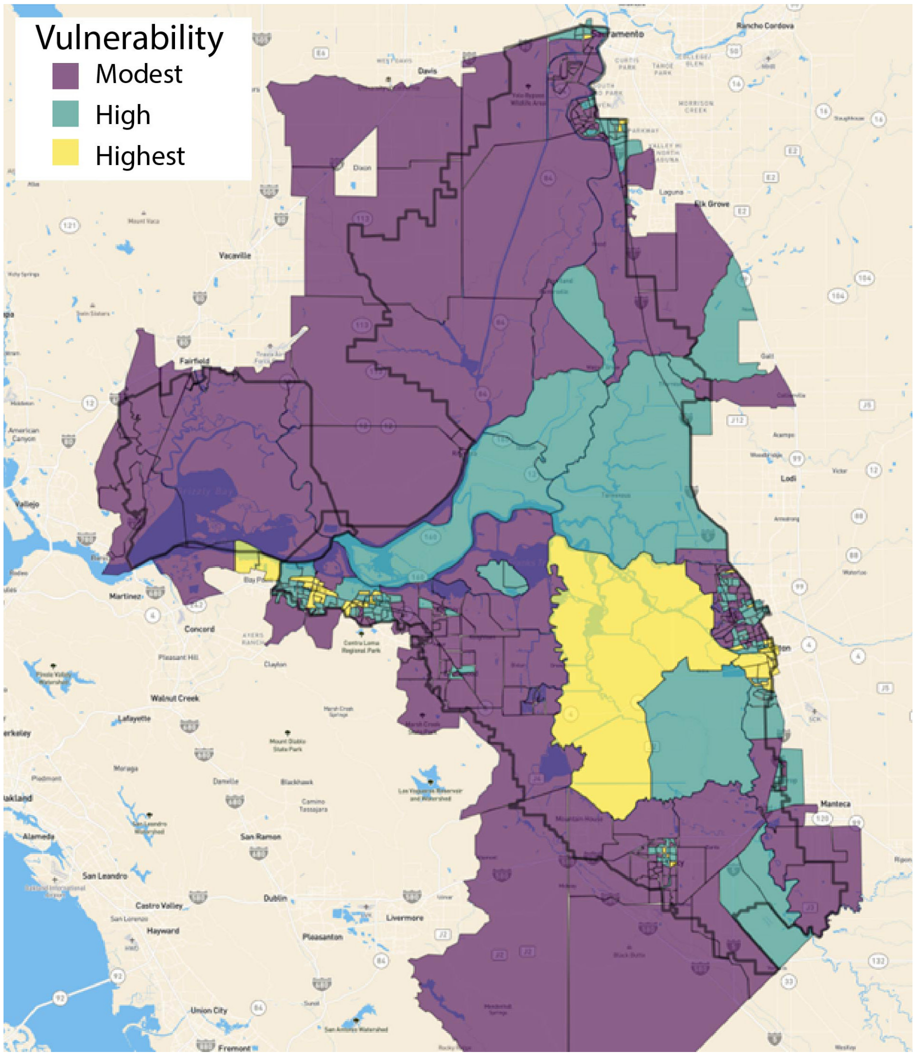

Figure 5 Social vulnerability rating for Delta Communities developed by the Delta Stewardship Council for the Delta Adapts report, see *https://deltascience.shinyapps.io/Delta_vulnerability_map/*.
Note: Modest = block groups with zero to three indicators; High = block groups with four to seven indicators; Highest = block groups with more than eight indicators. Indicators include children, older individuals living alone, poverty, language, education, tenancy, disability, race and ethnicity, vehicle access, health insurance, cardiovascular disease, food insecurity, and asthma (DSC 2021).

Environmental Protection Agency developed the tool CalEnviroScreen to identify communities in California most affected by the cumulative burdens of pollution and other environmental hazards, as well as communities that are socially vulnerable. While municipalities are required to provide minimum amounts of water for health and safety needs during droughts,(1 Cal. Code Regs., tit. 23, §§ 877.1(g), 878), when conservation measures or curtailments are in place, the cost per gallon of providing the water may increase. California Proposition 218, a constitutional amendment approved in 1996, limits the potential for publicly owned water utilities to charge more for water during droughts, which makes it difficult for public utilities to remain financially solvent and continue providing safe water to their consumers (Mount et al. 2018). Furthermore, private utilities do not have this restriction, and may pass increased costs on to consumers (Mount et al. 2018). Counter-intuitively, many water-conservation strategies and responses to drought can lower water bills for high-income households who are more able to reduce discretionary outdoor water use, while raising bills for low-income households who already use less water (Rachunok and Fletcher 2023).

Allocation of water for environmental needs is particularly contentious during times of scarcity. Sufficient freshwater in the Delta is crucial to support fish, waterfowl, and Tribal beneficial uses (Feinstein et al. 2017; SWRCB 2022), but political criticism often labels freshwater allocated for environmental flows as "wasted to the sea" when water use for direct human needs is curtailed (Reis et al. 2019). Other commentators maintain that not enough protections are given to California's fish during times of water scarcity (Shimabuku and Kammeryer 2022). One mechanism aimed at resolving some of the conflicts over beneficial uses of water is the Bay–Delta Water Quality Control Plan issued by the SWRCB. The Water Quality Control Plan is the regulatory mechanism for balancing water supply across agricultural, municipal, recreational, fish and wildlife, and Tribal beneficial uses, and is in the process of being updated for the first time since 2006 (SWRCB 2023e).

