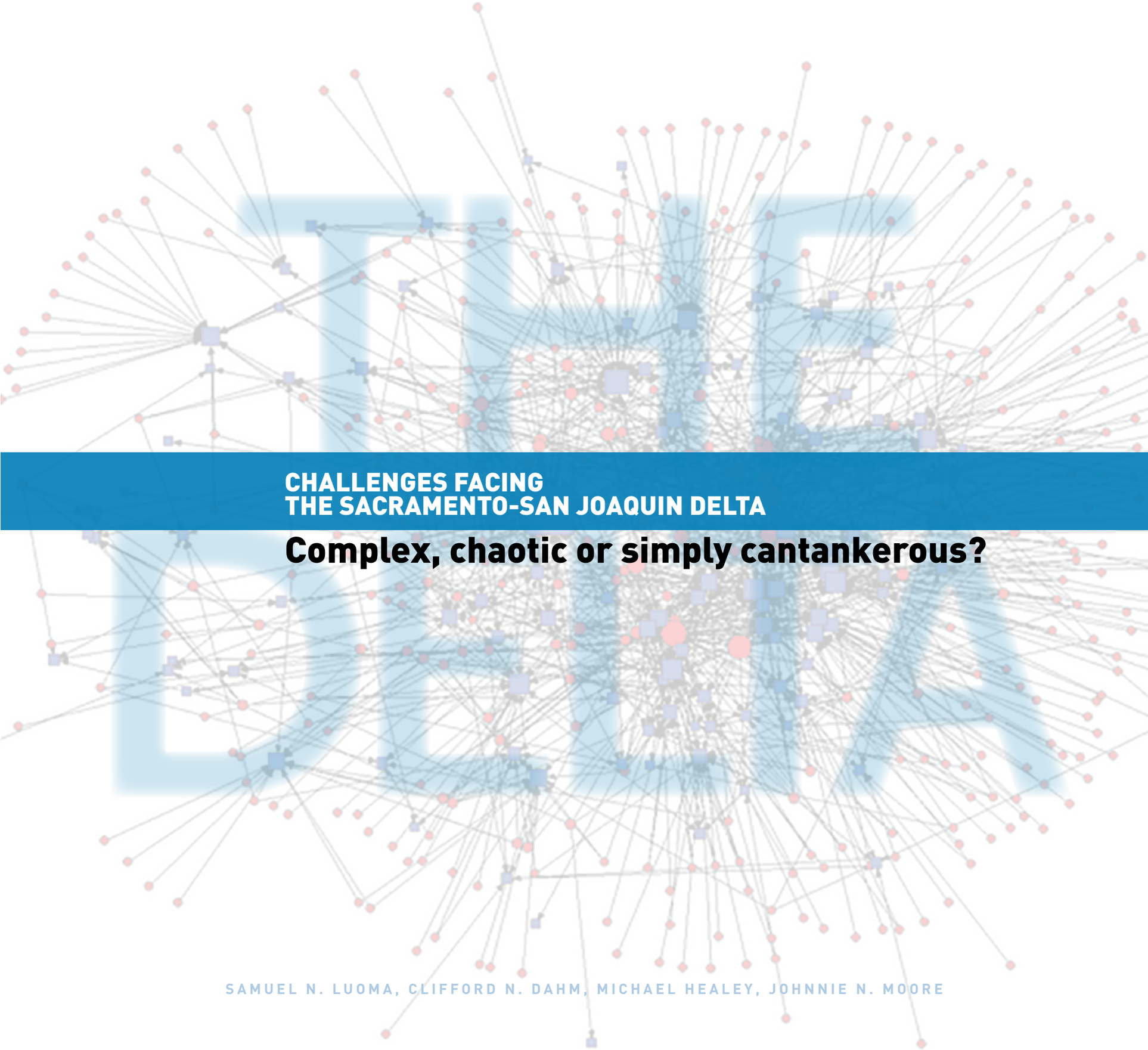

CHALLENGES FACING THE SACRAMENTO-SAN JOAQUIN DELTA

Complex, chaotic or simply cantankerous?

SAMUEL N. LUOMA, CLIFFORD N. DAHM, MICHAEL HEALEY, JOHNNIE N. MOORE

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Challenges Facing The Sacramento-San Joaquin Delta: Complex, Chaotic, or Simply Cantankerous?

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Photo: Rick Lewis

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EXECUTIVE SUMMARY

"In these times of uncertainty it is important to be nimble, be timely and be prepared in our decisions and our implementation. We cannot afford to shy away from bold actions but we must broaden the definition of "bold" to include more than engineering: conservation alternatives, the environment and governance must be a part of every decision."

— SAMUEL N. LUOMA

Executive Summary

In 2014, the California Natural Resources Agency and the U.S. Department of the Interior asked the authors of this paper, as four former leaders of The Delta Science Program, to summarize the challenges faced by water supply and ecological resource managers in this critically important region of Northern California. They concluded that the challenges are so complex as to meet the definition of a "wicked" problem. Such problems can't be ignored, defy straightforward characterization, and have no simple solutions. Yet they must be actively managed to maximize beneficial and minimize adverse outcomes.

Several runs of Chinook salmon in the Sacramento River are endangered or listed (juveniles pictured here). Photo: Roger Tabor, USFWS.

In California, water supply and demand are increasingly out of balance. At the same time, the very cornerstones of the water supply system are changing. Snowpack is declining with warming temperatures, groundwater is being pumped at an unsustainable rate, water infrastructure is aging, and human demand for water continues to grow. Meanwhile, many native species and ecological systems in the Delta are on the point of collapse. Add the uncertainties of drought and flood and a 60% chance of a significant earthquake by 2050 resulting in cascading levee failures, and the need for a new approach is urgent. Repeated management crises suggest that the status quo is unsustainable. Water managers no longer have the flexibility they once had in dealing with the multi-year droughts that are inherent to the California climate. Furthermore, management initiatives are often delayed by the multiplicity of agencies and actors involved and by litigation. Managing the water supply system alone is complicated. But add in the imperative to sustain the ecological and social values of the Delta and every decision becomes unimaginably complex.

In this context, the following paper calls for Delta management to become more nimble and better coordinated. The situation requires bold, timely, and well-considered actions, taken incrementally (in stages) where possible, with the understanding that any management action typically leads to new complexities that must also be managed. With water scarcity has come the awareness that problems are less amenable to traditional engineering solutions, and that attempts at dramatic, simple solutions may intensify the risk of unexpected, if not catastrophic, consequences. Simultaneous attention to a portfolio that includes actions like addressing overuse and mis-use of water, and improving ground water management and storage, should accompany any necessary water infrastructure adjustments. Renewed emphasis on reducing known stressors, restoring native ecosystems, learning from our actions, and managing collaboratively and adaptively is essential if native species are to be retained. Comprehensive modeling that takes account of the many dimensions of the Delta problem should provide a foundation for determining the best approaches to implementing restoration and water management initiatives and forecasting the degree to which they will be effective.

Thanks to the public's long-term investment in good science, the Delta is one of the most intensively studied systems in the world. Managers have information to work with, although important questions remain unsettled. Throughout decades of conflict over water issues, all parties have agreed that advancing the state of scientific knowledge is fundamental to making constructive progress. As we enter an era of increasing uncertainty about climate and water supply, science conducted in collaboration among multiple institutions must be brought to bear and decisions must transcend individual agency directives or the needs of special interests.

Forecasting the future of complex problems like the Delta will require scientific models that can simulate the consequences of different management approaches. Such models have been developed for water operations; are in their early stages for the ecosystem (DiGennaro et al. 2012) and climate change (Cloern et al. 2011); and have been used to envision alternative futures for the Bay-Delta (e.g., Lund et al. 2010).

WHAT IS THE DELTA?

The Delta is where the Sacramento and San Joaquin rivers flow out of the mountains and onto valley floodplains, spreading out onto a 3,000-square-kilometer landscape of islands and shallow waterways before flowing into the San Francisco Bay. Before it was diked, drained, and developed, the Delta was a vast wetland complex of low islands, shifting channels, woody debris piles, and tule marshes. Today, the Delta is a patchwork of largely agricultural islands separated by deep channels and protected by 1,100 miles of aging levees. It hosts farms, fisheries, water projects, recreational areas, and the state capitol in Sacramento. Geographically, it is the largest delta on the Pacific coast and encompasses an area almost the size of Rhode Island.

The Delta is...

