Title
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Journal
San Francisco Estuary and Watershed Science, 14(3)

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Publication Date
2016

DOI
https://doi.org/10.15447/sfews.2016v14iss3art6

OCTOBER 2016

SAN FRANCISCO ESTUARY & WATERSHED SCIENCE

Sponsored by the Delta Science Program and the UC Davis John Muir Institute of the Environment

SPECIAL ISSUE: THE STATE OF BAY–DELTA SCIENCE 2016, PART 2

California's Agricultural and Urban Water Supply Reliability and the Sacramento–San Joaquin Delta

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Volume 14, Issue 3 | Article 6
doi: *http://dx.doi.org/10.15447/sfews.2016v14iss2art6*

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ABSTRACT

Much of the water supplied in California for agriculture and cities is taken directly from the Sacramento–San Joaquin Delta (Delta) or indirectly from surface and groundwater diversions upstream. These water supplies have great economic and social value, and considerable ecosystem effects. Long thought of as the major source of water for economic growth in California, the reliability of water supplied from the Delta is threatened by drought, flood, climate change, earthquakes, growing water demands, and deteriorating conditions for endangered species and native ecosystems. Research in recent years has improved understanding of how management of the Delta ties together the quantity and quality of water available statewide. These ties run from the Sierra mountains and coastal streams, through the Central Valley, to the San Francisco Bay Area, and over the Tehachapi Mountains to southern California. For decades, Californians counted on reducing Delta outflows to supply water for growing water demands in its watershed and in water importing areas. With greater competition for water, concern for environmental effects, and a changing climate, the reliability of such supplies is now diminishing. This must lead to tighter accounting and modeling of water supplies in the Delta and throughout its watershed. This paper reviews issues about Delta water supplies, operations, regulations, and reliability; the economic value of supply; costs of unreliability in quantity and quality; and several directions for further scientific and technical work on water supply reliability.

KEY WORDS

Water supply, reliability, Sacramento–San Joaquin Delta

INTRODUCTION

The Sacramento–San Joaquin Delta (Delta) was created beginning about 6,000 years ago, after the last ice age, by sea level rise progressively drowning the confluence of the Sacramento and San Joaquin rivers, just upstream of San Francisco Bay. In modern times, the Delta has become the most central single feature of California's extensive and diverse water supply system. Consequently, water supply reliability is one of the state's "co-equal" goals for the Delta. Although the Delta's importance to the water supply system is widely known, its roles are

complex and often misunderstood. Public and policy discussions of potential diversion tunnels under the Bay Delta Conservation Plan (BDCP) and Water Fix proposals have enlivened interest in the Delta and its peculiarities in local and statewide water supplies (CDWR 2015b). This paper reviews California's water system, the Delta's roles in this system, and the fundamental economic demands for water from this system. It also reviews how the Delta ties the state together and is a source of conflict. Then I offer some fundamental observations about the Delta and water supply, along with some directions and limitations for the use of science to improve our understanding and management of water supplies both diverted from Delta outflow, and flows within the Delta.

OVERVIEW OF CALIFORNIA'S WATER SYSTEM

California has one of the world's most extensive and interconnected water systems, supporting over 38 million people and almost 9 million acres of irrigated agriculture within a $2.3 trillion economy that is tightly connected globally by trade, migration, and communication (Luoma et al. 2015). The supplies and demands of this water system are substantial and diverse, with supplies being particularly variable across seasons and years, as the ongoing drought highlights.

Figure 1 shows the distribution of runoff, which is the source of all surface and ground waters, across California. In space and time, water availability is highly mismatched with water demands. About 90% of California's runoff comes from 40% of its land surface, predominantly in northern and mountainous areas. Most human water demands are located in drier areas the in central (agriculture; 80%) and southern (cities; 20%) parts of California (CDWR 2013).

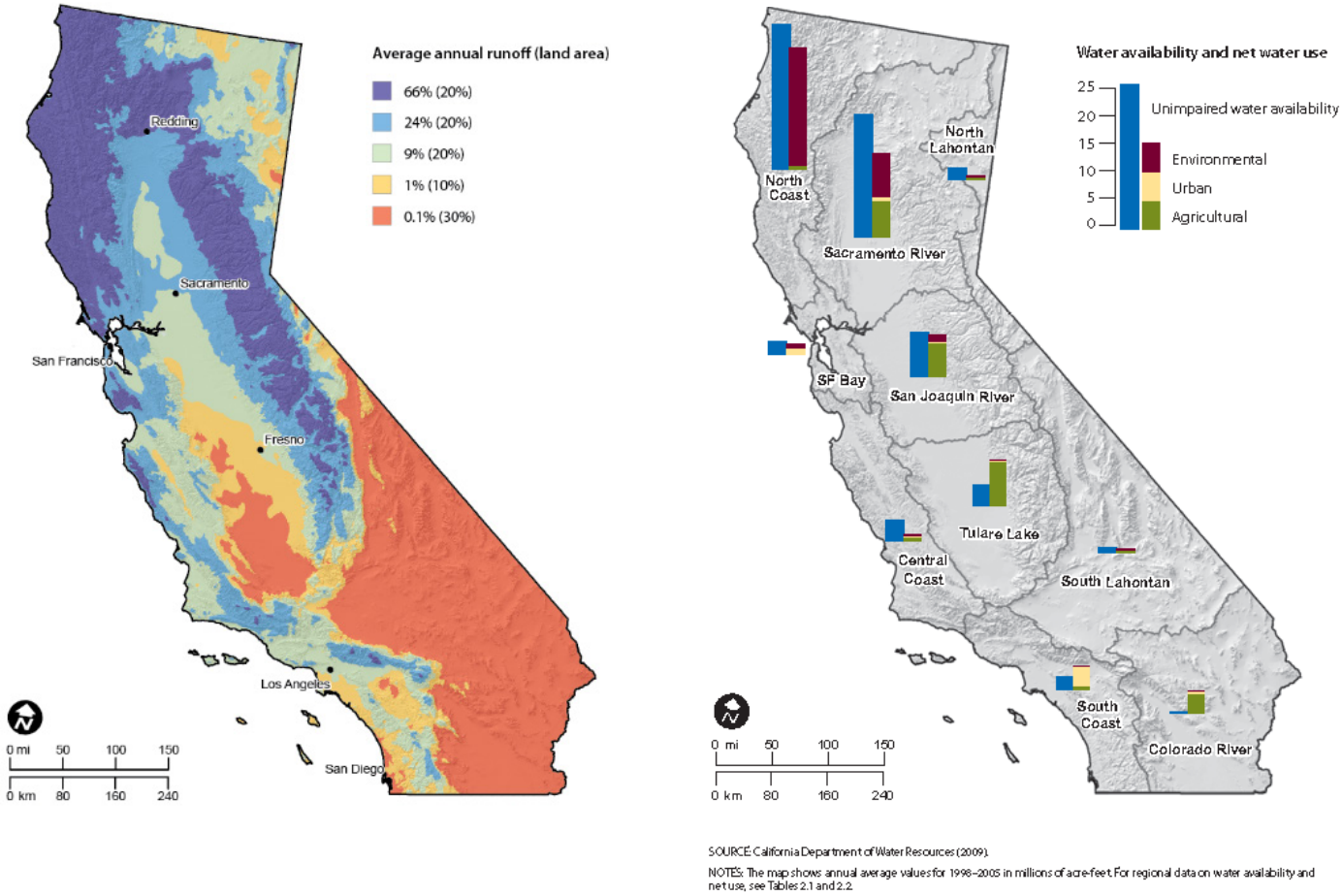

Figure 1 California's uneven geographic distribution of water availability and water use. (Source: Hanak et al. 2011.)

California's runoff occurs predominantly in winter and spring (Figure 3), sometimes with substantial flooding. This timing is seasonally opposite of most agricultural and urban water demands, which are mostly from crop and landscape irrigation during California's long dry summers. Climate warming and diminished spring and summer snowmelt will likely concentrate California's annual runoff more into winter months (Lettenmaier and Sheer 1991; Gleick 1987).

The flat topography and high land values of coastal urban areas make local storage of high winter runoff difficult and expensive. Even the Bay Area, with relatively high annual precipitation, imports most of its water from distant mountain reservoirs (diverting runoff that otherwise would have gone through the Delta).

In response to this mismatch of hydrology and human water demands, California has built an extensive system of water-management infrastructure, depicted in Figure 2 (Hundley 2001; Hanak et al. 2011). The Sacramento–San Joaquin Delta is the greatest single hub in this water system. California's extensive water management infrastructure is owned and operated by a wide range of hundreds of local, federal, and state agencies, as well as several private companies, and is subject to regulations by a myriad of federal, state, and local governments. Over time, the system has become increasingly inter-tied, as improvements in reliability often come more cost-effectively from more flexible operations and from sharing water. The institutional complexity of California's water system often exceeds even its great physical complexity (Luoma et al. 2015; Lubell et al. 2014).