Many Native Americans are particularly concerned with what they see as inadequate protections for salmon and other ecosystem components that are an integral part of their culture, and a coalition of Native Americans and their allies have petitioned the SWRCB to update the Water Quality Control Plan with greater protections for salmon (Winnemem Wintu Tribe et al. 2022). Increasing the participation of Tribal groups in water-policy decisions can significantly improve outcomes for all parties (Dolan and Middleton 2015), and the official recognition of Tribal Beneficial Uses of water by the SWRCB in 2016 (SWRCB 2016) may improve protections for Tribal uses, but many conflicts remain. In recent years, the SWRCB has increased activity centered on the Water Quality Control Plan update[4], holding multiple public workshops and assessing the benefits of the proposed plan (SWRCB 2017). Public water agencies have come forward with a Voluntary Agreement proposal—an approach that integrates environmental flows with habitat restoration (Voluntary Agreements Parties 2022) but has yet to include substantial input from Tribes.

WHAT TOOLS ARE AVAILABLE TO ADAPT TO DROUGHT?

Tools for managing drought have evolved over time (see Box 1); their continued development and improvement can support the state of California in maintaining water supplies for all human and environmental needs. Tools for managing drought in the Delta can be broadly grouped into three categories: (1) actions taken to increase water supply, (2) actions taken to decrease demand for water, and (3) actions taken to mitigate gaps between water supply and demand (Figure 6, Table 1). These categories can be further divided into two types of actions: (1) actions that can be conducted in any year to build resilience for future droughts (preparation) and (2) actions taken during a drought to respond to immediate needs (response).

Although not all these tools relate directly to the Delta, the interrelated nature of California's water systems means that management actions to reduce the effects of drought *anywhere* in the Delta's watershed or in the service area of the CVP and SWP will be needed when drought occurs in the Delta.

Supply-Side Tools

Preparation

Much of today's current water infrastructure was built to increase the state's ability to withstand droughts. With each successive drought, Californians have developed additional tools to increase drought resilience, though increasing population size, increased water demand, and projected changes in climate would make drought response increasingly difficult (see Box 1). The most important tool in preparing for droughts is just that: planning and preparation. In 2022, the California Natural Resources Agency (CNRA) developed a new water-supply strategy aimed at adapting to a hotter, drier future (CNRA 2022). This strategy identifies four categories of tools that need further development for the state to become more resilient:

1. Increased storage capacity,
2. Increased stormwater capture and desalinization capacity,
3. Increased water recycling and reuse, and

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[4] *https://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/comp_review.html*