- **One of the largest waterworks in the world.** This critical hub of a regional water redistribution system is a complex network of dams, pumps, canals, drains and reservoirs, all of which are managed jointly by local, state and federal institutions to meet goals of flood control, water supply, and environmental conservation.
- **A real place where people live and play,** with a rich cultural history. More than 570,000 people live in the greater Delta, mostly in the urbanizing regions around the margin of the Delta. Many of them derive their livelihoods directly from the Delta. Most of the rest use the Delta for transportation, recreation, and as a source of water.

- **The heart of California's agricultural economy,** which produces more food than any other state with $45 billion in sales per year. Because California produces most of the fruits and nuts and a high percentage of vegetables consumed in the US, restrictions on water for agriculture in the greater Delta affect the availability and price of these agricultural products throughout the US and elsewhere. If production relocates because of water shortages in California, some of the conflicts over water will also relocate.

- **Home to more than 750 species of plants and animals.** The California Floristic Province, of which the Delta is a part, is one of 25 hotspots of biodiversity across the world cited as highest priority areas for conservation of species (Myers et al. 2000). Some species are present year round, like Delta smelt, Sacramento splittail, salt marsh harvest mouse, and soft bird's beak. Other species are important culturally or economically, including salmon, sturgeon, and migratory waterfowl and shorebirds. The presence of migratory species connects the Delta to ecosystems far to the north, south, and west just as the existence of the water distribution system connects the Delta to regions far to the south and east. The Delta is truly an internationally connected ecosystem with contributions to local and state enterprise, to regionally valuable fisheries, and to global biodiversity.

Photos, this page: Birds Eye View

Challenges remain in merging models of various types and in ensuring the models are reliable and address issues at the geographic and temporal scales appropriate for management. If carefully implemented and interpreted, such models would provide valuable guidance and a foundation for both coordination and evaluation of management initiatives.

Water scarcity has defined and will continue to define the future of the Delta and all that is linked to it. California has risen to the challenge of water scarcity in the past to build an economy and a society that is, in many ways, the envy of the world. Accepting water scarcity raises economic, ecological, water infrastructure and organizational complexities in the Delta to a new level, well beyond traditional approaches that consider water supply solutions in isolation. Nevertheless, California has the tools and the intellectual resources to manage the multiple dimensions of the problem and thereby achieve the state's twin goals of a reliable water supply and an ecologically diverse Delta ecosystem.

DELTA CHALLENGES

- **California's water supply is over-allocated.** State water rights allocate more than 500% of average annual river flows (Grantham and Viers 2014). The current drought, climate change, and normal year-to-year variability in precipitation are increasing uncertainty in water supply.

Photo: Chris Austin

- **California's vast water management infrastructure is decaying** and overtaxed. This increases the risk of catastrophe.

- **Delta water availability uncertainties will have consequences throughout seven western states and into Mexico,** due to California's participation in the Colorado River Basin Compact. Although the California economy has proved resilient to year-to-year water shortages in the past (Hanak et al. 2012), negative consequences of a more permanent water scarcity will be increasingly difficult to avoid (Howitt et al. 2014) and will carry over to the economies of the region, the nation, and the world.

- **Native ecosystems and species are declining.** Multiple interacting factors affect their well-being, only some of which are well understood. Predicting the outcome of changes to water operations, landscapes, or levees is uncertain, at best.

Photo: NOAA

- **Upgrading levees to address growing risks will be costly** (risks include earthquakes, storms, rising sea level). Not all levees are fixable, sustainable, or defensible in perpetuity. Failure of levees in one part of the Delta, however, increases the risk of failure elsewhere. Multiple, simultaneous levee breaks would allow a massive salinity intrusion into the Delta. Turning the Delta brackish would threaten agricultural crops and urban water supplies that rely on high-quality water exported from the area.

Photo: Birds Eye View

- **Water quality is threatened by the complex spectrum of chemicals entering the Delta.** Sources include agricultural runoff, industries, wastewater treatment plants, urban stormwater discharges, and atmospheric fallout. Chemicals interact with physical conditions in the Delta, and with other stressors in the system, in a dizzying number of ways, making risks to water supply and native organisms difficult to assess.

- **Delta management is unusually complex.** More than 230 agencies, institutions and stakeholders are involved. Each plays a useful role. However, a number of these entities have very different core interests, conflicting visions, and competing priorities. The result: institutional fragmentation that slows decision-making and confounds collaborative management.

INTRODUCTION

Thermalito Afterbay, part of the State Water Project system downstream of Oroville Dam.
Photo: Matt Elyash, CDFW

If the problem were just about allocating freshwater flows, it might be solvable. Add in the complexity of moving water through a hydrologically and hydro-dynamically complex Delta and it becomes complicated. Add the uncertainty of ecological responses and the institutional complexity of many actors with many visions and the problem becomes wicked. Then add the ever-changing water supply and ecological and economic contexts within which decisions must be made, and the problem becomes devilishly wicked.

Introduction

California, the most prosperous state in the nation, has an economy and a lifestyle built on water — and an illusion that freshwater is always abundant. However, the current drought, now entering its fourth year, has brought sharply into focus the fact that water is a scarce resource. With snowpack in the Sierras at a record low, Governor Jerry Brown has decreed serious water rationing, stating: "This is the new normal and we'll have to learn to cope with it." (KTLA 5 News 2015).

Shortages of water and conflicts over water use are nothing new in California. The Delta of the Sacramento and San Joaquin rivers (the Delta; Fig. 1) is at the center of these conflicts. Major state and federal water projects began delivering water from the Delta in 1949 to agricultural and urban users in the San Joaquin Valley and southern California. This redistribution of water stimulated economic growth, but the projects were soon plagued by conflict over whether, when, and how to transfer water from the Delta (Hanneman and Dyckman 2009). Conflict intensified with the listing under the federal and state endangered species acts of more than 50 native species found in the Delta (DSP 2013). As public concern grew, new policies were put in place to address environmental effects. These initiatives also led to improved understanding of the Delta, the listed species, and the complexities of managing the Delta to achieve a reliable water supply and a healthy ecosystem. Nevertheless, listed species continue to decline and dissatisfaction with water deliveries continues to grow. There is concern that the present approach to water operations is unsustainable in the face of widening demands[1] and shrinking supplies. Frustration with management's inability to satisfy all the demands for water has led to litigation, distrust among parties, and the threat of policy paralysis, with cascading consequences for California, the semi-arid west and the nation (see *Delta Conflicts* at left).

Shasta Dam. Photo: USBR

In this paper we look at multifaceted questions about water and environmental management in the Delta. Our goal is not to evaluate specific recent initiatives, but to provide a larger framework to guide implementation of these and future initiatives. We illustrate how the complexity of the Delta problem complicates management and leads to inefficiency and conflict. We give examples of trade-offs, disagree-

DELTA CONFLICTS: CASCADING CONSEQUENCES

- Federal and State regulations curtail water exports from the Delta when legally protected species, like salmon and Delta smelt, are drawn into the pumps.
- Local restrictions on exporting water from the Delta impact the intricately balanced supply and demand of interdependent water transport networks throughout California and the Colorado River Basin.
- The Colorado River Basin Compact is a complicated deal that defines water rights of users in the seven states that share the river. Southern California obtains water from both the Delta and the Colorado River Basin. California's supply of Colorado River water was reduced with implementation of the Compact. Reducing supplies to Southern California from the Delta increases their reliance (within the bounds of the agreement) on water from places like Lake Mead in the Colorado River system (Fleck 2012). Integration of interstate water infrastructure via these complicated agreements means that decisions about water exports from the Delta have cascading consequences for flows in the Colorado River, as well as endangered species conservation and water supply disputes throughout the Colorado River Basin.
- With so much at stake, it is not surprising that water managers argue that water disputes throughout the arid and semi-arid western US cannot be resolved in the absence of decisions about managing the Delta (Austin 2015; Fleck 2012).

ments and the consequences of failure in managing these issues. We discuss why bold new approaches to managing Delta issues are urgently needed to address inefficiencies in water use, aging infrastructure, and the deteriorating condition of native species. We also show that it is important to ensure that those actions take full advantage of existing knowledge, are implemented incrementally where possible, and are accompanied by ongoing evaluations of outcomes and subsequent adjustments, as necessary. Our hope is that this paper will help managers and policy-makers better appreciate the complexity of water and environmental management in the Delta, and understand that there are ways to move forward.