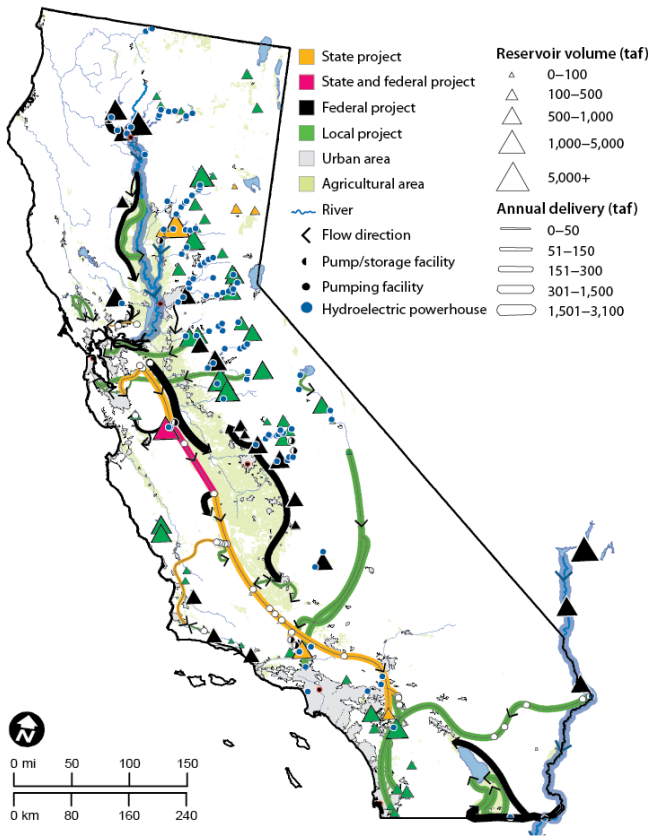

Figure 2 California's water supply infrastructure. (Source: Hanak et al. 2011.)

CLIMATE AND WATERSHED-BASED SUPPLIES

California has a highly variable climate, with great seasonal differences in precipitation and runoff (Figure 3) and large fluctuations between years (Figure 4). Much of the year-to-year precipitation variability derives from the few storms each year that provide much of the annual runoff totals. Across the Delta watershed, half or more of the average precipitation arrives in less than 10 to 15 wet days per year (Dettinger et al. 2011). Just a few storms can cause the difference between a dry and a wet year. Broadly speaking, water year totals range from about 50% to 60% of average to almost 200% of average with unusual frequency in California. Some of this year-to-year variation reflects global-scale climate processes such as El Niños and La Niñas (Schonher and Nicholson 1989) and their multidecadal counterpart, the Pacific Decadal Oscillation (PDO) (Mantua et al. 1997). However, more variation is from year-to-year variations in the number and size of large storms, most often as atmospheric rivers (Dettinger and Cayan 2014). The same storms that supply much of the state's water supplies also routinely cause large, dangerous floods. Flood- and water-supply management are inextricably joined in California (Lund 2012). The Delta is at the downstream end of both.

Much of California's climate is Mediterranean, with colder wet winters and dry hot summers. Seasonal snowpacks in California's high mountains store and

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shift large amounts of runoff from the winter to the spring and early summer (Figure 3). Higher temperatures reduce snowpack and accelerate snowmelt, reducing snowmelt-related shifts in seasonal runoff. Climate warming will diminish the State's snowpack to an extent that will depend on global greenhouse-gas concentrations and the resulting warming of California's climate (Anderson et al. 2008).

California's Mediterranean climate and long dry summers mean that each year California has a longer and more severe drought than the eastern U.S. has ever seen in history. The unimpaired flow[1] available to supply water demands varies greatly seasonally and between years, as depicted in Figure 3. This absence of precipitation during the main growing season, along with the state's strong year-to-year swings of precipitation, drought and floods (Figure 4), motivated development of California's extensive water system.

About three-quarters of the water flowing towards the Delta is from inflows from the Central Valley's surrounding mountains, so-called "rim flows" into the Central Valley and Delta. These flows are largely regulated by reservoirs, mostly along the Central Valley's rim, for water supply and flood control, with other purposes including hydropower, recreation, and, increasingly, support for ecosystems. The most common operations is to partially fill large reservoirs during the wet winter, while reserving considerable space to manage floods, and then allow this flood space to refill with snowmelt during the spring. These flood control and water supply operations of large reservoirs greatly dampen the seasonal effects of flows from watersheds on Delta inflows and outflows. Such reservoir operations can be improved with better coordination and forecasts (Graham and Georgakakos 2010; Maher 2011; Rheinheimer et al. 2016).

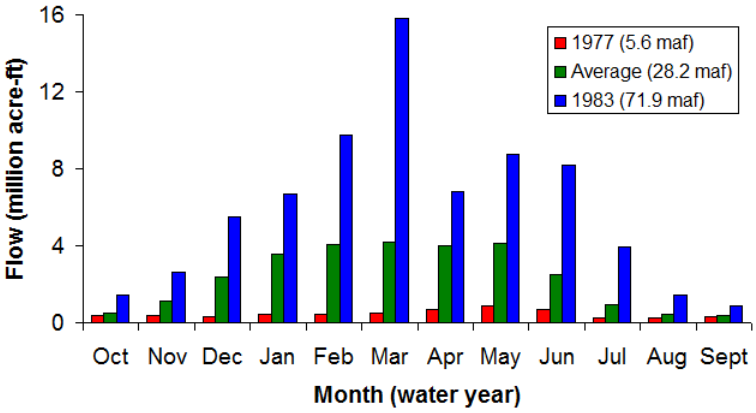

Figure 3 Unimpaired Delta inflow variability by month and year (Source: CDWR data.)

A warming climate is already shifting inflows from the spring to winter, as precipitation falls more as rain and less as snow, and snowpack melts earlier (Aguado et al. 1992; Cayan et al. 2008). Even if climate change brings similar amounts of precipitation, larger evaporation and evapotranspiration rates are likely to reduce streamflows (Null et al. 2010), including the effects of additional clear days (Viviroli et al. 2011).

Upstream flows also are affected by upstream watersheds conditions and activities, particularly forest conditions, which are themselves affected by climate, human land and fire management, and natural hydrologic and ecosystem processes (Bales et al. 2011; Brown et al. 2005; Ursino and Rulli 2011). Wildfire and watershed conditions also can affect water quality downstream (Smith et al. 2011; Bladon et al. 2014; Dahm et al 2015). Aggressive fire suppression has increased the density of trees in upstream forests, further increasing evapotranspiration, and reducing streamflow averages from natural conditions (McIntyre et al. 2015; Westerling et al. 2006). Restoration of mountain meadows also increases evapotranspiration losses and decreases average streamflows, while somewhat evening downstream flows (Hammersmark et al. 2008). The large reservoirs around the Central Valley's rim diminish the effects of upland activities on the timing of water supplies and floods to the valley floor. These rim reservoirs also support major upstream diversions upstream of the Delta that shift

1 "Unimpaired flow" is the streamflow that would occur with today's land uses, without upstream dams or diversions; it is the water available today for management. "Natural flow" is what streamflow would be without upstream diversions and land use changes—such as changes in watershed land use and levees—and has some relevance for riparian water rights and studies of natural ecology. Sadly, these terms are often used interchangeably and inappropriately. Both estimates are subject to differences in hydrologic judgment and calculation.

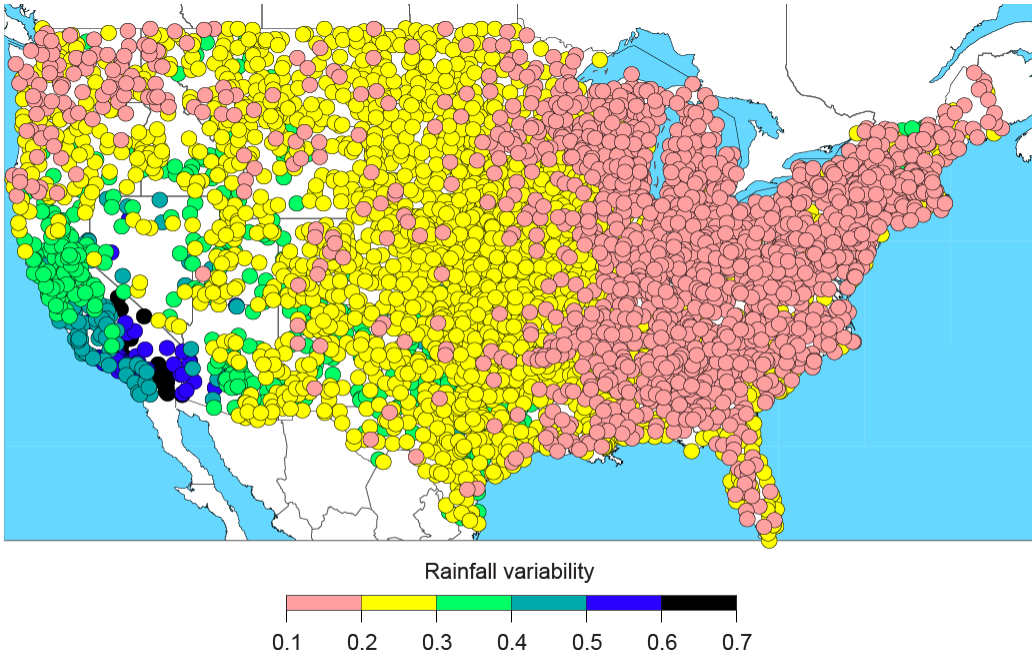

Figure 4 California's special precipitation variability compared to the nation. Note: Dots represent coefficient of variation of total annual precipitation at weather stations for 1951–2008. Larger values have greater year-to-year variability. (Source: Dettinger et al. 2011.)

seasonal and some inter-annual flows into the Delta and supply consumptive upstream agriculture and cities which diminish total Delta inflows.

WATER SYSTEM OPERATIONS IN THE DELTA

Water supply operations in the Delta consist of various water diversions, pumps, and gates in the Delta, as well as releases of water from reservoirs upstream, which are often coordinated to regulate Delta water quality. The operation of Delta pumping and gates varies with water demands, Delta inflows, and Delta water-quality conditions (driven by hourly, daily, and seasonal conditions of Delta tides, inflows, and diversions), and regulations to support endangered fish species. Figure 5 shows major annual Delta inflows and outflows for a wet water year (2011) and a critically dry year (2015).