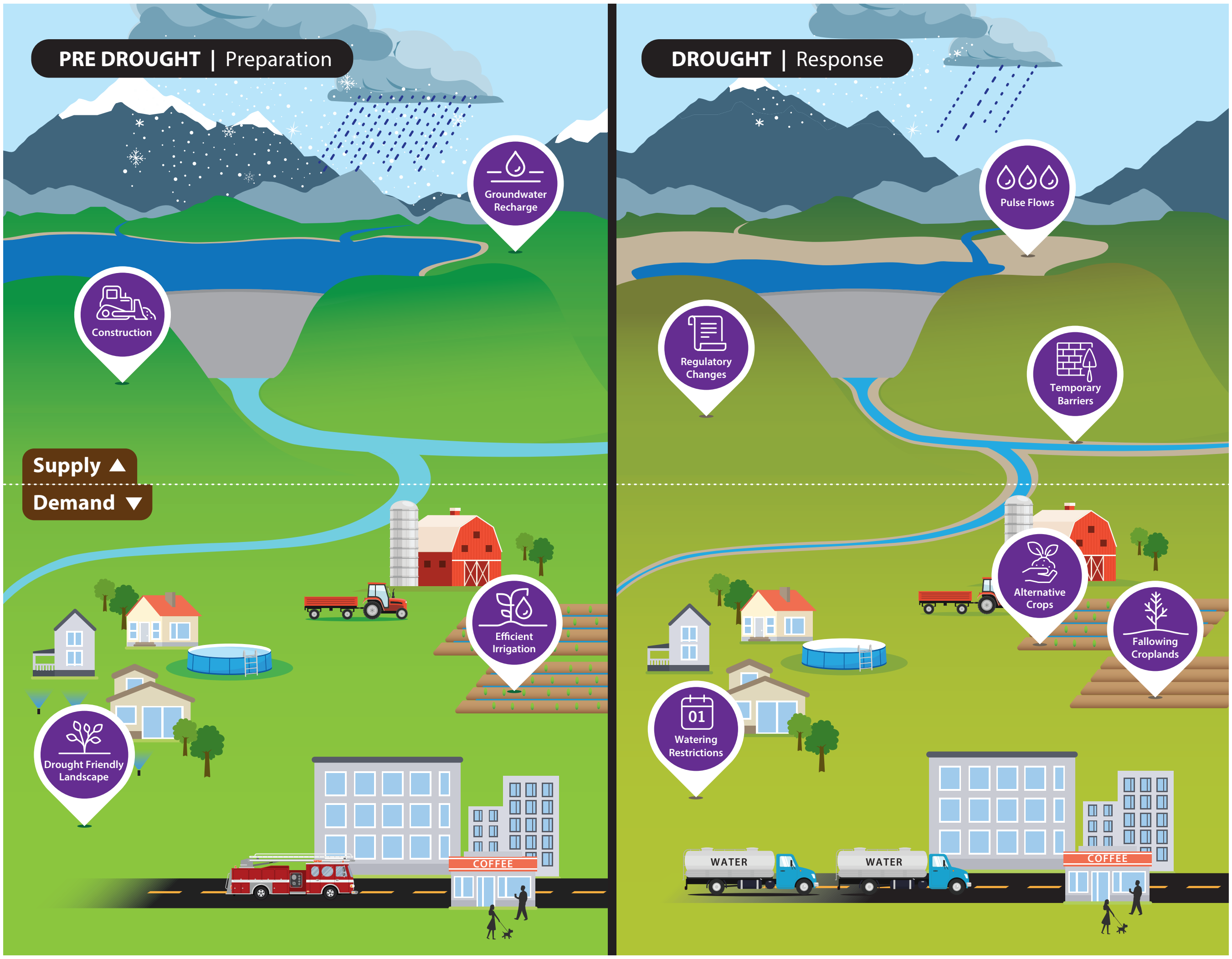

Figure 6 Conceptual model that shows categories of drought tools and how they can be classified as preparation actions that happen during non-drought periods and response actions that can happen during droughts. Actions can also be classified as actions that increase supply such as new water infrastructure, changes to the regulations that control water distribution, or actions that reduce demand such as improvements to irrigation or urban conservation efforts. Mitigation actions provide emergency relief without solving any underlying problems (such as providing bottled water to communities with dry wells or increasing hatchery production of salmonids). Credit: Illustration by Vincent Pascual with the California Office of State Publishing.

4. Increased conservation and water use efficiency.

The first two categories of tools in the CNRA water-supply strategy—increasing storage capacity and increasing stormwater capture and desalination—are designed to increase freshwater supply to prepare for droughts. Other planning tools that have recently been developed include the “drought toolkit” and drought contingency plans required by the SWP and CVP Biological Opinions and Incidental Take Permit, released in 2019 and 2020, respectively (USFWS 2019; CDFW 2020). These regulations were developed on the heels of the historic 2012–2016 drought and, as a result, they required these drought plans to improve the system’s ability to respond to droughts.

Increased storage capacity is the first step in the CNRA water-supply strategy, which has been the most common form of supply-side preparation throughout history (see Box 1 for more on history). Storage recommendations include some

Table 1 Drought management tools in use or planned in California. This table is not comprehensive, but it provides an overview of many of the most important tools at a high level. For each action, we provide a brief description, stage of development, agency or group responsible for implementing the action, and a reference or two that describes the action in more detail.

Category	Drought action	Description	Stage of development	Responsible party	Sources
Supply — response	Temporary, urgency change petitions	Modifications to water rights decisions responding to urgent needs	Used frequently	SWRQCB	Green Nylen et al. 2018
Supply — response	Drought Salinity Barriers	Temporary barriers in the Delta to prevent salinity intrusion in the Central Delta	Used in 1977, 2015, 2020, 2021. Long-term permitting in progress	CDWR	CDWR 2019 Kimmerer et al. 2019
Supply -preparation	Forecast Informed Reservoir Operations (FIRO)	Water management approach that allows managers to selectively retain or release water, based on forecasts, to increase drought resilience	Being evaluated at Lake Mendocino, Prado Dam, Yuba/Feather River basin	CDWR and local partners	CW3E 2023 Delaney et al. 2020
Supply — preparation	Desalination	Construction of desalination plants to provide "drought-proof" water supplies	Desalination plant recently built at Antioch, but technology remains too expensive for widespread use	Local utilities	Xu et al. 2022
Supply — preparation	Groundwater management	The Sustainable Groundwater Management Act (SGMA)	In implementation	CDWR and local groundwater basin groups	Leahy 2015 Liu et al. 2022
Supply — preparation	Flood Managed Aquifer Recharge (FloodMAR)	"Flood-MAR" is an integrated and voluntary resource management strategy that uses flood water resulting from, or in anticipation of, rainfall or snow melt for managed aquifer recharge (MAR) on agricultural lands and working landscapes, including but not limited to refuges, floodplains, and flood bypasses.	In pilot implementation	Dam managers	*https://water.ca.gov/programs/all-programs/flood-mar* Alam, Borthakur et al. 2021 Goharian et al. 2020 Maskey et al. 2022 Scanlon et al. 2016
Supply — preparation	Improvements to data and reporting	Improvements to data collection and storage technology, as well as regulations requiring data collection, allow us to make better forecasts and decisions	Implementation and continuous improvement	CDWR, state and regional water boards	Dodd 2016 Dziegielewski et al. 1993
Supply — response	Operational modifications	Changing intake locations for temperature control, pump-back actions, etc.	In implementation	Dam managers	USBR 2022
Supply — response	Modified diversion schedules	Contractors voluntarily consider modified diversion schedules in summer and fall to protect environmental uses for water	Used frequently	USBR ("Reclamation") and contractors	USBR 2022
Supply — response	Water transfers	Contractors voluntarily participate in water transfers by making water available through groundwater substitution and cropland idling/crop shifting	Used frequently	CDWR, and the SWRQCB, where relevant	Berbel and Esteban 2019 Israel and Lund 1995 Rosegrant 1995
Supply — response	Curtailments	The SWRQCB can direct post-1914 water rights holders to stop diverting in order to retain flow for downstream users or environmental uses.	Used frequently	State and regional water boards	*https://www.waterboards.ca.gov/drought/delta/curtailment-compliance-and-responses.html* Green Nylen et al. 2018 Schwarz 2015