The Problem

At its simplest, the problem of the Delta is similar to water challenges throughout the arid and semi-arid western U.S.: growing demands and over-allocated resources. For example, California has water rights that allocate over 500% of average annual river flows (Grantham and Viers 2014). Media reports often focus on the conflict over whether water should be exported from the Delta or left flowing through the Delta to San Francisco Bay to sustain listed native fish species. All this attention to flows and fish creates the impression that if only water managers in the major river basins would "get their act together," the problem could be solved. But the problem of the Delta is more complex than a simple decision about allocating flows. It is a problem with many different dimensions (Table 1) and interactions that confound simple answers.

Historically, the problem of water management was about supply: not enough

TABLE 1. *The Delta Problem: A nationally important but "wicked" problem with many dimensions and potentially contradicting solutions.*

Dimension	Problem	Some Characteristics
Physical	Natural system seasonal and episodic	Strong seasonality of water supply; highly variable year-to-year; drought and floods the norm; changing climate; high earthquake damage potential.
Socio-Economic	Unsupportable demand from population, economy	Growth nearing limits of water supply; inadequate awareness that water is scarce; directly linked to the rest of the semi-arid West.
Water Supply	Increasingly vulnerable water infrastructure	Aging conveyance and levee systems stretched to limits; snowpack declining; groundwater exploited at an unsustainable rate; water used is out of balance and inadequately tracked.
Environment	Multiple stresses on ecosystem	Many native species at risk; scale of change massive, difficult or impossible to reverse; stresses difficult to manage, may act in combination, can change over space and time.
Ecosystem Restoration	Difficulty ensuring project success	Some projects help native species while others attract invasive species; benefits of water diversion mitigations questionable; successes, failures, and challenges inadequately tracked.
Institutional	Insufficiently unified vision for the Delta	Plethora of institutions with their own visions and contradicting missions; monitoring programs plentiful yet uncoordinated; management programs inconsistently coordinated and evaluated.
Science	Key uncertainties remain	Multi-institutional, collaborative approach requires new support; equal need for broadly applied science and research focused on immediate policy issues; data sharing must be improved.
Management	Contradictions among solutions	Problems can be characterized in many possible ways; single-focus problem solving can create unanticipated outcomes; management must be continual and adaptable.

THE DELTA: A WICKED PROBLEM

- If the problem were just about allocating flows, it might be solvable.
- Add in the complexity of moving water through a hydrologically and hydrodynamically complex Delta and it becomes complicated.
- Add the uncertainty of ecological responses and the institutional complexity of many actors with many visions and the problem becomes *wicked* (Dryzek et al. 2013).
- Then add the ever-changing water supply and ecological and economic contexts within which decisions must be made, and the problem becomes *devilishly wicked*.

water in the south and more abundant water in the north. California's impressive water system was designed to address this supply problem. But California's water problems can no longer be solved through supply management and traditional engineering solutions alone. Water supply and demand are increasingly out of balance, and the cornerstones of the water supply system are changing. Snowpack is declining with warming temperatures, groundwater is being mined at an unsustainable rate, the infrastructure is aging, human demand for water continues to grow and the Delta ecosystem continues to deteriorate. The accelerating pace of these changes introduces a new urgency into the need to find novel ways to manage the host of variables that affect water and the Delta ecosystem.

Human use of the Delta and surrounding lands has changed the landscape and water quality in ways that create serious environmental challenges (Fig. 2). We know that multiple factors (e.g., water flows, water quality, invasive species, predation pressure, and habitat loss) interact to increase risks to native species. Despite measures to address individual stresses, the situation for many native species is increasingly dire (Sommer et al. 2007). Largely because of massive landscape transformations, the Delta cannot be restored to what it once was (NRC 2012). But the situation for native species can be improved, and there is a new urgency in taking advantage of whatever opportunities exist to do that. Exactly how to reduce the cumulative impacts of the stresses on the ecosystem is not clear (Baxter et al. 2010), but the need to address this multiplicity of problems and their interactions is as urgent as the need to address water-supply issues.

Another aspect of the problem is that more than 230 agencies, institutions and stakeholders claim a role in water and environmental management but come with different core interests — and often conflicting visions of how the Delta should be managed. The resulting institutional fragmentation creates conflict and slows decisions. Addressing the water supply and ecosystem problems of the Delta will require management institutions that are both nimble and sufficiently coordinated to take bold, timely and well considered actions.

Formally, the problem of water and environmental management in the Delta fits the definition of a "wicked" problem in the sense of Rittel and Webber (1973; see *The Delta: A Wicked Problem* above). Recognition of the Delta as a wicked problem presents a new way to think about management. Wicked problems have no single correct

Fresh water from the Delta system supplies both irrigation water for farms and drinking water to cities as far away as Los Angeles. Delta waters also sustain fish and wildlife and recreational activities. Photos: NeilArmstrong2 (left); Bird's Eye View (center and right).

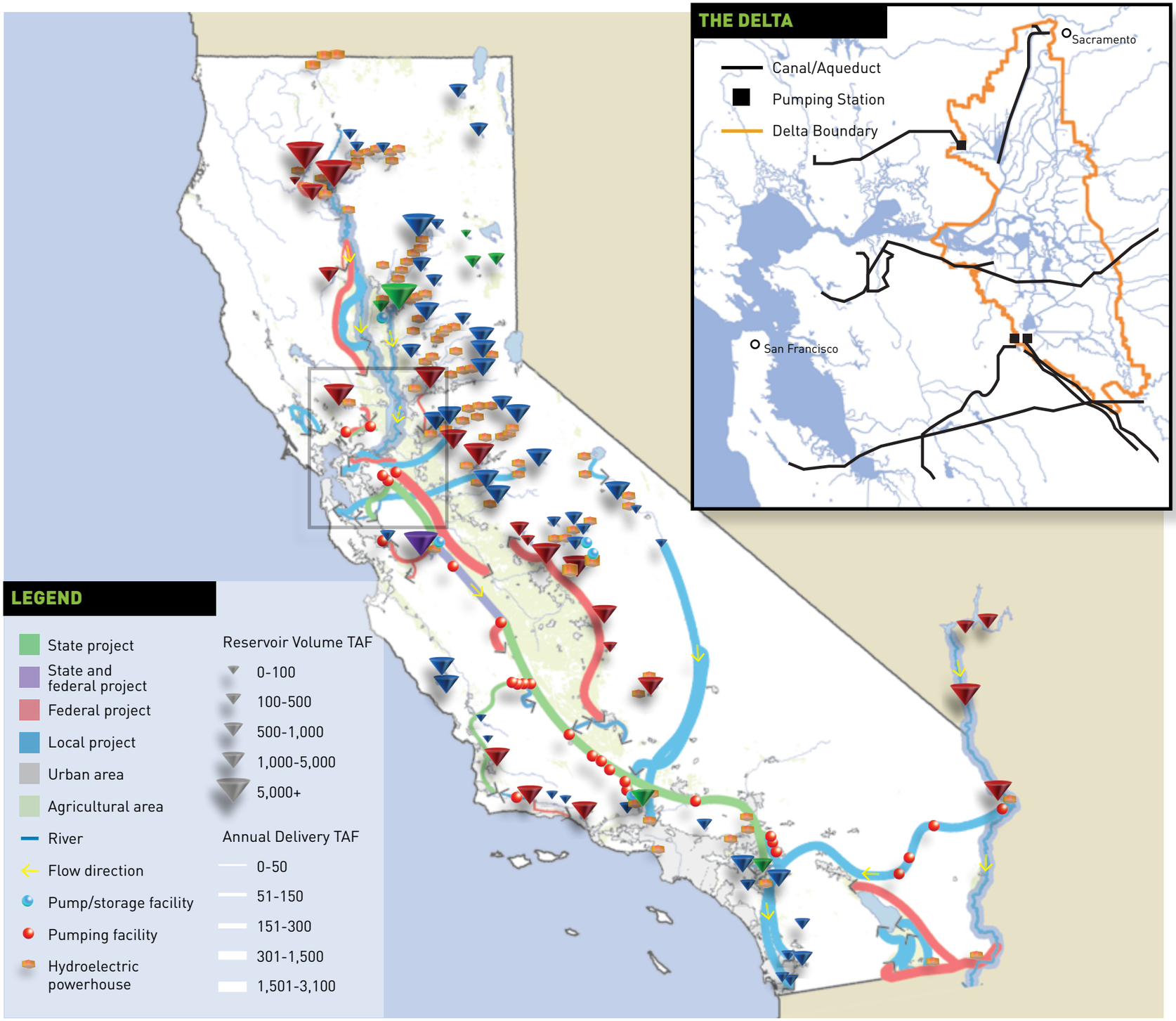


FIGURE 1. *Water supply system in California (large map) showing reservoirs and canals storing and transporting water from the wetter northern areas of the state to the drier southern and coastal areas. The Delta (inset) is at the heart of the system, pumping water to the south from two large pumping plants in the southern Delta. Reservoir volume and annual delivery is in millions of acre feet. Within the Delta, different zones are dominated by different uses and economic productivity. Agriculture is the most important economic activity in the Delta's economy producing $800 million annually in crops (e.g., corn, alfalfa, tomatoes, wheat, and wine grapes). Adding all value-added activities (wineries, dairies, canneries, etc.), the Delta produces $2.6 billion in total economic output and 13,000 jobs for the counties encompassing the Delta and $5.3 billion and 25,000 jobs statewide. Recreation is the second most important economic activity in the Delta, generating $312 million and over 3000 jobs annually within delta counties, and over 5300 jobs and $353 million statewide. Natural gas from the Delta also produces more than 20% of California's gas-powered electricity (DPC 2012).*