Local agricultural and urban water diversions, and local water quality—particularly in the western Delta—reflect strong tidal and seasonal variations in water quality. For example, until the early 1900s, the city of Antioch directly diverted Delta water year-round. Beginning in the early 1900s, upstream irrigation diversions reduced summer Delta outflows and increased salinity in the western Delta. Over time, despite the operation of upstream reservoirs, Delta and upstream diversions have greatly reduced Delta outflows (SFEP 2015). Today, Antioch still diverts some of its water use directly from the Delta in wetter months; Contra Costa Water District (CCWD) supplies the remainder of its water (Brown and Caldwell 2011). Likewise, CCWD's intake on Mallard Slough (opposite Chipps Island) is only used in wet periods. As western Delta salinities often vary substantially over the tidal cycle, local diversions sometimes can continue by varying diversion locations and quantities with the tides.

The CCWD delivers about 100 taf yr^{-1} to its customers, with 160 taf of storage capacity in Los Vaqueros Reservoir, giving it considerable operational flexibility for seasonal and over-year storage and blending of different water qualities. This flexibility is enhanced by interties to the East Bay Municipal Utility District's (EBMUD) upstream Mokelumne River diversions and storage. Agricultural water operations in the Delta divert much more water than local cities and vary considerably among the different

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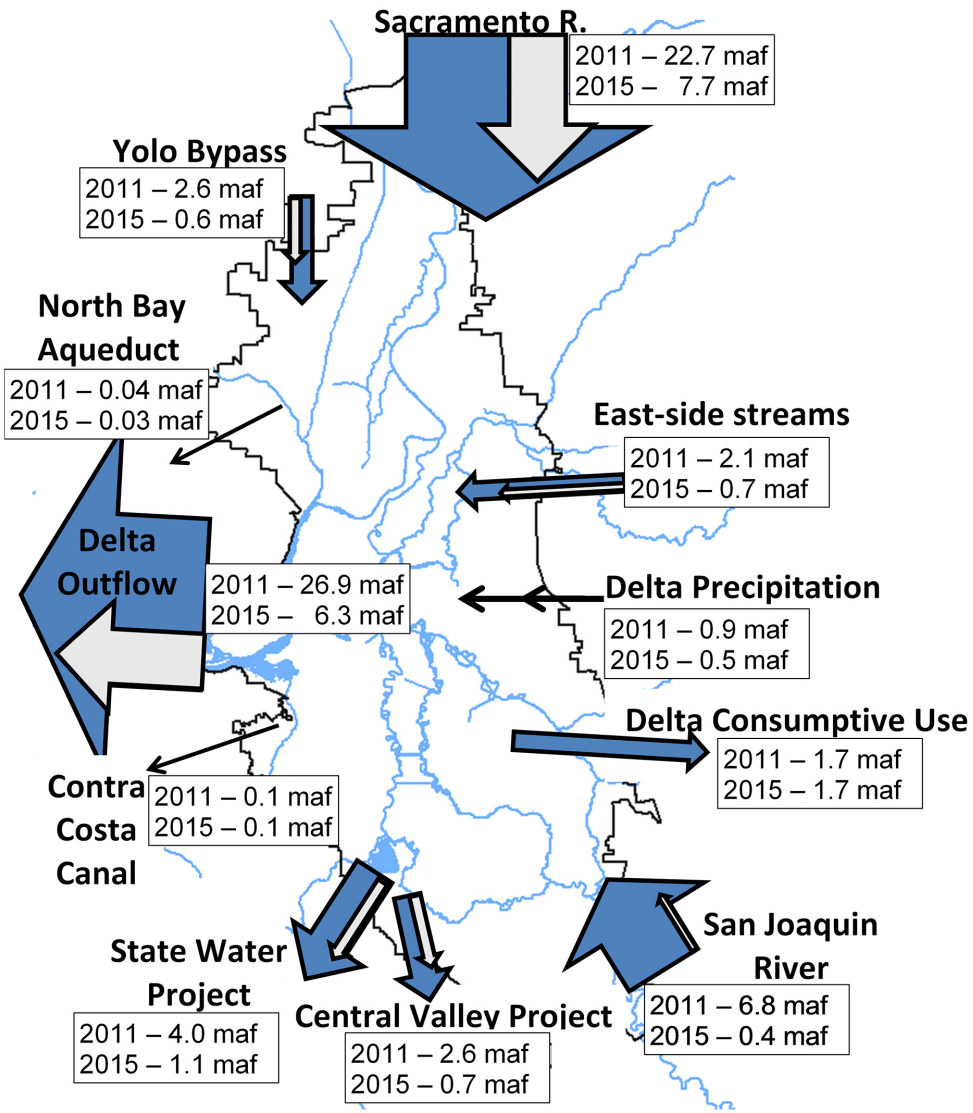

Figure 5 Major Delta net annual inflows and outflows, wet 2011 (solid arrows) and critically dry 2015 (patterned arrows) water years. (Source: CDWR Dayflow data.)

Delta islands, having different elevations, soils, and cropping patterns (Siegfried et al. 2014).

Since the 1950s, water projects in the Delta began pumping large amounts of water. Upstream water diversions also have grown, apparently reducing average annual Delta inflows (and outflows) at a faster rate than direct Delta pumping, as seen in Figure 6. (Upstream diversion growth is not at a statistically significant positive rate, given the high inflow variability. Central Valley unimpaired inflows, not shown, have a slight statistically insignificant increasing historical trend.) Delta project diversions (for the State Water Project [SWP], federal Central Valley Project [CVP], and CCWD) have significantly increased since the 1950s, except for the most recent decade, when droughts, environmental regulations, and reductions in CCWD demands have significantly reduced Delta project diversions.

Large SWP and CVP Delta diversions have more effect on Delta flows than smaller diversions and are regulated more by state and federal agencies. These larger diversions also have more access to

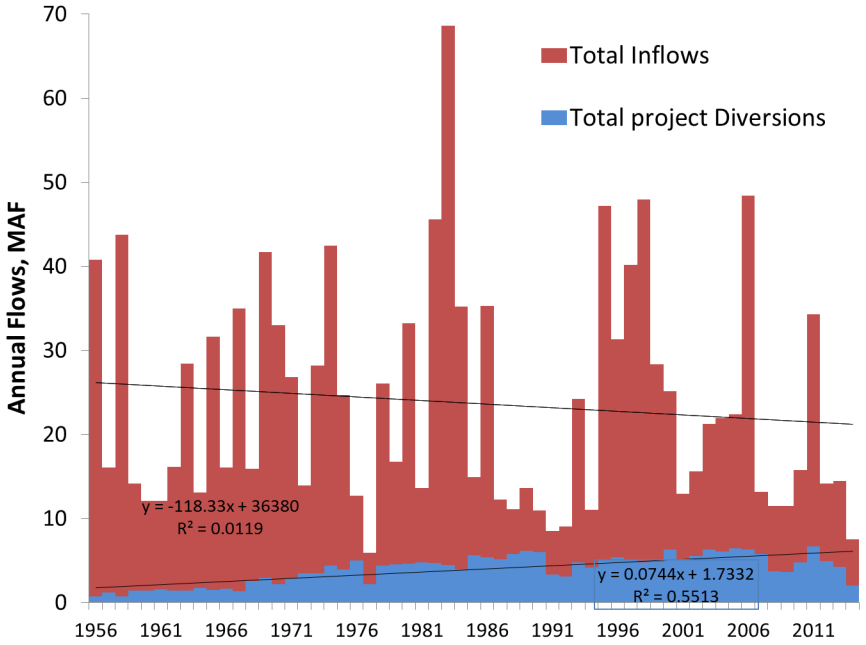

Figure 6 Delta inflows and project diversions from 1956–2014. (Source: CDWR Dayflow data.)

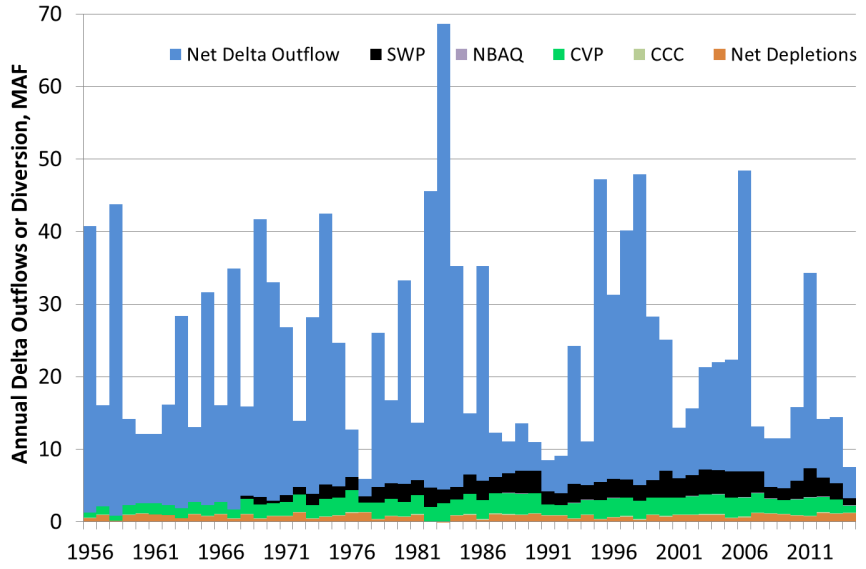

Figure 7 Delta outflows and water project diversions, 1956–2014. Note: Net depletions are in-Delta agricultural net diversions; NBAQ and CCC diversions area each less than 100 taf yr^{-1}. (Source: CDWR Dayflow data.)

water-storage capacity, allowing water diverted in wetter times to be carried over to drier times. The SWP and CVP have much larger intakes in the southern Delta at Banks and Jones pumping plants, respectively. These projects (with a combined physical Delta pumping capacity of about 15,500 cfs, but less permitted capacity) often store water in the off-stream San Luis Reservoir (2.1 maf capacity). Total water project diversions vary considerably by year and season (Figures 6-10). Importing water users also have access to several million acre-feet of groundwater and surface water storage capacity in the southern Central Valley, Southern California, and the Santa Clara Valley to help even out supply availability.