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Table 1 *(continued)*

Category	Drought action	Description	Stage of development	Responsible party	Sources
Supply — response — Drinking water / human systems	Private dry well grant program	Funding available to provide drinking water and improvements to private wells	In implementation	CDWR/USDA	*https://water.ca.gov/Water-Basics/Drought/Drought-Funding/Small-Community-Drought-Relief*
Supply — response — Drinking water / human systems	Drought assistance for small systems	Emergency funding for small water systems	In implementation	State Water Board	*https://www.waterboards.ca.gov/water_issues/programs/grants_loans/sustainable_water_solutions/safer.html*
Supply — preparation	Infrastructure improvements	Lower pump intakes to allow irrigation at lower flows, improvements to hydroelectric plants, improvements to fish hatcheries, other water control structures to allow better operations at low flows, wastewater improvements	Varies	Water system managers	Lund 2016 Lund et al. 2007 Medellín-Azuara et al. 2013 Porse et al. 2023
Demand — response	Land fallowing grant programs	CDWR and the Delta Conservancy started a pilot grant program to encourage farms in the Delta to use less water	In pilot implementation.	CDWR and Delta Conservancy	*http://deltaconservancy.ca.gov/grant-program/delta-drought-response-pilot-program/*
Demand — preparation	Irrigation improvements	Irrigation improvements, such as drip irrigation, which allow more crops to be grown using less water	Efficiency constantly improving	Farmers	Berbel and Esteban 2019 Tindula et al. 2013
Demand — preparation	Land use change	Taking agricultural land out of production	As needed, generally responsive rather than planned	Local planning agencies, farmers	Gebremichael et al. 2021
Demand — preparation	Other agricultural improvements	Planting different crops, etc.	In implementation	Local planning agencies, farmers	Gebremichael et al. 2021 Morris and Bucini 2016
Demand — preparation	Soil organic matter additions	Carbon sequestration and improves soil water retention	In development and pilot implementation	Farmers	Iizumi and Wagai 2019 Lepsch et al. 2019 Morris and Bucini 2016
Mitigation — response — drinking water	Emergency bottled water, hauled water, temp tank programs	Funds to provide emergency water to small systems and/or individuals who run out of water	In implementation	State and regional water boards	Tortajada et al. 2017 *https://www.waterboards.ca.gov/drought/drought_assistance.html*
Mitigation — response — agriculture	Insurance for crop failures	Insurance program to provide business expenses if crops fail from drought	In implementation	USDA Department of Agriculture	Tortajada et al. 2017
Demand — Drinking water / human systems	Urban conservation incentives	Compensation to homeowners to remove lawns, fix leaks, purchase water saving appliances, etc.	In implementation	Cities/local government	Bolorinos et al. 2020 Vahmani and Ban-Weiss 2016
Demand — Drinking water / human systems	Urban water management plans	Drought shortage contingency plans for small systems	In implementation	Cities/local government	California Water Code, §10610-10656 and §10608, *https://water.ca.gov/Programs/Water-Use-And-Efficiency/Urban-Water-Use-Efficiency/Urban-Water-Management-Plans*
Mitigation—preparation — Environmental / endangered species	Habitat restoration	Increasing habitat quality and quantity to increase resilience	Many projects have been constructed or are under construction, more planned	Varies	Herbold et al. 2018 *https://resources.ca.gov/Initiatives/California-EcoRestore*

Table 1 ***(continued)***

Category	Drought action	Description	Stage of development	Responsible party	Sources
Mitigation—preparation — Environmental / endangered species	Environmental monitoring	Increased monitoring of conditions triggered by droughts, such as wildlife disease, HABs, aquatic vegetation	Some triggered monitoring exists, but it is difficult to quickly respond to extreme events	Multiple agencies, scientific community	Hartman, Stumpner et al. 2024 Herbold et al. 2018
Mitigation—response — Environmental/ endangered species	Alternative salmonid release sites	When conditions in the rivers are too hot or too low for out-migrant survival, hatchery fish are trucked downstream or to the ocean	In implementation	USFWS and/or CDFW	Durand et al. 2020 Sturrock et al. 2019
Mitigation—response — Environmental/ endangered species	Pulse flows	Artificial triggers to help salmon migration and/or prevent salmon eggs from drying.	A few use cases, not widespread	Varies	Sellheim et al. 2020
Mitigation—response — Environmental / endangered species	Improvements to hatcheries	Use of alternative water intakes to reduce water temperatures. Water chillers may also be installed, but are only cost-effective in small hatcheries.	In development	USFWS or CDFW	USBR 2022
Mitigation—response — Environmental/ endangered species	Changes to hatchery practices	Released juveniles during flow augmentations. Spread fish around so they are not all at the same facility.	In development	CDFW, USFWS	Herbold et al. 2018 Johnson and Lindley 2016
Mitigation—response — Environmental / endangered species	Scientific research	Increase our understanding of responses to drought through monitoring and studies	In implementation	Multiple	Durand et al. 2020 Hartman, Stumpner et al. 2024 Herbold et al. 2018
Supply — preparation	Forecast improvements	New snow survey methods and improved forecast models	In development and pilot implementation	CDWR	*https://cdec.water.ca.gov/snow/* Hedrick et al. 2018
Mitigation—response — Environmental / endangered species	Biogeochemical models	Predict the extent and location of harmful algal blooms and other problems	In development	Agency and academic researchers	Mori et al. 2022

of the more traditional tools such as construction of new dams and reservoirs, as well as newer ideas for using flood flows to replenish and enhance water stored in the ground—sometimes called flood managed aquifer recharge or FloodMAR (Alam et al. 2020; Goharian et al. 2020; Alam, Borthakur et al. 2021; CNRA 2022; Maskey et al. 2022). FloodMAR may be able to reduce flood peaks as well as address up to 60% of groundwater overdraft, but will require significant investment in water conveyance and recharge basins before these benefits can be realized (Alam et al. 2020).