characterization and no single correct solution, only better or worse approaches to management of the situation. This means the Delta's problems cannot be solved in the traditional sense, but they can be actively managed to minimize adverse outcomes and maximize beneficial outcomes (Healey 2008). Difficult political decisions and bold actions will be necessary, and this will require thinking outside the box, thinking holistically, making learning integral with doing, and finally and honestly embracing the equivalent value of water supply and ecological health. Addressing demand will be as important as addressing supply; restoring ecological function (as Moyle et al. [2012] suggest) will receive as much attention as re-engineering water-distribution infrastructure; and broadly coordinated actions will take precedence over individual institutional missions. The Delta Stewardship Council, the Delta Reform Act, and the Delta Plan provide an institutional and policy framework for this kind of operational innovation.

Why is the Delta Problem Important?

As the hub of a regional water-redistribution system, the Delta is a critical node in a complex network of dams, pumps, canals, drains and reservoirs, all of which are managed jointly by local, state and federal institutions to meet goals for flood control, water supply, and environmental conservation (Fig. 1). This engineering marvel is one of the largest waterworks in the world. Through California's participation in the Colorado River Basin Compact, uncertainties about water availability from the Delta have consequences throughout seven western states and into Mexico.

Water is a fundamental driver of the economy of the western US. California's economy is the most productive in the country (Fig. 2; see *Economy Underpinned* below). The water system is the lifeblood of this economic powerhouse and fuels the nation's most productive agricultural sector. The Delta contributes to the California economy in myriad other ways. Commercial shipping moves through the Delta to and from the ports of Stock-

THE INTERNATIONAL, NATIONAL AND STATE-WIDE IMPORTANCE OF AN ECONOMY UNDERPINNED BY AVAILABILITY OF WATER FROM THE CALIFORNIA DELTA

- A gross domestic product of $2.2 trillion.
- The 8th largest economy in the world, equal to Brazil's.
- Contributes 13% to the total economic output of the United States.
- Ranks 1st in the nation for patents.
- Outpaces all other states in venture capital investment with 41% of all companies in the U.S. receiving venture capital from California.
- Has the highest rate of employment by U.S. subsidiaries of foreign companies.
- Exports $174 billion of products annually ($48 billion from computer and electronics goods) for 11% of total U.S. exports.
- Imports more than $230 billion in goods from other states and countries.
- Entertainment industry in California accrues over $47 billion per year.
- California produces more food than any of the 50 states with $45 billion in sales per year, including:
  - 40% of annual national agricultural production; 45% of all the fruits and vegetables, including:
    - 98-99% of U.S. almonds, walnuts and pistachios.
    - 90-95% of broccoli, strawberries, grapes, and tomatoes.
    - 74% of all lettuce.
    - Produces many crops year round supplying the nation with fresh produce throughout the winter.
- Because California produces most of the fruits and nuts and a high percentage of vegetables consumed in the US, restrictions on water for agriculture in the greater Delta affect the availability and price of these agricultural products throughout the US and elsewhere.
- If production relocates because of water shortages in California, some of the conflicts over water will also relocate.

References in footnote 3, p. 30.

CONSTRUCTION OF DAMS

Blocked fish migration; altered hydrology and temperature; reduced sediment transport.

Photo: USBR

WATER DIVERSIONS

Changed hydrology and hydrodynamics; fish entrainment; migratory fish signal impairment; altered water quality.

Photo: CDFW/Matt Elyash

COASTAL UPWELLING

Affect coastal marine ecology; changes abundance and types of migratory species in the Estuary from year-to-year.

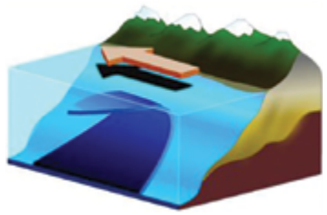


Image: NOAA/OER

CLIMATE CHANGE

Warmer temperatures; altered timing and intensity of precipitation; more rain and less snow; earlier snowmelt; reduced runoff, sea level rise.

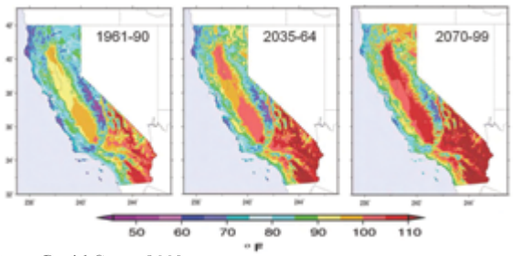


Image: Daniel Cayan, 2009

ATMOSPHERIC RIVERS

Major source of precipitation and dominant cause of flooding.

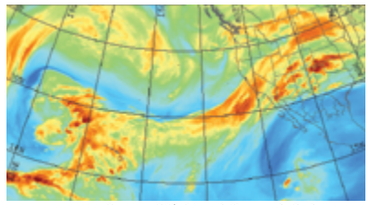


Image: US Naval Research Laboratory

EL NIÑO/LA NIÑA

Affect precipitation patterns and amounts throughtout the US: major contributor to wet and dry years in California.

INVASIONS BY NON-NATIVE SPECIES

Non-native species competition with native species; predation pressure; habitat alteration.

Photo: DBW

Photo: Cindy Brown

SALINITY INTRUSION

Driven by drought, sea level rise, tidal surges, or catastrophic levee failure.

Photo: Bird's Eye View

TRANSFORMATION OF THE LANDSCAPE

Habitat reduction and alteration; altered hydro–dynamics; native species declines and non-native species increases.

Photo: Aerial Archives/Alamy

LEVEES

Disconnected rivers and channels from floodplain and wetlands; earthquake vulnerability; storm and tidal surge vulnerability.

Photo: DWR

DISCHARGE OF NUTRIENTS AND TOXIC SUBSTANCES

Nutrient inputs drive algal blooms and enhance growth of invasive plants; toxins affect species survival and bioaccumulate, making fish unsafe to eat.

Photo: Bird's Eye View

FIGURE 2. *The Delta ecosystem responds to factors both within the physical Delta and from regional stressors and drivers of change, including the ocean. Eleven major factors affecting the current Delta are highlighted in this regional view of the Delta and surrounding landscapes. Aerial photo research: Amber Manfree.*

ton and Sacramento, and several major rail lines cross the Delta. Natural gas is generated and stored in the Delta. Silicon Valley, the heart of America's electronics industry, gets half its water directly from the Delta. California's entertainment industry — America's largest export — is also centered in cities dependent upon Delta water (Farhi and Rosenfeld 1998). Although the California economy has proved resilient to year-to-year water shortages in the past (Hanak et al. 2012), negative consequences of a more permanent water scarcity will be increasingly difficult to avoid (Howitt et al. 2014) and will carry over to the economies of the region, the nation, and the world.

The Delta is also of considerable ecological importance. With San Francisco Bay, it is home to more than 750 species of plants and animals. The California Floristic Province, of which the Delta and Bay are a part, is one of 25 hot spots of biodiversity across the world cited as highest-priority areas for conservation of species (Myers et al. 2000). Some species are present year-round, like Delta smelt, Sacramento splittail, salt marsh harvest mouse, and soft bird's beak. Other species that are important culturally or economically, including salmon and sturgeon, utilize the Bay and Delta seasonally. Migratory waterfowl and shorebirds use the Bay and Delta as a feeding and nursery habitat during only a brief part of their lives, but these species could not exist without these systems. The presence of migratory species connects the Delta to ecosystems as distant as Alaska, the Pacific Ocean and South America, just as the water distribution system connects the Delta to regions far to the south and east. The Delta is truly an internationally connected ecosystem with contributions to local and state enterprise, to regionally valuable fisheries, and to global biodiversity.