The large southern Delta pumping plants often create reverse net flows (compared to their natural net flow directions) in Old and Middle rivers and other parts of the Delta. The highest pumping rates can even reverse the ebb tide flow, creating uni-directional flow for days or weeks, resulting in concern for native fish species, particularly during migration periods. South Delta pumping brings large quantities of higher-quality Sacramento River water into the southern Delta that benefits water exporters as well as local urban and agricultural diverters. San Joaquin River inflows are generally small, especially in the irrigation season, and often are less than local agricultural diversions in the south Delta in summer.

Various agencies and court decisions limit Delta water supply operations. The State Water Resources Control Board (SWRCB) is the major state agency that regulates in-Delta and upstream water diversions. Federal agencies and court rulings primarily establish endangered species limits on water operations. Regulations on Delta operations include limits on pumping

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rates (usually established by water rights or fish agencies), standards for Delta flows and salinity at various locations to protect Delta water diversion quality, and additional regulations to protect native fish species (SWRCB 2010). These regulations include minimum outflow requirements, regulation of outflows reflected in the location of the 2,000 mg L (or 2 psu near-bed salinity) salinity concentration (so-called X2 requirements), ratios of exports to inflows, reverse flows in Old and Middle rivers, and salinity conditions at particular locations in the Delta (SWRCB 2010).

Changes in regulatory standards in recent years and decades have reduced the reliability of Delta water exports. Early restrictions by the SWRCB were for water quality—primarily salinity—in the western and central Delta. The Federal listing of several Delta fish species as threatened or endangered has added legal restrictions on water export pumping, particularly seasonal limits on negative flows in Old and Middle Rivers in the Central Delta, according to Biological Opinions established by federal fish agencies (the National Oceanic and Atmospheric Administration [NOAA] and the U.S. Fish and Wildlife Service [USFWS]). SWRCB permitting, water quality, and minimum flow conditions now address a broader range of environmental objectives. For those managing Delta project diversions or seeking to transfer water across the Delta, project pumping is reduced or limited by a combination of: (1) Delta outflow requirements, (2) additional Delta outflow required to increase south Delta exports ("carriage water"), (3) required releases from storage from SWP and CVP storage reservoirs under their Coordinated Operating Agreement, and (4) other salinity, flow, and endangered species regulatory limits (both internal Delta flows and Delta outflows). Since 2007, newer environmental restrictions have greatly limited water exporter's abilities to capture unregulated winter inflows to the Delta, and forced the more aggressive operation of reservoir storage to supply water for Delta diversions (SWRCB 2010).

In drought, some environmental flow requirements are relaxed, and additional limitations emerge as a result of water right limits and curtailments. Future water exports from the Delta could be shaped as much or more by the health of native fish species as by climate, drought, and water demands.

WATER DELIVERY RELIABILITY ESTIMATION

The reliability of water supplies for agriculture and cities is often difficult given California's highly variable hydrology, and its complex environmental and water rights regulations. Given the system's complexity and the wide range of conditions it must prepare for, the reliability of water deliveries are estimated using computer-based simulation models (USBR 2016). The most routine estimation of water delivery reliability directly from the Delta is the California Department of Water Resources' biannual SWP delivery capability report series (CDWR 2015).

Traditional modeling estimation of reliability employs a historical record of unimpaired streamflows (perhaps modified for climate change) to represent hydrologic variability. These flows are then entered into a simulation (computer) model that includes representations of water demands, regulations, operating policies, and infrastructure for a specified current or projected future time. As an example, Figure 8 shows the simulated volume of total Delta water project diversions that could occur in each water hydrologic year shown on the x-axis, assuming 2015 regulatory and water demand conditions and the existing and proposed infrastructure and operation of major Delta water projects. The resulting water delivery volumes are then plotted in terms of their frequency, as in Figure 9. For example, with existing facilities and operation, total Delta water project diversions are predicted to exceed 5 maf yr^{-1} in about 56% of years, whereas under the BDCP facilities and operation proposal (similar to the more recent WaterFix proposal), exports exceed this amount in about 62% of years. In these examples, the proposed alternative changes represented in the figures would raise the ability to divert water from the Delta in wetter years, and decrease water exports in about 25% of drier years compared with current infrastructure (CDWR 2015).

Figure 9 also includes levels of Delta project exports that actually occurred during the severe drought years of 2014 and 2015. These are substantially below the worst levels of exports expected from the simulation modeling, which omitted the easing of Delta outflow requirements during these drought years. Although modeling of water supply reliability is important and offers insights to decision-makers,

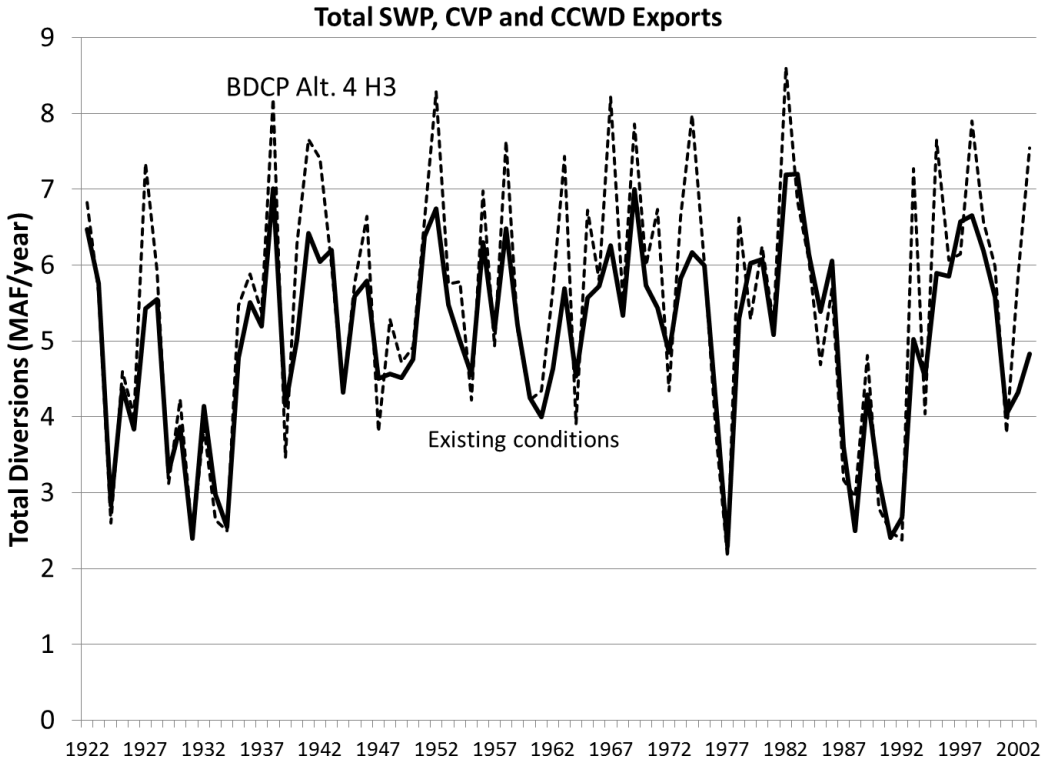

Figure 8 Total Delta water project deliveries (SWP, CVP, and CCWD) estimated over historical hydrologic conditions (water years) with 2015 level of development and regulations (black solid line with diamond markers) and with BDCP Alternative 4 H3 conditions. (Source: Data from CDWR 2015.)

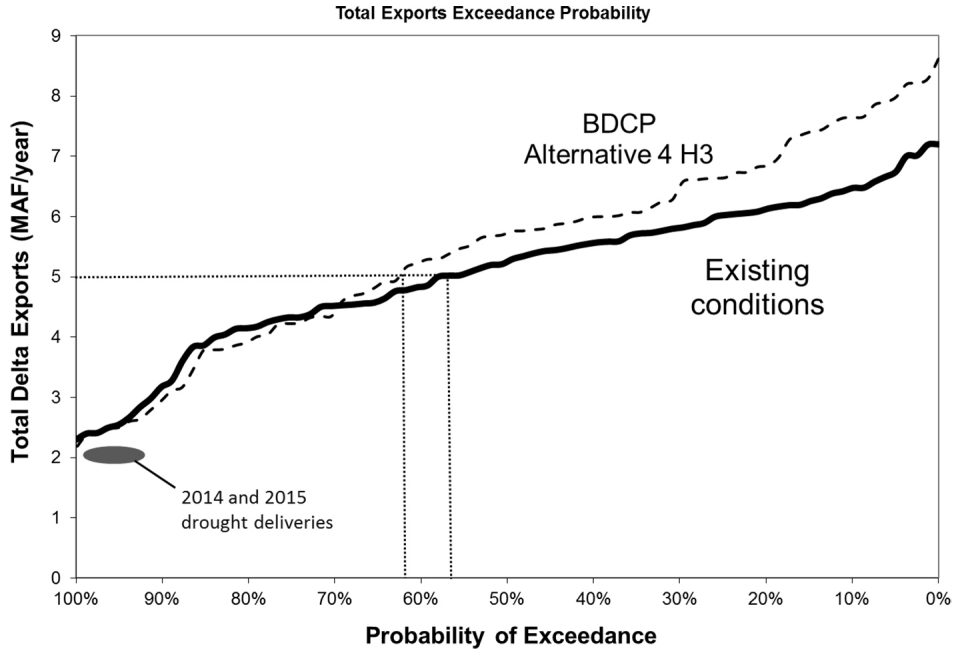

Figure 9 Estimated probability distribution of total Delta project water deliveries (CVP, SWP, and CCWD) for 2015 and BDCP Alternative 4 H3 conditions. (Source: Data from CDWR 2015.)