Water also needs to be moved to and from these new storage locations, which may also require additional infrastructure. For example, the state of California is planning the Delta Conveyance Project to route water around the Delta in an underground tunnel. This project is designed to increase drought resilience by allowing more water to be captured and stored during wet years through greater operational flexibility and capacity, as well by reducing the potential for salinity intrusion during dry years (CDWR 2023b). However, it is currently controversial because of concerns that water quality within the Delta will suffer (see comment letters in CDWR 2023b). New dams and aqueducts can also be accompanied by smaller improvements to water-supply infrastructure, such as reducing leaks and improving efficiencies (Lund 2016).

Greater regulatory flexibility and more accurate forecasting would benefit the effective use of increased storage capacity. For example, the "storm flex" provision codified in the Water Infrastructure Improvements for the Nation (WIIN) Act allows more flow to be captured in high-flow years (Cornyn 2016). Similarly, Forecast Informed Reservoir Operations (FIRO) is a relatively new framework for managing reservoirs that prioritizes storage when dry conditions are forecast and prioritizes releases for flood control when rain is forecast (CW3E 2023). Studies have found this approach may increase storage during dry periods and provide greater capacity to control floods during wet periods compared to use of a single target water level regardless of forecast future precipitation. (Delaney et al. 2020). Forecast-Informed Reservoir Operations is currently being piloted at a few reservoirs in California (Lake Mendocino, Lake Sonoma, Prado Dam, Seven Oaks Dam, and Howard Hanson Dam), but has yet to be adopted more widely (CW3E 2023).

Improving our ability to forecast flow based on soil moisture, snowpack, and precipitation would allow water managers to capture stormwater, and balance water storage with flood management, more effectively. For example, the difference between the magnitude of predicted and observed April–July flow in major river basins has increased over the period from 1997 to 2018 in most of California[5], indicating new forecast methods are needed. Increased temperatures are resulting in lower soil moisture and increased evaporative demand (Dewes et al. 2017; Vicente–Serrano et al. 2020; CNRA 2022), changing the relationship between precipitation and streamflow (Vicente–Serrano et al. 2020). In particular, forecasts early in 2021 significantly under-predicted runoff, and dry conditions forced the CDWR and USBR to apply for a Temporary Urgency Change Petition (TUCP; a request for emergency modifications to flow regulations) later in the season (SWRCB 2021; Auditor for the State of California 2023). Use of new airborne imagery techniques to replace point surveys for snowpack, as well as new modeling techniques, can improve forecast accuracy (Hedrick et al. 2018). To that end, the CDWR has recently improved several water-supply forecast tools, including switching from a linear regression model to a machine-learning model, and modernizing snow survey techniques (2023 email from S. DeGuzman to RKH, unreferenced, see "Notes"). Real-time operational forecasts during storm events have improved significantly, allowing for better optimization of reservoir operations, such as FIRO, described above (CW3E 2023). However, improved seasonal precipitation forecasts that could provide longer lead times for predicting drought conditions might provide even greater benefit (Guirguis et al. 2019).

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[5] *https://cdec.water.ca.gov/snow/bulletin120/B120_error_fcast_plots.html*

Desalination is also recommended in the CNRA water-supply strategy to enhance water supply (CNRA 2022) and is often suggested in various plans and strategies as a "drought-proof" source of fresh water (Badiuzzaman et al. 2017; Ibrahim et al. 2021). As mentioned in the "Drinking Water Reliability" section, the city of Antioch recently constructed a brackish-water desalination plant to buffer its water supply against future salinity intrusion (City of Antioch 2023). However, desalination technology is still expensive, very energy-intensive, and disposal of brine from desalination plants remains a challenge (Cooley and Ajami 2014; Elsaid et al. 2020). Desalination plants have also received criticism for inequitable distribution of benefits and effects (O'Neill 2023), and could hurt communities' ability to adapt if projected changes in climate were to occur (Tubi and Williams 2021). Desalination of brackish water from the Delta or salt-laden groundwater may be less energy-intensive than desalination of seawater, but supplies are more limited (Badiuzzaman et al. 2017; Xu et al. 2022).

Increasing use of recycled water—including use of grey water, indirect potable reuse, and direct potable reuse—increases water supply by converting a waste product into a fresh source of water (Badiuzzaman et al. 2017; Olivieri et al. 2020; CNRA 2022). However, public relations must be significantly improved to enhance the public's perception of human consumption of recycled water (Olivieri et al. 2020).

Any tools designed to increase water supply for human uses may have negative effects. For example, the Delta Conveyance Project may allow for increased water supply during droughts, but the environmental impact report for the project lists many potential negative effects on agricultural land, water quality, fish, and wildlife in the Delta (CDWR 2023b). Capturing storm flows with new reservoirs or groundwater recharge would reduce flood risk and increase storage, but also alter the natural hydrograph, and potentially negatively affect native fish populations (Poff and Zimmerman 2010). Construction of new dams or water-conveyance facilities may introduce migratory barriers or increase entrainment of fish (Kimmerer 2008; Zeug et al. 2011). While preparing for drought can forestall some of the negative effects, there will inevitably be trade-offs between beneficial uses for water when water becomes scarce.

Response

Drought responses—actions taken once a drought is in place—can be effective in the short term, but actions taken to prepare for droughts *before* they occur may provide larger benefits over the long term. For this reason, most of the tools in the CNRA's water-supply strategy prioritize long-term preparation over short-term responses (CNRA 2022). Many supply-side response tools—including water markets and exchanges, regulatory constraints, flexible or reconfigured water rights, and mandatory supply reductions—are aimed at improving the flexibility of the state's water regulatory systems to enable water to move more easily between places with water and places without water. (Table 1). Water markets have been extensively developed in California, greatly reducing the economic effects of drought on the large scale (Zilberman et al. 1994; Rosegrant and Gazmuri 1995; Arellano–Gonzalez et al. 2021).