Finally, the concept of the Delta as a place, enshrined in the 2009 Delta Reform Act, makes tangible the human dimension of issues such as water export and management, environmental management, and habitat restoration. All these activities go on in a real place, a place where people live and play, a place with a rich cultural history. More than 570,000 people live in the greater Delta itself, mostly in the urbanizing regions around the margin of the Delta (Secondary Zone, Fig. 1). Many derive their livelihoods directly from the Delta. Most of the rest use the Delta for transportation, recreation, and as a source of water. The importance of this social dimension of the Delta is a critical consideration in every decision that affects the fate of the region.

Sandhill cranes, listed species in California. Photo: Rick Lewis

The Delta, a Study in Complexity

Physical System Complexity

The Delta began forming about 10,000 years ago when rising sea level slowed the outflow of the Sacramento and San Joaquin rivers through Carquinez Strait. Sediments accumulated east of the strait and created a complex of low islands, shifting channels, large woody debris, and tule marshes (Whipple et al. 2012) that bedeviled early settlers but were the natural habitat of many species now in trouble.

Human activity has transformed the original complex wetlands and river floodplains into a 3,000 square km patchwork of approximately 57 islands separated by 1,100 km of sloughs and winding waterways (CDWR 2015). It is the largest delta on the Pacific coast of North America (almost the size of the state of Rhode Island). The islands of the central Delta are used primarily for agriculture, although there is a small amount of residential property. Only remnants of the original marsh remain, and many of these are highly managed (Ferner 2012).

The physical character of the Delta is at the center of some of the most complex and contentious aspects of the Delta problem. The islands of the Delta are protected by 1,800 km of levees (Fig. 3). The levees are aging and at risk of failures from numerous causes. In the 1990s, 160 levee breaches occurred, and breaches continue at a high rate (Bates and Lund 2013). Delta islands have subsided, particularly in the center and western portion of the Delta where the surfaces of many islands are now five meters or more below sea level (Moore and Shlemon 2008), increasing the risk of levee failure. Droughts and floods also increase the risk of levee failure, and this risk will likely increase as these events become more frequent and more severe with climate change. Rising sea level, another consequence of climate change, further increases the risk of levee failure. Finally, the levee system is highly vulnerable to earthquakes. There is an estimated 60% probability that an earthquake of magnitude 6.5 or greater will occur in or near the Delta sometime in the next 35 years (Moore and Shlemon 2008). Levee maintenance is costly and upgrading levees to address the growing risks is costlier still. Ultimately, prioritization of maintenance and land uses will be necessary, and incremental approaches to this have been proposed (DSC 2015). But the levee system is also interconnected, making solutions more complex. Breaks or intentional breaches in one levee could increase the risk of levee failure elsewhere in the Delta. If any of these risks results in multiple, simultaneous levee breaks, there would be cascading consequences for water transit, water exports, local economics, and use of islands to benefit the ecosystem.

Remote sensing photography of Delta levee vulnerability from a joint NASA, DWR & CalTech project.

A most important consideration in the discussion of levee maintenance is that the levees are an essential part of the California water-distribution system. Delta channels are designed, in part, to channel Sacramento River water from the north Delta to the south Delta, where it is exported via massive pumps to the Central Valley and southern California (Fig. 1). This makes the levees critical to all the human uses of Delta water. One of the greatest concerns of Delta water managers is that multiple levee failures would allow a massive salinity intrusion that would threaten the many agricultural crops and urban water supplies that rely on high-quality water exported from the Delta. Desalini-

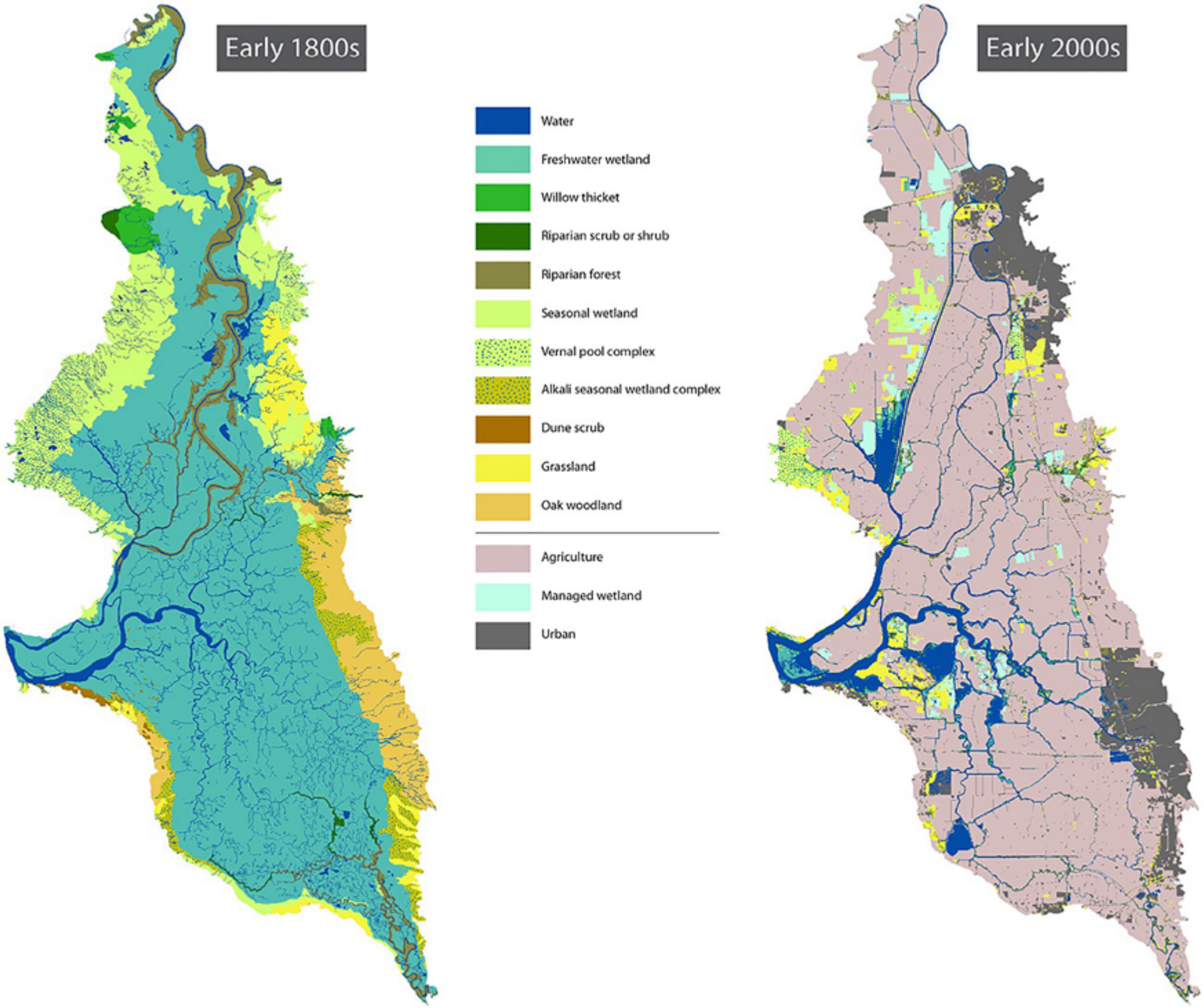


FIGURE 3. *Maps of the Delta showing the transformation from a complex system of river and distributary channels of multiple sizes and shapes to the present water transport system dominated by straightened and simplified channels. Transformation also included a major simplification of native landscape types to an agriculturally dominated landscape. From the Sacramento-San Joaquin Delta Historical Ecology Study, available at: www.sfei.org/DeltaHEStudy (Whipple et al. 2012)*

zation is not economically feasible to remove salt from irrigation water because of the volumes (and thus cost) involved. Water treatment facilities can remove salt from drinking water, but at a considerable increase to the cost of drinking water. In addition, there is a potential risk to human health from carcinogens that form during water treatment when the source water contains higher levels of organic matter and bromide (Richardson and Postigo 2012).