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actual results are likely to vary, and the results of different modeling efforts are unlikely to entirely agree.

The original plans and contracts for the SWP included additional project facilities (particularly a large 22,000 cfs peripheral canal around the Delta) to increase water exports. With additional environmental regulations in recent decades, the reliability of Delta export water deliveries has deteriorated substantially. These changes from expectations in the late 1970s and early 1980s have led to the use of a more integrated portfolio of water management alternatives—especially groundwater use and banking, conservation, and water markets—to bolster reliability. For agriculture in the southern Central Valley, the loss of Delta exports has led to increased groundwater overdraft.

WATER QUALITY

Water quality is a critical aspect of water delivered from the Delta. Contaminants of major concern include salinity and disinfection by-product precursors (especially bromide and dissolved organic carbon) (CCWD et al. 2005; Chen et al. 2010). Salinity affects crop yields in the Delta and in water-importing areas, and limits urban use and reuse of some Delta waters (Medellín-Azuara et al. 2014, 2008; Shoups et al. 2005). Removing dissolved salt from diverted water would require expensive water treatment for urban users and would be prohibitively expensive for most agriculture.

Contaminants and water quality for urban and agricultural water supplies vary considerably in the Delta with location and over time (Table 1, Figure 10). Organic carbon in Delta waters is from drainage of peat soils in the Delta and other sources upstream (CCWD et al. 2005; *http://www.water.ca.gov/waterquality/drinkingwater/*). Bromide is mostly from sea water, and secondarily from San Joaquin River drainage.

Major sources of salt in Delta waters include sea water from San Francisco Bay and agricultural drainage from the San Joaquin River, as well as some salts from upper watersheds and other agricultural and urban wastewaters. Agriculture in the Delta concentrates salt from irrigation water and discharges it back into the Delta. (*http://www.water.ca.gov/waterquality/drinkingwater/*; CCWD et al. 2005) Delta outflows remove most salt from the Delta. Export pumping removes some salt, to the detriment of export water quality. As sea levels rise, more Delta outflow or changes in Bay and Delta geometry will be needed to repel ocean salinity (Fleenor et al. 2008).

ECONOMIC MOTIVATION FOR DELTA WATER AND LAND MANAGEMENT

Most human management of water and land in the Delta supports the economic purposes of land owners and water users. Most water diverted from the Delta upstream and within the Delta is for commercial agriculture, with almost all remaining diversions

Table 1 Water quality for selected stations in the Delta

Location/ Constituent	Mean TDS (mg L^{-1})	Mean EC (µS cm^{-1})	Mean Chloride (mg L^{-1})	Mean Bromide (mg L^{-1})	Mean DOC (mg L^{-1})
Sacramento River at Greens Landing	100	160	7	0.018	2.5
North Bay Aqueduct at Barker Slough	192	332	26	0.015	5.3
SWP Clifton Court Forebay	286	476	77	0.269	4.0
CVP Tracy Pumping Plant	258	482	81	0.269	3.7
CCWD Intake at Rock Slough	305	553	109	0.455	3.4
San Joaquin River at Vernalis	459	749	102	0.313	3.9

Source and notes: CCWD et al. 2005, Sampling period varies, but generally is between 1990 and 1998. mg L^{-1} = milligrams per liter, TDS = total dissolved solids, EC = electrical conductivity, µS cm^{-1} = microSiemens per centimeter, DOC = dissolved organic carbon.

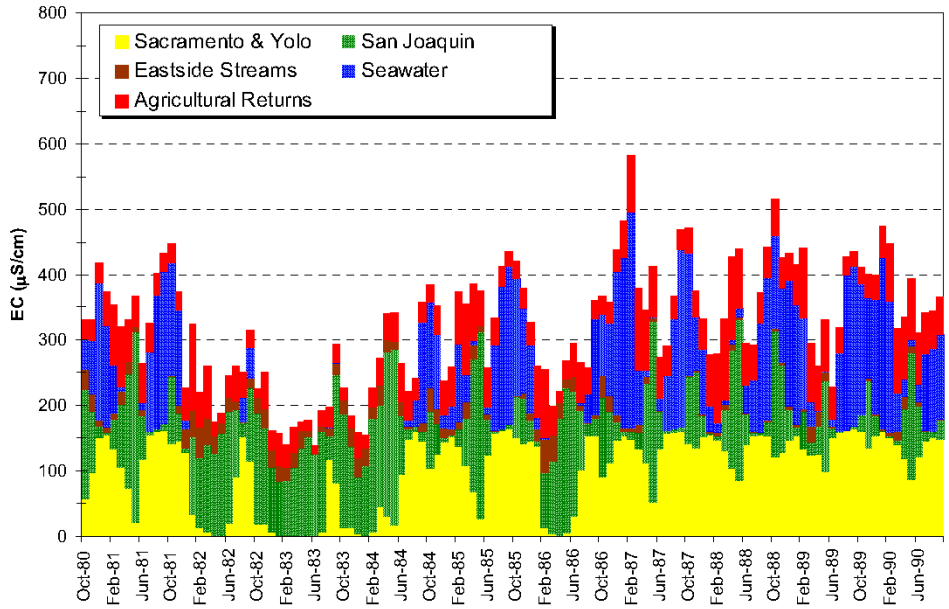

Figure 10 Sources of electrical conductivity (salinity) at Empire Tract in the eastern Delta for water years 1981–1990, Stockton water intake location. (Source: CCWD et al. 2005.)

being for urban uses, as summarized in Table 2 (Lund et al. 2010).

The demand for water from the Delta is significantly affected by changes in water users and the availability and cost of other water supplies. Higher agricultural commodity prices bring pressure to increase crop production and irrigation. Growing populations displace some agricultural land and irrigation, but can increase urban water demand, although at a decreasing per capita rate depending on urban water conservation, landscaping, and population densities. Reductions in per-capita urban water use will continue to dampen growth in urban water use, and perhaps reduce it a bit (Wilson et al. 2016). For southern California and the San Francisco Bay Area, which are the largest urban users of Delta water, non-Delta supplies include generally expensive options for wastewater reuse, local stormwater collection, brackish and ocean water desalination, less expensive brackish desalination, and investments and costs for water conservation. For the southern Central Valley, alternative water supplies are quite scarce, given its dry climate, immense agricultural water demands, and the long-standing natural reuse of most return flows, wastewater and stormwater in local aquifers and streams. As net groundwater use in the southern Central Valley is reduced to eliminate groundwater overdraft, some water uses will be discontinued and demand will likely increase for other water sources, especially the Delta (Nelson et al. 2016; Dogan 2015).

Tanaka et al. (2011) examined the costs of changes in Delta exports in terms of scarcity costs from diminished water use and operating costs for alternative water supplies. Although these annual costs could be as high as $3 billion per year for ending Delta exports entirely, California's water system appears able to withstand some significant changes in Delta water availability, albeit at substantial expense. Sunding (2013) also estimated the economic benefits of improvements in water supply reliability for some long-term Delta conveyance options as part of the Bay Delta Conservation Plan (BDCP) effort. The economic effects of reduced Delta water availability are dampened by the allocation of scarce water to the most economically valuable agricultural and urban uses by farmers, water utilities, and water markets.

The development of land with levees and drainage systems for farming and towns also has changed water flows and reduced wetlands and aquatic habitat (Medellín–Azuara et al. 2012). Historical Delta land reclamation for commercial agriculture reshaped the Delta, and continues to drive how Delta

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Table 2 Gross water diversions from the Delta and economic value (about 1998–2009)

Use	Average annual gross use (taf yr^{-1})	Typical incremental economic value ($ af^{-1})
Upstream diversions for agriculture	9,650	$100–$280
Upstream diversions for cities [a]	1,450	$500+
In-Delta agriculture	1,150	$120–$180
In-Delta cities	150	$500+
Export agriculture	3,400	$150–$550
Export cities	1,700	$500+
Total upstream	11,100	
Total in-Delta	1,300	—
Total export	5,430	—
Total diversions	17,830	—
Total Delta outflow	17,140	

a. Includes San Francisco Public Utilities Commission (SFPUC) and EBMUD diversions.
Sources: CDWR, C2VSIM, Dayflow, and CALVIN and SWAP model results.

lands are managed (Thompson 1957). Agricultural land in the Delta is often sold for $4,000 to $10,000 per acre, less than much of California's agricultural land, although urban land has much higher economic value (California ASFMRA 2013). (For example, Metropolitan Water District of Southern California (MWDSC) recently bought 20,000 acres on four subsided islands for $8,500 per acre.) Some subsided Delta lands have been abandoned because of high seepage and costs and risks of levee repair compared to the revenues available from these lands (Thompson 1957; Deverel et al. 2015). Upstream leveeing and drainage of lands have brought several other problems through accelerated flood waves, reduced seasonal habitat for migratory fish and birds, reduced supplies of sediment to the Delta (Wright and Schoellhamer 2004), and reduced some potential for groundwater recharge. The economics of land and water use in the Delta and elsewhere drives most Delta management.