The SWRCB uses surface-water curtailments (or restrictions on use) to manage surface-water availability and quality in the Delta (and other watersheds) during droughts. They use curtailment orders to limit allocations to certain water users within and beyond the Delta, according to the state's water-rights prioritization system. The SWRCB has implemented curtailment actions to varying degrees during all major multi-year droughts since the 1970s (Green Nylen et al. 2018; Green Nylen et al. 2023). During the last two droughts (2012–2016 and 2020–2022) the SWRCB "expanded the breadth and depth of its curtailment related efforts," issuing the first curtailment orders specifically intended to protect minimum fish flows (Green Nylen et al. 2023 p. 56). Using emergency regulations to support their curtailment orders led to various legal proceedings that questioned whether the state has the authority to use these powers, particularly to curtail the allocations of very senior water-rights holders (Green Nylen et al. 2023).

Droughts can also trigger infrastructure changes, and, while many changes cannot be constructed quickly enough to respond to droughts in the moment, some notable exceptions include the emergency drought salinity barriers installed during the 1977, 2015, and 2020–2022 droughts to reduce salinity's intrusion into the Delta (Kimmerer et al. 2019; CDWR 2022b; CDWR 2024a). Changes to operations of existing infrastructure are more common, including temporary use of alternative intake locations to protect water quality, changes to operational rules to conserve supplies (Delaney et al. 2020), and TUCPs temporary urgency change petitions to alter flow standards (Green Nylen et al. 2018).

However, many tools may also increase inequitably distributed drought effects, particularly curtailments of junior water-rights holders (Feinstein et al. 2017; Sugg 2018; Wikstrom et al. 2019), decreased environmental water availability (Stewart et al. 2020), decreased water quality, and increased groundwater pumping (Liu et al. 2022).

Demand-Side Tools

Preparation

On the "demand" side, drought preparation actions focus on reducing consumption through improvements to water use efficiency and conservation. The CNRA water-supply strategy (CNRA 2022) places a high priority on these actions, calling for a decrease in demand of over 500,000 acre-feet of water to be made available through conservation and efficiency actions. These actions could be increasingly important because projected climate changes would increase both evaporation from reservoirs and evapotranspiration from both agricultural and natural landscapes (Orang et al. 2013; Dai et al. 2018; McEvoy et al. 2020; Vicente–Serrano et al. 2020), though some studies have projected evapotranspiration to remain roughly stable (Lofgren et al. 2011; Vahmani et al. 2022). Research is currently underway to better quantify evapotranspiration in the Delta (Eichelmann et al. 2018; Medellín–Azuara et al. 2018), and these data are being used to parameterize the new forecast techniques described in the "Supply-Side Tools–Preparation" section.

Agricultural actions to prepare for drought include incentives for farmers to plant fallowable crops and cover crops, perform rotational fallowing, and invest in water-saving irrigation technologies (Tindula et al. 2013; Wolf et al. 2017; Berbel and Esteban 2019). However, many of these water-saving actions, which could buffer the system against droughts, are used instead to increase acreage under cultivation or development (Berbel and Esteban 2019). Increasing soil organic carbon can also buffer fields against water shortage (Iizumi and Wagai 2019).

Legislation in 2018 (Senate Bill 606 and Assembly Bill 1668) accelerated efforts to reduce urban water demand by implementing stricter indoor and outdoor water-use standards. These measures aim to surpass the water-conservation targets set by SB X7-7 (California Water Code [WC] §10609.2[d]). The 2018 legislation resulted in the formation of the California Water Use Efficiency Partnership—a collaborative stake-holder group—to advise, implement, track, and report on meeting these goals. Some specific actions that various municipalities and local governments have adopted throughout the state to reduce water use include providing incentives for urban users to plant drought-friendly landscaping and to purchase water-saving appliances. Changes to urban landscaping can also reduce temperatures through increased nighttime cooling, though reducing irrigation can increase daytime temperatures (Vahmani and Ban–Weiss 2016).

The SGMA of 2014 required improved management of aquifers so groundwater would be available during future droughts to make up for loss of surface water supply (Leahy 2015). However, the SGMA has come under criticism for not adequately incorporating stake-holders in the planning process (Dobbin 2020; Bostic et al. 2023; Perrone et al. 2023), and many private and public wells are still at risk (Bostic et al. 2023).

One key aspect of drought preparation involves identifying vulnerable communities and providing them with tools and resources to improve their water supplies before drought occurs. While many of these agricultural and urban conservation actions occur outside the Delta, they are connected to drought in the Delta because the Delta is a major source of water for such a large proportion of the state's urban and agricultural water users. The Delta Reform Act's goal to reduce reliance on water from the Delta is expected to also reduce the effect of droughts on the Delta by lowering demand for its water (Simitian and Steinberg 2009).