Under the current levee configuration, river flows out of the Delta provide a flow barrier that prevents intrusion of seawater from San Francisco Bay. If river flows drop too low, circulation driven by the tides (the strongest hydrodynamic force in the Delta) can carry salt, dissolved organic materials, bromide, and other chemicals to the water supply diversion points in the Delta. Reservoir releases are crucial in maintaining river flows in summer and fall when rainfall is limited. Thus, exports of high-quality water from the Delta depend upon a complex interaction among climate, reservoir operations, and levee configurations. For example, during prolonged droughts, there is increased risk that reservoir supplies will not be sufficient to maintain the flows that keep salinity away from the interior Delta. At the present time, after four years of drought, reservoir supplies are shrinking, the flow barrier is weakening, and water managers are adjusting levee configurations, each with their own problems, to ensure the quality of freshwater delivered from the Delta (Rubissow-Okamoto 2014).

Water Supply Complexity

The complexity of Delta water issues partly revolves around widening demand for water from a supply that is not only limited but also highly variable and growing increasingly uncertain. California's water supply is based upon four pillars: surface water, snowpack, groundwater, and the massive human-built infrastructure that stores and redistributes water from these sources. The human-built system is effective in managing seasonal variability and regional redistribution of water. Large storms that occur in late fall, winter, and early spring are a major source of California's water supply, contributing 30% to 45% of all precipitation in central and northern California (Dettinger et al. 2011). These storms are associated with atmospheric rivers, bands of warm, moist air from the subtropics that sweep across the Pacific and make landfall as a series of high-intensity rainstorms (with snow in the high mountains). These intense storms are a mixed blessing, sometimes providing much-needed water and at other times causing significant flooding and property damage.

California precipitation comes both as rainfall and snowfall in the high mountains. Rainfall runs off immediately, and water managers must decide whether to store this water in reservoirs for water supply or to release water to reduce future flood risk (Knowles et al. 2006). Snowpack provides a critical second source of water. California reservoirs begin to release their stored water as precipitation declines in late spring. These reservoirs are then refilled by snowmelt from carefully metered mountain snowpacks. Typically, snowpack provides just under half of California's water supply (Dettinger 2015), allowing seasonal redistribution to proceed into the late fall when the rains normally begin again.

Year-to-year variability in precipitation is a predominant feature of the California climate and is by far the greatest in the U.S. (Dettinger et al. 2011). If one or two large winter storms do not materialize, the year will be dry; if there is an additional large storm or two, the year will be wet. Complex cycles of ocean climate[2] contribute to a tendency for wet or dry periods to occur over multiple years, adding another layer of complexity to the water supply picture (Cayan et al. 1998). The reservoirs were originally designed to buffer the effect of precipitation variation, but as demand has grown the system has become increasingly less flexible. The capacity of reservoirs in the Sacramento and San Joaquin basins is about 1.1 times average annual runoff (Lund et al. 2007). Thus, reservoirs allow water managers flexibility for within-year water management but no longer provide much flexibility for dealing with multi-year droughts. Finally, long-term trends in California's water supply associated with climate change portend growing uncertainty in water supply and uncertainty about strategies for coping with increasing variability (see *Uncertainties* at right).

For decades, groundwater has provided the backup to lessen the effect of surface water variability. Of the total California water supply, about 40% comes

UNCERTAINTIES ABOUT CALIFORNIA'S FUTURE WATER SUPPLY ARISING FROM CLIMATE CHANGE

- More precipitation falls as rain in late winter and less as snow in mid-winter.
- Spring snowmelt occurs earlier because of higher temperatures.
- Less snow and earlier melting means less water stored as snowpack and more uncertainty about water availability from reservoirs in the late summer and fall.
- Higher temperatures yield less runoff from the same rainfall amount.
- Average precipitation increases in northern California but decreases in southern California.
- More frequent extremes: prolonged drought, floods from atmospheric rivers.
- Greater dependence on groundwater as a buffer from extremes.
- Increasing costs and decreasing availability of that buffer as groundwater is over-exploited.

Sources: Cloern et al. 2011, Dettinger and Cayan 2014

from groundwater wells (CDWR 2014). But in some regions groundwater is being used faster than it is being replenished. For example, groundwater supplies in the Central Valley have decreased by about 79 million acre feet since the early 1960s (CDWR 2014; Famiglietti et al. 2011). The current drought has greatly exacerbated the issue. From spring 2013 to spring 2014, before the worst of the present drought hit, groundwater levels dropped in 88% of the wells in California, with 22% of those wells dropping by more than 10 feet in that one year. As groundwater levels drop, costs increase, availability declines, and land subsidence occurs (Faunt and Sneed 2015). These signs of groundwater depletion add considerable uncertainty to the supply picture for the future. Exact measurements of groundwater reserves and the cost to access and use groundwater under different future climatic scenarios are crucial to understand the implications of current rates of groundwater depletion. In 2014, California passed legislation requiring that groundwater reserves be measured and groundwater use regulated. Implementation of this new law will require increased study and monitoring of the groundwater system at local, regional, and statewide scales.

Water Quality Complexity

A broad array of nutrients and potentially toxic chemicals enters the Delta from agricultural runoff, and there exists a long legacy of mining and industrialization in the watershed (van Geen and Luoma 1999; see *Contaminants* at right). Today, more than one hundred industries, wastewater treatment plants, and urban stormwater discharges release waste streams to the Bay and Delta (van Geen and Luoma 1999). The waste streams are mostly treated, but the Bay and Delta are, nevertheless, listed under the federal Clean Water Act as impaired because of the presence of a variety of toxic contaminants. People are advised not to eat striped bass, white sturgeon, and some diving ducks caught in the Bay and Delta because they may contain high concentrations of mercury, selenium, PCBs, or DDT breakdown products.

The complex spectrum of chemicals entering the Delta is continually changing over time as regulations, industry processes, and consumer preferences change. Federal and state regulations (e.g., the Clean Water Act, passed in the 1970s) have made substantial progress in reducing inputs of some toxic chemicals (metals, some organic compounds) into the Bay and Delta (van Geen and Luoma 1999) and reversed adverse ecological effects around what were once contamination hot spots (Hornberger et al. 1999). Nutrient input remains a source of concern, although management has improved in some areas (see *Nutrients* p. 20). Newly emerging contaminants pose another concern, and include pharmaceuticals, flame retardants and personal care products that are shown to cause endocrine disruption in fish and other organisms. There is evidence of toxicity to invertebrates at the base of the food web, at least near the sources of inputs for some pesticides (Weston and Lydy 2010) and PCBs (Jannsen et al. 2011). In addition, selenium causes reproductive effects in some native fish (Stewart et al. 2013). Finally, the fate of chemical wastes is interwoven with the physical characteristics of the modern Delta. Many aspects of water quality are affected by river inflows, Delta hydrodynamics, connections to the Bay, and changing temperature and turbidity. All of these interact with each toxic chemical to create variable exposures over time and space. In short, there is cause for concern about the potential for adverse effects from toxic contaminants, even though exact risks are difficult to assess and are confounded with the effects of other stressors.

Ecological Complexity

Before European colonization, the Delta was a vast, 3000 square km complex of low, forested islands, tule marsh, and meandering channels (Fig. 3). Parts of the Delta flooded and drained with each tidal cycle, and most of the Delta flooded during the spring, after which parts dried out during the long period of low river flow in the summer and autumn. The tidal and seasonal cycles of flooding, draining, drying, erosion and deposition created and sustained the Delta. This was the environment in which native species evolved and in which they thrived. The life cycles of many native species were cued to these natural rhythms. As tides rose and inundated island marshes, fish would invade the marsh along tidal

CONTAMINANTS IN THE DELTA AND SAN FRANCISCO BAY

- Mercury from historic mining sources contaminates food webs.
- Selenium from Central Valley irrigation drainage and Bay refineries affects reproduction of native predator species in the Bay.
- Organic chemicals remaining in sediments from historic use accumulate in food webs including DDT and its breakdown products, and polychlorinated biphenyls (PCBs).
- Pharmaceuticals, flame retardants, and personal care products from waste treatment facilities disrupt endocrine systems of aquatic organisms and birds.
- Multiple, changing pesticides from agriculture and urban uses cause toxicity at least near their points of release.
- Nutrient inputs from waste water treatment facilities and other sources affect Delta food webs.
- Nitrogen, phosphorous and other nutrients stimulate nuisance or toxic algal blooms and water weeds as turbidity of water declines.

Emergency barrier erected on the False River in 2015 to prevent salinity intrusion into areas tapped for drinking and irrigation water. Photo: Bird's Eye View

"Times of severe drought provide a stark reminder of the complexities of current and future Delta challenges. Drought also underscores the importance of planning for a rapidly changing world. Quick fixes to solve one problem may be necessary, but holistic integrated solutions are ultimately required."