DROUGHT

Droughts have always brought innovations for water management in California, such as the development of irrigation systems in the late 1800s, the development of major dams after the 1930s drought; the development of urban water conservation, water markets, and integrated urban water planning from droughts in the 1970s and 1980s; and the development of new Delta governance and some improvements in water conservation and data from the 2009 drought. The current drought has similarly tested the current water system, highlighting weaknesses, bringing focus and attention to problems, and motivating solutions. So far, this most recent drought has led to major legislation and policy changes statewide in groundwater overdraft, urban water conservation, and water rights administration (Hanak et al. 2015).

For the Delta, the current drought has brought consideration of salinity barriers for several parts of the Delta (the first since 1977), installation of a major salinity barrier at False River in 2015, reduced freshwater inflows; greatly reduced Delta water exports; lower counts of Delta Smelt and other native fishes; expanded areas of water hyacinth, Brazilian waterweed (*Egeria densa*) and other invasive species (clams, fish, other plants, phytoplankton, and zooplankton), and greater attention to the Delta overall. This drought also has brought higher temperatures in the Delta, a likely precursor of future climate warming (Williams et al. 2015), with likely effects on ecosystems, water quality, and perhaps on human water demands.

Direct water diversions from the Delta fell dramatically during this drought, with levels not

seen since the 1976–77 drought. These reductions are more than would be anticipated based on water delivery capability studies (Figures 9 and 10), and reflect some of the difficult-to-predict problems and opportunities involved in real-time drought management. For water users in southern California, the southern Central Valley, and San Francisco Bay Area, the drought led to serious and sometimes unprecedented cut-backs in Delta supplies and much higher market values for water (Howitt et al. 2015). The CVP was unable to meet all exchange contractor demands, and many contractors were given zero allocations for the first time (*http://www.usbr.gov/mp/cvo/deliv.html*).

Economically, most in-Delta, upstream, and water importing areas have managed well during the drought, with economic suffering far less than the proportions of lost water supply (Medellín–Azuara et al. 2015; Howitt et al. 2015; Hanak et al. 2015). Access to groundwater, system flexibility, water market transfers and exchanges, and preparation create much of this robustness. New laws requiring groundwater users to implement sustainability plans should improve long-term water supply reliability, but require some additional land fallowing (Nelson et al. 2016). Better and more comprehensive accounting of consumptive use, employing remote sensing, or other cost-effective approaches in the Delta and statewide, could improve management. The drought experience indicates that short interruptions of Delta supplies, if properly prepared for and not too frequent, can be endured economically with sizable local yet modest statewide costs (Howitt et al. 2015).

Drought effects on water quality and ecosystems have not yet been well investigated. It seems likely that the higher temperatures during this drought and the longer residence times resulting from reduced inflows, reduced Delta project pumping, and installation of a major Delta barrier will have affected many aspects of Delta water quality and the movement and success of different aquatic plants and animals. These effects might ultimately affect the quantity and quality of water supply deliveries.

CHALLENGES FOR DELTA WATER SUPPLIES

For decades, water diversions upstream or within the Delta have been the primary source for expanding agricultural and urban water use in California (Figures 11 and 12). Water use upstream of the Delta continues to grow (Figures 6 and 12). But, after decades of continuous increases—interrupted only by occasional droughts (Figures 6 and 7)—recent years have seen large reductions in Delta water exports, because of drought and environmental regulations.

The current Delta water supply system is unsustainable. Climate change, rising sea levels, and additional environmental regulations can be expected to reduce the ability of Delta water projects to divert water from the Delta (Anderson et al. 2008; Fleenor et al. 2008). Fleenor et al. (2008) estimated that a 1-foot sea level rise would require almost 500,000 acre ft yr^{-1} of additional Delta outflow to meet salinity requirements, about a 10% reduction in overall Delta project diversions. Larger sea level rises, a warming climate, and drier extremes would increase difficulties in sustaining

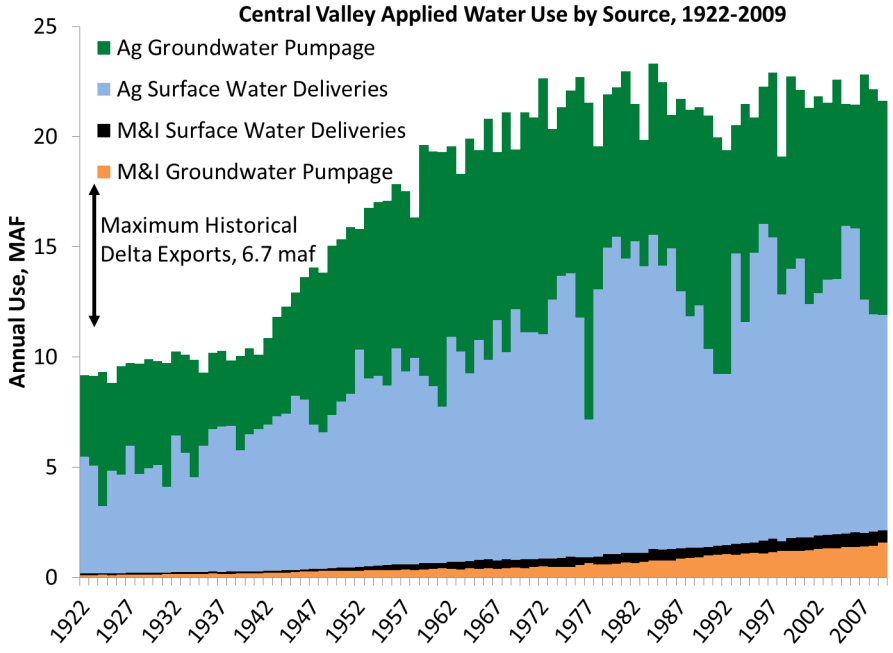

Figure 11 Central Valley gross water use by source, 1922–2009. (Source: CDWR C2VSIM data.)

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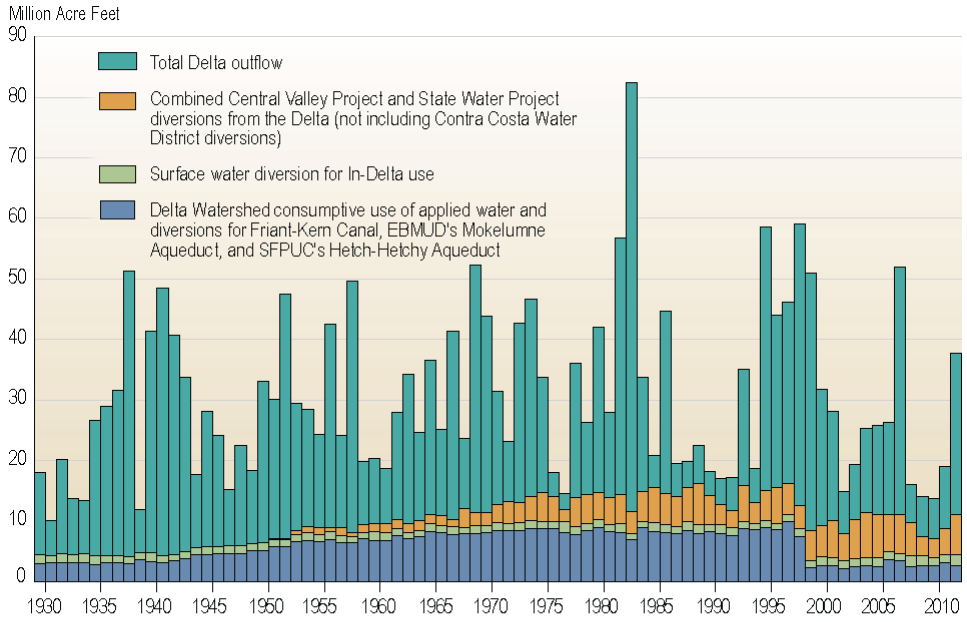

Trends in Destinations and Uses

Period	Average Annual Total (MAF)	Outflow	in-Delta	Exports	Delta Watershed
1930 to 1949	25.80	81%	5%	0%	14%
1990 to 2005	31.71	67%	4%	4%	24%
1950 to 1969	34.34	51%	5%	15%	29%
1970 to 1989	32.85	48%	4%	17%	31%

Note: Data from 1930-1997 comes from the *Delta Vision Blue Ribbon Task Force 2008 Final Report* and data

Figure 12 Historical Delta water availability, diversions, and outflows. Note the discontinuity in the later 1990s, probably reflecting use of incompatible water accounting systems. (Source: California Water Plan 2013, Figure D7.)

recent Delta diversion levels. Figure 13 shows the results of a federal study that examined change and variability in total Delta exports for different climate conditions (USBR 2016), with climate change more likely to reduce Delta exports. Most climate change predictions show some loss of runoff for California, if only from additional evapotranspiration from warmer watersheds, particularly south of the Delta (Woodhouse et al. 2016; Null et al. 2010). Increased wetland surface area from habitat restoration or inundation with sea level rise, might somewhat increase evaporative losses of freshwater and reduce available water supply, depending on pre-restoration land and water use.