Response

Drought responses targeted toward reducing demand include tools such as education programs and incentives to encourage water conservation, as well as mandates that legally limit water use (e.g., curtailments, see "Supply-Side Tools–Response" section). Public education and outreach to reduce urban demand for water during droughts was identified decades ago as an important tool for drought response (Berk et al. 1981; Dziegielewski et al. 1993). Statewide legislation and mandates have also become frequent components of drought response (Figure 2). The California Water Use Efficiency Partnership developed the "Jumpstart Water Shortage Toolkit" to help local municipalities and agencies implement extra water-conservation methods, including communication and outreach, improved metering, remote-sensing tools, leak detection, customer support, and enhanced enforcement (CalWEP 2021). Public education and outreach alone may not be enough for the public to adopt water-conservation methods. Several studies of short-term educational campaigns show mixed results in California (Taylor et al. 2007; Koop et al. 2019; Hayden et al. 2023). However, a combination of education, economic incentives, and ordinances often provides higher rates of conservation (Hilaire et al. 2008; Koop et al. 2019). Tiered water-rate systems, particularly during droughts, and restrictions on outdoor water can reduce water consumption by over 20% where voluntary reductions fail (Mini et al. 2015).

Agricultural demand during water shortages can be reduced through mandatory curtailments or through incentives to farmers to fallow fields or plant more drought-tolerant crops (Green Nylen et al. 2018). The SWRCB's curtailments of surface water frequently lead to increased groundwater consumption, contributing to overdraft of aquifers (Dogrul et al. 2016). Frequency of curtailments on Sacramento and American River water-rights holders is expected to increase if climate change continues to increase the frequency of droughts (Schwarz 2015). To reduce the effects of overdraft and curtailments, the CDWR and the Delta Conservancy partnered during the 2021–2022 drought to provide grants to farmers in the Delta to plant alternative crops or to fallow fields6. The first year of this program produced some reduction in water use, although benefits were more modest than expected (Delta Conservancy 2023). Incentive programs of this type become less effective when farmers have shifted to orchard crops, vineyards, or other high-value crops, which, if not watered continuously, will cause economic hardships (Berbel and Esteban 2019).

Mitigation Tools

Preparation

In our typology of drought actions, we classify "mitigation" tools as those that help alleviate the effects of drought without increasing supply or reducing demand. Drought preparation actions that mitigate how drought affects **human** populations primarily involve establishing relief programs to provide aid if a drought occurs (Jedd 2023). These programs include emergency management funds, stockpiles of emergency supplies such as bottled water and water tanks, and crop insurance (Medellín–Azuara et al. 2022). Many farmers purchase insurance, which must be purchased in both good and bad years to be economically viable, to mitigate loss of crops from droughts and other natural disasters, (Tortajada et al. 2017).

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6 *http://deltaconservancy.ca.gov/grant-program/delta-drought-response-pilot-program/*

Actions to mitigate environmental effects of drought are less developed than other mitigation tools. Some tools include restoring habitat (Herbold et al. 2018), increasing resilience of fish populations by providing adequate flows during wet periods, and developing refuge populations or hatcheries as a safeguard against extreme climatic events (Shimabuku and Kammeryer 2022). However, despite decades of management and mitigation designed to increase resilience of native fishes in the Delta, most native fish populations have been in decline (Moyle et al. 2016; Nobriga and Rosenfield 2016; Welch et al. 2021; Munsch et al. 2022), and even many non-native fishes have declined (Mac Nally et al. 2010). With lower abundance during wet years, populations are more vulnerable to droughts, and drought response tools become less effective (Hanak et al. 2015; Herbold et al. 2018; Munsch et al. 2020).

Response

Response tools to mitigate how drought affects humans typically involve either providing bottled drinking water or monetary payments to people whose water supplies and livelihoods have been put in jeopardy (Jedd 2023). The SWRCB's SAFER program provides funding for short-term solutions such as bottled water, tanks and hauled water, and point-of-use treatment for failing systems (SWRCB 2023d). Several executive orders and legislation during recent droughts included funding for emergency food and drinking water for disadvantaged communities (Tortajada et al. 2017). The US Department of Agriculture's Farm Service Agency has several programs that provide disaster relief and emergency loans to farmers who do not have insurance or whose insurance does not adequately cover losses (Brusberg and Shively 2015; USDA c2015).

Many tools to mitigate how drought affects the environmental are designed to restore as close to a natural hydrograph as possible, given limited water supply (Brown and Bauer 2010; Kiernan et al. 2012; Klimley et al. 2020). Use of hatcheries and refuge facilities also provides a buffer for wild salmon and smelt populations in the Delta during droughts (Lessard et al. 2018; Sturrock et al. 2019). Salmonid hatcheries increase production during droughts, install water-cooling technology, and use alternative release sites, including trucking salmon all the way to the ocean to avoid stressful conditions in the rivers (Sturrock et al. 2019). However, use of hatcheries as a backstop for wild fish populations—and trucking salmon from hatcheries, in particular—can have unintended negative consequences that lead to reduced genetic diversity, reduced life-history diversity, increased straying, and lower population resilience (Herbold et al. 2018). For Delta Smelt, the extreme drought of 2020–2022 prompted acceleration of plans to use captive-reared smelt to supplement populations (CDFW 2021). The same drought also sped up the effort to re-introduce winter-run Chinook Salmon above Shasta Dam (NOAA Fisheries 2021).

Responses can also center on removing unwanted species that flourish during droughts, including tools to reduce (1) cyanobacterial HABs (Paerl and Otten 2013; Lehman et al. 2022), (2) invasive aquatic vegetation (Conrad et al. 2023), and (3) non-native predatory fishes (Mueller 2005; Cavallo et al. 2013; Treves et al. 2016; Bridges et al. 2019)—though many of these actions have limited effectiveness (Michel et al. 2020; Rasmussen et al. 2022).

FUTURE DIRECTIONS

Each new drought spurs the development of new approaches to adapting the socio-ecological systems of the Delta to water shortage. However, because changes in climate are projected to increase the frequency and severity of droughts, and because human demands will increase, new science and new management tools will be needed to protect human and environmental uses of the Delta's water.