— CLIFFORD DAHM

NUTRIENT INPUTS: A CHANGING ISSUE WITH REGIONAL IMPLICATIONS

- The waterways of the Delta are enriched with nitrogen, phosphorus, and other nutrients that come from natural sources, agricultural inputs and wastewater treatment facilities.
- Nutrients typically fuel the growth of phytoplankton (open water algae) and aquatic plants that form the base of the food web in the Delta. Plant productivity determines the availability of food resources to zooplankton, aquatic invertebrates, and fish.
- Annual primary production of the phytoplankton in the Delta has typically been low compared with other estuaries because of limited light penetration into turbid waters and the low residence time of water in the Delta (Jassby et al. 2002). Feeding by bottom-dwelling animals that filter the water column also reduces phytoplankton availability to the pelagic food web.
- Summer blooms of a harmful algae (*Microcystis aeruginosa*), that began in 1999, are a new concern (Lehman et al. 2005), for the first time raising the specter of ecological problems from nutrient inputs.
- The problem has been accentuated by an increase in the clarity of the water that allows more light penetration. This occurred as the residual sediments from hydraulic mining passed through the ecosystem and dams captured sediments that originated upstream.
- Nutrient availability, especially ammonium from wastewater treatment plants, facilitated the invasion of two non-native aquatic plants (Brazilian waterweed and water hyacinth) which are now well established in the Delta (Santos et al. 2009). Both grow well in high nitrogen environments if light is available, and are effective at using ammonium as a source of nitrogen.
- Programs are being initiated to reduce nitrogen discharges. A sustained commitment to experimental nitrogen-removing technologies illustrates that creative new ways to address stressor problems exist. Although it is uncertain to what degree nitrogen reductions alone will shift trajectories for native species, it is an example of bold, prudent action with a low probability of cascading negative outcomes.

Photo: Bird's Eye View

channels, feeding on the abundant food resources of the marshes before retreating into the main Delta channels as the tide ebbed. Shorebirds would also populate the emerging mud flats to probe for food. Fish species such as splittail were adapted to the seasonal flooding, moving onto the floodplains to spawn during the spring floods and retreating to the main river channels with their young as the flood receded.

Very little of this historic ecosystem remains (Fig. 3). The modern Delta is a patchwork of leveed islands separated by channels. These islands do not flood on tidal or even seasonal cycles, unless levees fail. Little wetland habitat remains, and what does is not subject to the extent of flooding and drying that characterized the historic wetlands.

Beyond transformation of Delta habitats, human development imposes a wide array of additional drivers of environmental change (Fig. 2) with effects that vary among species, locations, and with time. The severity of the cumulative effects of these stresses is manifested in the estimate that 80% of native fish species are in decline (Hanak et al. 2011). Many of the risks from individual stressors are understood, but the relative importance of each stressor to the cumulative consequences is difficult to pinpoint. Moreover, natural cycles and climate change constantly shift the baseline conditions in the ecosystem (Cloern and Jassby 2012), adding to the complexity of determining why changes are occurring. As a result, predicting the outcome when water operations, land forms, or the levees are changed is uncertain, at best.

Since passage of the Central Valley Project Improvement Act of 1992, federal and state agencies have focused attention on how to sustain viable populations of native species in the Delta while still maintaining water exports from the Delta. Early attention focused on prevention of mortality at the export pumps (see *Preventing Mortality* p.21) and management of flows through the Delta for the benefit of native species. More than a decade of litigation has been driven by uncertainties about the effectiveness of the regulations that curtail exports, and how these curtailments and other water management operations, in real time, negatively affect the populations of legally

PREVENTING MORTALITY OF LEGALLY PROTECTED FISH SPECIES IN THE DELTA

- One focus of Delta management is regulations that curtail water exports when legally protected species, such as salmon and Delta smelt, are drawn into the pumps.
- At a larger scale, water project operations also affect water movement and water quality throughout the greater Delta changing, for example, cues that fish such as salmon use to direct their seasonal migration from spawning rivers to the sea and back.
- Today only 5% of the young salmon that enter the Delta in their seaward migration survive to enter the ocean (del Rosario et al. 2013). That proportion dropped from 40% in the 1990s.
- It is difficult to determine unambiguously how much of this mortality is caused by water operations, how much by habitat change or how much by interactions with other causes of mortality such as predation by non-native species (Fig. 2).
- Survival of migrating chinook salmon has been improved to 86 – 94% by scientifically supported actions in the Columbia River system (northwest US; Muir et al. 2001). This means improving migratory survival is feasible and is an example of an opportunity to improve the situation for native species.

Steve Martarano/USFWS

HOW MUCH WATER FOR THE ENVIRONMENT?

- It is common to hear that only 50% of California's water supply is diverted for human use and that the other 50% goes to the environment. (Different sources give slightly different figures for the water balance.)
- In general, one-third of all California water (60% of the environmental water) is in wild and scenic rivers far north of the Delta watershed. These rivers are protected by laws that were established in the 1960s and have been repeatedly declared off limits to the Delta because of poor accessibility, environmental protection and economic reasons.
- The most controversial segment of all water is the approximately 10% (20% of environmental water) that flows through the Delta.
- Most of this water is used for increasing flow that prevents salinity intrusion into the Delta pumping stations. This water may be beneficial to the environment, but it is just as important to human water uses.
- 1-2% of the water is used for wetlands maintenance, which is not highly controversial.
- Most of the controversy is over the 1% or so of the water used to protect endangered species of fish.
- California's recent water wars are about this last remnant of the original inflows to the Delta, a sign of the tightening supply versus demand equation.

Sources: Fox 2015; Mount 2011

THE PELAGIC ORGANISM DECLINE

- Four pelagic species, two native species (Delta smelt and longfin smelt) and two introduced species (juvenile striped bass and threadfin shad), declined to record low numbers in only a few years beginning in 2002 - 2004.
- The collapse of these populations occurred despite management actions intended to improve conditions in the Delta and relatively moderate hydrological conditions at the time.
- Before this event, most attention had focused on water exports as the principal cause of the declining abundance of native species. Careful re-examination and re-analysis of data was catalyzed by the dramatic change in fish populations.
- Although different stresses (Fig. 2) figured most prominently in different studies, all showed that direct effects of water exports was only one factor - and perhaps no the most important factor - in this most recent species decline in abundance.
- Conceptual models, rooted in ecological theory, are developing ideas about how a number of drivers of change interact to cause precipitous declines in species. These models are qualitative and generalized, but do provide a useful framework for organizing and synthesizing both data and ideas related to the conservation of pelagic fish species.

Delta smelt. Photo: Dave Giordano, Ecositemedia

protected fish species. Even defining water allocations for the environment versus human use has been a source of controversy (see *How Much...* p. 21).

As more has been learned about the Delta ecosystem, it is clear that recovery of native species will require cumulative effects from all stressors to be addressed. A good example of the dire circumstances that characterize the Delta ecosystem is the recent sharp decline of several native fish species, termed the pelagic organism decline or POD (see *Pelagic Organism* above). Statistical studies, improved conceptual models, and improvements in quantitative modeling of the environment all point to multiple causes for the POD, and perhaps a broad change in the overall ecological regime of the Delta. Initial studies of the POD were focused on declines in abundance of a few species such as Delta smelt or longfin smelt and their link to water diversions. But broader conceptual models (e.g., IEP MAST 2015) led to the recognition that more species and other events were involved with this change. The idea that focusing action on one problem will allow relaxation of the regulation of others has underlain much of the contentious dialogue about Delta restoration. The POD studies and others show that concerted action on multiple fronts offers the best opportunity for progress.

It is difficult to pin down the causes of events such as the POD, in large measure because today's Delta is essentially an alien habitat to the hundreds of native species that try to live there. Under these circumstances, it is no surprise that many native species are struggling to survive and that many factors are implicated in their low population numbers. The Delta cannot be returned to the way it was 200 years ago. The great challenge is to figure out how to provide enough suitable living space in the modern Delta for these species to persist (Moyle et al. 2012). The challenge is increased by the continually evolving nature of the ecosystem as new species arrive, and as land use and climate change (see *Non-Native Species* p. 23).

Institutional Complexity

Because managing water and environment is inherently complex, the tendency is to break the perceived problem down into what seem like manageable pieces and address each piece more or less independently. The result has been a plethora of agencies, departments, and commissions at federal, state, regional and local levels of government, each dedicated to addressing one or more components of water and environmental management (Fig 4). Private interests, like the State Water Contractors, and non-governmental organizations, like the San Francisco Estuary Institute and the Nature Conservancy, are also involved. The repeated crises in management of the Delta have only served to increase this institutional complexity (DSC 2013).