Water demands on the Delta are likely to increase because of reductions in water availability from climate change, eliminating groundwater overdraft; upstream and in-Delta efforts to restore native ecosystems; diminishing supplies from Delta tributaries, the Colorado River, and other water sources; growing profitability of agriculture; and growing urban populations (Wilson et al. 2016; Nelson et al. 2016; Dogan 2015). Agriculture and cities in the southern Central Valley currently overdraft groundwater by 1 to 2 maf yr^{-1} as a major water source (Faunt et al. 2009). The growing economic value of Central Valley agriculture and state policy to end groundwater overdraft under the Sustainable Groundwater Management Act (SGMA), will raise economic demands for additional water from the Delta and upstream sources (Nelson et al., 2016; Dogan 2015). Greater urban water use efficiencies, local water supply development, reduced irrigated land area from salinization and urbanization, greater water rights enforcement, and

environmental regulations will somewhat reduce overall growth in Delta water demands.

The physical reliability of water quantity and quality for diversion is threatened by increasing water demands for ecosystem management and growing numbers of endangered species (which reduce flexibility in water diversion operations), risks of levee failure from subsidence, floods, earthquakes and sea level rise, more stringent water quality and drinking water standards, increasing upstream water diversions, and climate warming (Lund et al. 2010; Anderson et al. 2008). If the trajectory of recent decades continues, the average quantity of water available for diversion from the Delta will likely diminish, particularly in drier years (Figure 13).

As water becomes less available from the Delta, the incremental economic value of water diversions from the Delta will likely rise. Overall, economic demand for Delta diversions seems likely to grow, while inflow to the Delta seems likely to decrease. Delta management will attract growing scrutiny, and, as a result, continuing to expand exports from the Delta could entail increasing difficulties.

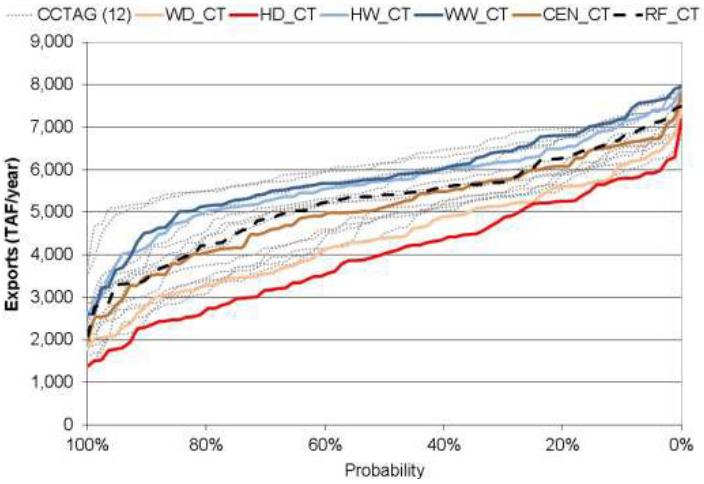

Figure 13 Annual exceedance plot of total Delta exports for an ensemble of climate scenarios with current trends socioeconomic conditions. (Source: USBR 2016.)

OPTIONS AND OPPORTUNITIES FOR DELTA WATER SUPPLIES

Many suggestions have been made to address these changes in water supply reliability for and from the Delta. Water conservation, wastewater reuse, water markets, desalination, conjunctive use of surface and groundwater, surface storage expansion, shifting Colorado River water to urban uses, and changes in Delta water diversion infrastructure (including major diversion tunnels) have been suggested most seriously (CDWR 2013, 2015b). Many of these activities are being implemented, some with considerable success.

Given growing upstream uses and water uses for ecosystems and ending groundwater overdraft, greatly expanding Delta and upstream water diversions would involve great expense in increasing export conveyance and storage capacities for increasingly rare and diminished "surplus" water in wet years. Modest expansions—and even retention—of existing Delta diversion quantities, relative to "No Action" cases, are envisioned under WaterFix, but require expensive and controversial changes in regulations and infrastructure for moving water across the Delta in coordination with upstream and downstream water storage (CDWR 2015b). Water availability and regulations seem likely to limit the ability to use expanded storage and conveyance infrastructure under most hydrologic conditions (Lund et al. 2014).

So far, the greatest successes have come from a portfolio approach to water management, initiated locally and regionally. An orchestrated portfolio of water supply and demand management actions and incentive policies often provides more reliable, economical and environmentally-effective performance (Table 3) (MWDSC 2015; SCVWD 2010). Such a mix of actions and policies also increases flexibility for water systems to adapt to changing conditions, such as droughts, new environmental regulations, and climate change. This more integrated resource management approach often involves internal and external partners who coordinate activities over a range of conditions using water markets, prices, and contracts. The success of urban areas in the current drought is substantially as a result of these mostly local and regional activities.

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Table 3 Elements of modern water supply system portfolios

Supply

- System re-operation
  - Surface and groundwater reservoirs
  - Conveyance and interconnection
- Conjunctive use of surface and groundwater (recharge and pumping)
- Expanded conveyance & storage
- Urban reuse
- New water treatment
  - Wastewater reuse
  - Ocean or brackish desalination
  - Contaminated aquifers
- Stormwater capture
- Source protection

Demand Management

- Agricultural water use efficiencies, recharge, and reductions
- Urban water use efficiencies (e.g., plumbing codes) and reductions
- Ecosystem water use efficiencies and allocations

Incentive Policies

- Pricing
- Markets and exchanges
- Subsidies, taxes
- Education

Agriculture also has benefitted during the drought from these actions, but has relied more on pumping groundwater (Howitt et al. 2015).

Even with a portfolio approach, the Delta faces strategic issues of cross-Delta water conveyance, levees, and ecosystem management, all of which affect water supply reliability. The Delta might be California's best example of how major changes in basic conveyance infrastructure, changed diversion locations, operations, channel geometries, etc., if properly done, have potential to provide both water supply and ecosystem improvements (although not necessarily for all water users and all species) (Lund et al. 2010). The effectiveness of water storage initiatives throughout the Central Valley is reduced without better ability to move water across the Delta (Lund et al. 2014; Dogan 2015). The value of cross-Delta conveyance capability increases substantially with a drier, warmer climate and the end of groundwater overdraft (Harou et al. 2010; Dogan 2015; Buck 2016).

Challenges to Delta water supplies are substantial and growing, and will require improvements in scientific and technical analysis and information for local, state, and federal decision-making. Changing conditions and a wide range of long-term and short-term options make it important to realistically and quantitatively assess mixed alternatives for the Delta to supply water in the future.

ANALYTICAL CAPACITY

Water agencies in California spend substantially on analysis of water problems and management. A major difficulty in water supply management and analysis is the lack of a common and complete water accounting and model development across state agencies and programs (Escriva–Bou et al. 2016; Grantham and Viers 2014). Water use by surface water rights holders has been reported poorly, if at all, until very recently. Only applied and not consumptive use is reported. Groundwater use remains unreported, and is estimated partially, using different models and water balances. Return flows from users back to the system are coarsely and differently estimated by different agencies. Lacking a common authoritative framework to account for water use and availability, different state programs develop different partial accounting frameworks and models, conflicts deepen, and transparency diminishes. A common accounting framework and improved data collection would improve the usefulness and transparency of water data for analysis, enforcement, and management.

Most regional and many local water agencies maintain and use computer models of their water systems to provide a more coherent picture of their water use and management. State and federal agencies maintain dozens of computer models of water management and water availability, with little coordination.

Modeling efforts have focused predominantly on surface water, and been rooted in traditional infrastructure development and operations, despite the growing importance of groundwater, conjunctive use of surface and groundwater, water conservation, and water markets. Most water supply analysis has been based on comparison of results with and without proposed changes in facilities or operations. This comparative approach was attractive in the era of large-scale infrastructure development, because it required less attention to model testing against field data, but is unlikely to serve the state well in the future (Close et al. 2003). The tighter water management required for implementing the Sustainable Groundwater Management Act (SGMA), water rights curtailment during drought, and environmental flows imply a performance standard for water supply modeling success based on field conditions, rather than comparisons of model results.

Today, two modern groundwater models exist for the Central Valley: the state's California Central Valley Groundwater–Suface Water Simulation Model (C2VSIM) (Brush et al. 2013) and the U.S. Geeological Survey's Central Valley Hydrological Model (CVHM) (Faunt 2009). Despite their great advances over previous models, large differences remain between them, mostly reflecting fundamental uncertainties in estimating water availability and use. Implementing the state's new Sustainable Groundwater Management Act would seem to require reconciling and improving these representations, which also will affect understanding Delta water availability and demands, and aid in managing environmental flows and surface water rights.

Unfortunately, fragmentation, inconsistency, and poor or delayed documentation of modeling, both among and within state agencies, often leads to opacity and confusion. For water supply system models, the state Department of Water Resources Modeling Support Branch has the CALSIM II, unreleased CALSIM III (now nearly 10 years in development), and CalLite models (Draper et al. 2004; Islam et al. 2011). The same Department's Planning branch has a proprietary WEAP (Water Evaluation And Planning) model for the California Water Plan. Operators of the State Water Project employ both a large spreadsheet model and their own different version of CalSim II, which are not publicly available. The State Water Resources Control Board employs a different WEAP model for developing environmental flow criteria. The federal Bureau of Reclamation employs the CALSIM models (which it co-develops with CDWR), but has a separate version of CalLite which runs on a different proprietary software platform. Each of these models involves different groups of consulting hydrologists and engineers, often with their own model versions and without substantial documentation. Although this diversity of modeling capability supports a range of modeling approaches, the degree of fragmentation and compartmentalization of information seems to contributes to the opacity and expense of Delta water supply operations modeling and discussions, and diminished development and use of insights from modeling analysis. The difficulty in modifying CALSIM II to analyze new scenarios has led some consultants to develop spreadsheet-based models of the CVP–SWP system.