The CNRA water supply strategy highlights the need to create additional storage space, increase water-recycling efforts, increase conservation, and investigate desalination (CNRA 2022). While the CNRA water-supply strategy lays out implementation steps to achieve its goals, many of the steps will require existing tools to be improved (particularly research into desalination technology and groundwater recharge; Alam et al. 2020); a systematic identification of opportunities; modernization of forecasting, data management, and water rights; and more research into the environmental and social effects of the proposed tools (CNRA 2022). There are recommendations to ensure that future water-management decisions address users' needs as equitably as possible (Wikstrom et al. 2019) which would align with California's commitment to the human right to water, the SWRCB's creation and protection of Tribal Beneficial Uses, and the creation of the California Racial Equity Commission to increase equity across state government (Newsom 2022). Increased drought frequency and severity will require more planning with more advanced modeling frameworks and tools (Auditor for the State of California 2023), and will likely include pre-permitting of many major drought actions, such as the Delta drought salinity barriers (CDWR 2022d). It will also require a continued commitment to programs such as SAFER and CDWR's drought relief program to ensure that small, vulnerable water users and systems are better equipped to prepare for and respond to the next drought.

Further social science research on how drought affects the Delta's communities is also needed. Much of the social science research cited in this paper was conducted in upstream regions or in areas of the Central Valley that rely on Delta water exports, but there has been relatively little analysis of how droughts affect the people of the Delta itself. Targeting research within the Delta will allow for a more place-based understanding of needs than is typically included in a statewide "lessons learned" assessment.

Additional tools to mitigate environmental effects of drought may be developed with continued scientific research. For example, Delta Smelt constrict their range in the fall of dry years, as the isohaline with a value of 6 practical salinity units (psu) moves upstream (Sommer and Mejia 2013). However, laboratory experiments have found Delta Smelt can survive and grow at much higher salinities (up to 12 psu; Kammerer et al. 2015). Understanding why their range is limited to less than 6 psu in dry years can help us better mitigate for the reduction in suitable habitat area. Similarly*, Microcystis* sp. and other HABs increase during droughts, but exactly when, where, and what species will form algal blooms remains unknown, with similar dry years often having quite different cyanobacteria bloom development (Lehman et al. 2018; USBR 2022; Bouma–Gregson et al. 2024). Developing biogeochemical models of how flow affects cyanobacterial bloom dynamics may allow managers to develop targeted tools to reduce the frequency of blooms (such as in Yuan and Pollard 2017). Other research needed includes better understanding of species' thermal tolerance, mechanistic studies of species' responses to drought (Hartman, Stumpner et al. 2024), and scientific evaluation of the effectiveness of previous drought actions (Durand et al. 2020). Also poorly understood is the role of nutrient inputs and contaminants—which may increase in concentration during droughts—on the ecosystem (Fong et al. 2016; Cloern et al. 2020).

Environmental management tools will most likely involve increasing drought resilience of species and ecosystems and human communities during non-drought years to bolster native species populations (CNRA 2016; Herbold et al. 2018). Actions that mimic a natural flow regime as closely as possible may also help to make the best use of scant water resources (Chilton et al. 2021), and increasing connectivity will better allow fish species to access limited habitats that are suitable during droughts (Shimabuku and Kammeryer 2022). However, we need a better understanding of the tools we currently have for mitigating ecosystem effects. Hatcheries provide an important buffer against drought years for salmonids, but recent research has found some hatchery practices weaken overall population resilience by limiting life-history diversity and increasing straying (Sturrock et al. 2019). Restoration of tidal wetland habitat is hypothesized to increase the resilience of fish populations by providing food and habitat resources across the landscape in all flow conditions (Brown 2003), but most tidal restoration sites in the Delta are too new for their effectiveness to be evaluated. Bolstering fish populations in wet years to allow them to withstand dry conditions is often done through managed flow actions. Some of these actions, such as pulse flows on tributaries for salmon, show clear benefits (USBR and CDWR 2022), whereas other actions, such as Fall X2 management for Delta Smelt, have had mixed results (FLOAT–MAST 2021).

Improving seasonal forecasting would also improve both human and environmental drought-management tools. With better predictions of seasonal conditions, prioritizing multiple needs would be easier, particularly for flood protection and storage (as FIRO is piloting) (CW3E 2023). How the interaction of warming and drought affects evaporation demands remains unclear. Some studies forecast that change in plant physiology will limit increases in evapotranspiration (Baldocchi et al. 2019; Vahmani et al. 2022), but other studies show evaporative loss will outpace changes to plant physiology (Dai et al. 2018). We will need a better understanding of these dynamics in the landscape of the Delta to improve forecasting tools and better understand changes to supply and demand.

Despite the tools available and currently in development, supplying the current demand for water in the Delta during prolonged drought will likely still be difficult. Drought conditions already cause conflict between human and environmental uses, and, with the possibility of more extreme droughts in the future, providing for all users' needs may not be possible.

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DATA ACCESSIBILITY STATEMENT

Data for Figure 3 is available on the California Natural Resources Agency Open Data platform: *https://data.cnra.ca.gov/dataset/dayflow/resource/776b90ca-673e-4b56-8cf3-ec26792708c3*

Data for Figure 4 is available on the State Water Board's SAFER dashboard: *https://www.waterboards.ca.gov/drinking_water/certlic/drinkingwater/saferdashboard.html*

Data for Figure 5 is available from the Delta Stewardship Council, online at: *https://deltascience.shinyapps.io/Delta_vulnerability_map/*

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NOTES

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