Typically, model simulations are reasonably reliable for near-average hydrologic conditions, but are usually less reliable for extreme hydrologic conditions or finer time-steps and locations. Simulated operations in drought, for example, often show unrealistically low storage levels while maintaining deliveries, but actual operators commonly hedge to store more water (delivering less) in case drought conditions worsen. These deficiencies in modeling may lead to errors in identifying and estimating project benefits and beneficiaries in a comparative analysis of with and without project conditions.

The California Water and Environment Modeling Forum (CWEMF) has fostered useful conversations and presentations on model and data development among technical audiences, including external reviews of some models. However, this largely voluntary effort has not yet been effective in fostering systematic coordination and quality improvements in model and data development and applications. The many state agencies and programs have no common discussion or clear strategic vision of the models and data needed and how they should be developed and maintained to support water management and policy. As the need for more common and widely-accepted water accounting becomes more important, state agencies need to lead in developing a common multi-agency technical data and modeling program.

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Modeling results will inevitably differ. Modeling results for BDCP alternatives in 2013 often differed by 200 to 700 taf yr^{-1} in average water deliveries and flows, when evaluated by different models and modelers (MBK Engineers and Dan Steiner 2014). This reflected differences in model errors and differences in the professional judgments of the consultants. This divergence also reflects something of the uncertainties inherent in using model runs to estimate water supply performance over long planning horizons. The economic incentives to contest even unavoidable modeling error are apparent when a modeling difference of 10 taf yr^{-1} for water valued at $300 af, is worth $3 million per year or a long-term, present value of $60 million at 5% interest.

The size and unavoidability of technical uncertainty and variability in water availability is illustrated by statistical uncertainty in the average flow of the Sacramento River, California's largest river. The measured long-term average annual flow of the Sacramento River is 21.7 maf, but there is a 32% statistical chance that the true long-term average differs more than 1 maf yr^{-1} from this value[2]. Such unavoidable uncertainty has considerable economic value.

Water policy and management in California, and the Delta, must deal with sizable and unavoidable uncertainty. To discourage unnecessary and counterproductive squabbles, state regulators and water rights administrators must act with reasonable and firm authority and due process. This reasonableness must include adequate dedication to continuous improvement in modeling, data, and water accounting. Technical information and insights should be developed transparently, better organized, and better articulated and documented. Decision-making processes should be organized to better support and assimilate the development, analysis, and discussion of promising technical and policy alternatives.

2 With an average annual flow of 21.7 maf, and a standard deviation of observed annual flow of 10 maf over roughly 100-years of record, the standard deviation of the mean is 1 maf/year (=SD_{sample}/SQRT(n)), so there is a 68% confidence range the true mean annual flow of the Sacramento River is 20.7-22.7 maf/yr, and a 92% chance that the average is more than 100 taf in error, neglecting climate change.

OBSERVATIONS AND DIRECTIONS FOR WATER SUPPLY SCIENCE AND ANALYSIS

Several observations, questions, and directions for further work seem apparent for policy-makers, scientists, and technical managers.

1. California is a mostly dry place where climate and geography have motivated development of extensive water supply and flood management infrastructure to serve economic purposes of human settlement and agricultural production. This infrastructure now also must serve newer, and sometimes conflicting, environmental objectives.

2. The Sacramento–San Joaquin Delta is California's major hub for transferring water from wetter to drier regions. Outflows from the Delta have been reduced mostly by diverse upstream diversions and secondarily by in-Delta diversions, which are mostly from state and federal water projects (SWP and CVP) (Figures 6 and 13). Internal flows in the Delta are significantly affected by channel geometries and the location and operations of major water project pumping plants.

3. California's nearly statewide water network makes most of the state interdependent for water supply, water quality, flood management, and ecosystem performance, including remote upstream areas and water users in the Bay Area, southern California, the Central Valley, and particularly the Delta. Local interests tend to protect local interests and avoid comprehensive solutions (Madani and Lund 2012). Statewide efforts are needed to help bring local interests together while regional and statewide interests are addressed.

4. The complexity and diversity of California's water supply system makes it rich in physical possibilities for management—and remarkably reliable, robust, and adaptable to change and disruptions (Tanaka et al. 2011; Harou et al. 2010; Medellín–Azuara et al 2015; Howitt et al. 2015). Many agencies and the state benefit from diverse portfolios of water sources, water use management, and coordinated operations to improve water supply reliability, reduce costs, and reduce effects on Delta and upstream ecosystems. For example, when a SWP contractor

in northern California conserves water or is protected from floods by a state reservoir, the water retained becomes available for others in the SWP, including those in Southern California.

5. The Delta, as a hub, is perhaps the water system's most vulnerable component (Lund et al. 2010; Tanaka 2011; Dogan 2015; Buck 2016). Its management and condition often affect economic and ecosystem performance throughout California. The management of such a central element will always engender controversies and conflicts among upstream, in-Delta, and water-importing regions.
6. The failure to authoritatively and systematically quantify actual water rights, diversions, and return flows (including groundwater flows) is a major shortcoming and hinders management of water supplies (Escriva–Bou et al. 2016).
7. Fragmentation of water measurement, accounting, and analysis often leaves the state with inconsistent, insufficient, and often incomprehensible analyses of water management performance and alternatives.

Some directions for scientific and technical work on the reliability of water supplies taken directly and indirectly from the Delta include:

1. Better and more systematic estimates are needed of water supply reliability, given many ongoing and impending changes from sea level rise, climate change, Delta levee conditions, worsening conditions of native species, upstream diversions, and difficulties making decisions with a myriad of governmental agencies and interests. This challenge calls for the integrated attention of physical, social, and biological sciences and engineering—and more effective coordination among different water agencies, uses, interests, sources, and facilities.
2. More explicit estimates of trade-offs among California's water supply and environmental objectives for the Delta would better inform policy discussions. Delta conflicts are not only between water supply reliability and ecosystem health, they also involve in-Delta flood safety, property protection, land development, recreation, and other local issues. Water supply interests often involve different upstream, in-Delta, and water export diversions and water quality. Ecosystem interests are spread across recreational fisheries and upstream, anadromous, and resident native species. In some cases, it might be best to pursue compromise–reconciliation approaches to jointly provide ecosystem and economic benefits from land and water use (Moyle 2015; Rosenzweig 2003).
3. Explicit analysis and comparison of portfolios of water management activities would better inform governmental agencies and interests of the trade-offs from different management activities and policies. Such work should identify more promising sets of activities and give insights about their selection, implementation, and adaptive management as conditions change. This approach should explicitly integrate economic and environmental performance objectives using models that integrate Delta water management and groundwater and surface water management in and outside of the Delta. Many components for such analyses are available, but need to be made more transparent and accessible, technically integrated, and consistently supported across agencies.
4. An authoritative water accounting framework is needed for the state to quantify water rights, diversions, and discharges or return flows to support management of the Delta, groundwater, environmental flows, and surface water (Escriva–Bou et al. 2016). This will require development of more authoritative means for estimating water balance components as part of such a framework, such as evapotranspiration, groundwater, etc. This framework must be common across state agencies.
5. Better organization and documentation of data and analysis, and more consistent and authoritative development and availability of such data are needed (Escriva–Bou et al. 2016). Information for water accounting remains underdeveloped and often incoherent. A disadvantage of decentralized water management and governance is the fragmentation of data, information, and analyses. More common documentation and data management would be helpful overall, and make analyses more comparable and insightful.

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6. The sociology of water problems is often harder than their more purely technical aspects. More explicit thinking about the organization of Delta governance and analysis might be helpful. Game theory has some potential to improve understanding of Delta management and water supply conflicts and for crafting more durable adaptive management strategies (Madani and Lund 2012).

Organizing Delta discussions and policy processes to be more data-driven and performance-driven might be helpful. Providing information for such discussions is a major problem for technical managers in the state—and starts with reporting water use. Agency decision-making processes also need to be organized to better ensure integrated scientific and technical results, and insights into their deliberations.

CONCLUSIONS

All water supply systems require cooperation and engender some forms of conflict. This game theory aspect applies to water supply reliability and the Sacramento–San Joaquin Delta as well. The many conflicts of the Delta reflect the differing benefits to local and statewide interests from a functioning Delta. Scientific and technical work on the Delta and its management, which have implications for water supply reliability, can better highlight the benefits to all interests from cooperation and relative trade-offs in management and policy. Although better technical and scientific work should aid in the difficult strategic and operational decision-making needed for the Delta, it cannot fully overcome the fundamental trade-offs necessary for decisions involving different benefits and costs to different interests. Decision-makers must actively seek and support scientific insights to inform these decisions. Developing and using science for decision-making requires changes in both science and decision-making.

ACKNOWLEDGEMENTS

This chapter benefitted from suggestions and comments from Michael Anderson, Roger Bales, Cliff Dahm, Michael Dettinger, Andrew Draper, Robert Gailey, Greg Gartrell, Ellen Hanak, Michael Healey, Jon Herman, Josué Medellín–Azuara, Bonnie Magnuson, David Mitchell, Scott Stephens, and two anonymous reviewers. I thank Erik Reyes, Tariq Kadir, Francis Chung, and Nazrul Islam of the California Department of Water Resources for kindly providing additional data. But responsibilities for limitations, errors, omissions, and misconceptions remain mine.

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