When so many institutions with different mandates are involved in management of a critical resource such as the Delta, integration and coordination are critical.

Small irrigation pump draws from Delta waterway infested with invasive aquatic plants (left); Overbite clam (below). Photos: Bird's Eye View and Andrew Cohen (respectively).

Although there are notable examples of long-standing cooperation and integration among state and federal agencies (the Interagency Ecological Program, for example), there are also notable examples of decision-making that is fragmented and uncoordinated, leading to inefficiency and poor outcomes (NRC 2012). One consequence of the fragmentation of responsibility and authority over the Delta is the increased difficulty of addressing Delta problems. The complexity provides a multiplicity of ways for individuals and organizations that are dissatisfied with water or environmental management to seek redress for their dissatisfaction through litigation. The Delta Reform Act of 2009 attempted to address this complexity by establishing the Delta Stewardship Council with responsibility for achieving the coequal goals of a more reliable water supply for California and protecting, restoring, and enhancing the Delta ecosystem. Time will tell whether the Council can achieve sufficient cooperation or has sufficient authority to address institutional complexity.

NON-NATIVE SPECIES AND THE RESTORATION CONUNDRUM

- Aquatic and terrestrial habitats are heavily invaded by non-native species delivered by international shipping, recreational boating, the horticulture and pet industries, agriculture, or deliberate introduction.
- San Francisco Bay and the Delta have been described as the most heavily invaded estuary in the world (Cohen and Carlton 1998). Cohen and Carlton (1998) showed that 40-100% of species found in various aquatic habitats was non-native.
- The consequences of invasions by exotic species can be dramatic.
- A 1986 invasion of the overbite clam changed phytoplankton dynamics in Suisun Bay, and eliminated what was once a large spring bloom of plants essential to native food webs.
- Introduced predators, like striped bass and largemouth bass, have grown to large populations in the Delta, and their predation on native fishes is thought to contribute to the decline of such species.
- Restoration of shallow water habitats is often plagued by invasive plants and invasive predators instead of fostering more habitat for native species. Currently, it is unclear how best to reduce populations of invasive species or how to increase the certainty that new habitat will be best suited for native species.

The Role of Science

As we noted earlier, the Delta is one of the most studied ecosystems in the world. A growing understanding underpins ongoing adaptations in managing the Delta. Throughout the decades of conflict over water issues, all parties have recognized that advancing the state of scientific knowledge is fundamental to making constructive progress. As we enter an era of increasing uncertainty about climate and water supply, commitments to multi-institutional science that informs policy beyond agency decisions are critical. Continuing advancement of scientific understanding and effective integration of science into management will require science that embraces differences of scientific opinion, structures science in a way that is useful for management decisions, and quantifies uncertainty. Looking into the future of complex problems like the Delta will require scientific models that can simulate the consequences of different management approaches. Such models have been developed for water operations; are in their early stages for the ecosystem (DiGennaro et al. 2012) and climate change (Cloern et al. 2011); and have been used to envision alternative futures for the Bay-Delta (e.g., Lund et al. 2010). The understanding necessary to integrate and strengthen these models is growing rapidly, but is scattered among agencies and research institutes and needs to be brought together. Challenges remain in merging models of various types, and in ensuring the model output is sufficiently reliable for management. But if carefully implemented and interpreted, such models can provide valuable guidance to policy, management, and science (Healey et al. 2008).

Continuously improving models and scientific understanding of the Delta problem is necessary but not sufficient to manage successfully the complex technical, political and resource challenges facing the Delta. There will always be uncertainties that surround any action. Difficult political choices will be necessary. Adaptive management is the preferred approach to implementing management actions in the face of uncertainty. Regular monitoring and evaluation of the Delta's response to management is the best way to detect unexpected outcomes and adjust management actions to deal with uncertainties. Although a number of monitoring and assessment programs exist to aid in such evaluations, there is not as yet a unified set of performance criteria for the key dimensions of the Delta problem. As adaptive management becomes more fully implemented, such criteria must be developed, implemented, and reported on regularly. Effective adaptive management also requires collaboration, communication, and transparency among all interest groups as well as a willingness to overcome the institutional barriers to collaborative decision-making. Recent commitments to collaborative decision-making are encouraging (e.g., the Collaborative Adaptive Management and Policy Team) but sustaining those initiatives has always been a challenge.

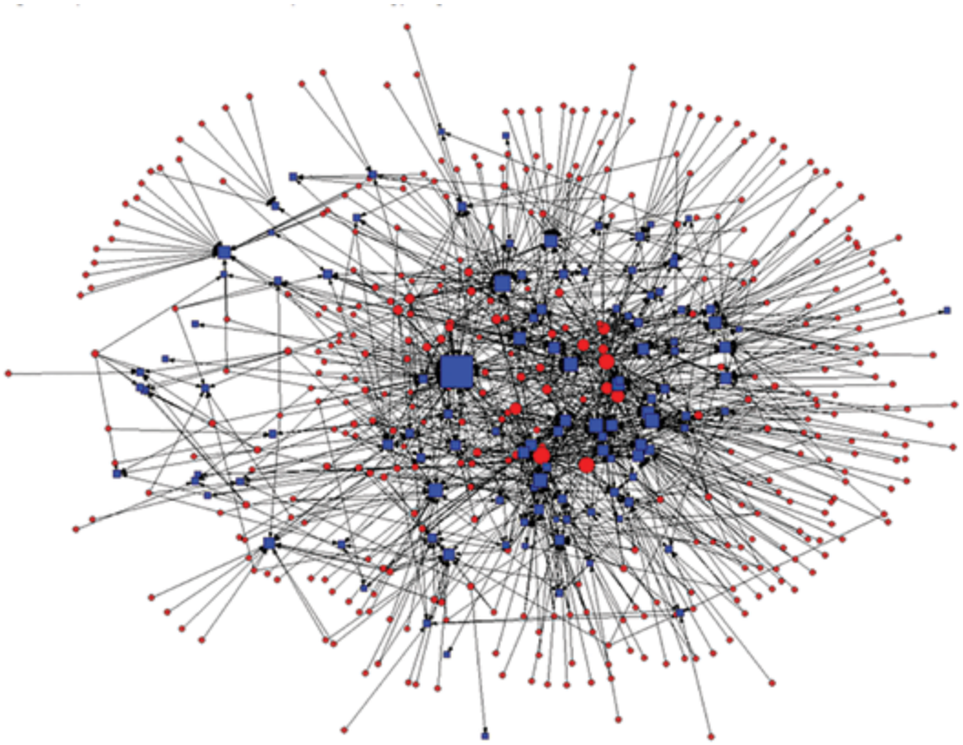


FIGURE 4. *Complexity diagram of actors (red circles) and institutions (blue squares) involved in water governance of San Francisco Bay (With permission from Lubell et al. 2014).*

CONCLUSION

Fishing family along the Sacramento River. Photo: Bird's Eye View

Continuously

improving models and scientific understanding is necessary but not sufficient to manage successfully the complex technical, political and resource challenges facing the Delta. Difficult political choices will be necessary in the face of uncertainty. Risks can be reduced by tracking the response of the Delta, in all dimensions, and adjusting actions accordingly

Conclusions: Coping with Complexity

The Sacramento-San Joaquin Delta is at the hub of an interconnected water-delivery system that feeds the impressive economy of California and also influences the economies of most of the western U.S. At the same time, the Delta is an ecological resource of international significance with a rich social and cultural history. The challenge in managing the Delta is to preserve all these important functions in the face of a widening demand for water that frequently exceeds available supply, including demand from a growing population, a growing economy, valuable agriculture, and a unique environment. The challenge is enhanced by climate change, which is raising temperatures, changing storm patterns, and reducing snowpack, leading to an increasingly uncertain supply of water and changing environmental conditions. Unsustainable mining of groundwater (Bredehoeft and Alley 2014) is increasing costs and decreasing the availability of a source of water that has long provided a buffer against drought. Water managers no longer have the flexibility they once had in dealing with the multi-year droughts that are inherent to the California climate. Managing the water supply system alone is complicated. But add in the imperative to sustain the ecological and social values of the Delta and every decision becomes considerably more complex. The current arrangement for addressing this combination of complexity, uncertainty, and change is unsustainable as evidenced by both declines in native species and dissatisfaction with water deliveries.

From an environmental perspective, the ecosystem of the Delta is vastly transformed from its original state, making life difficult for a host of native species. Multiple interacting factors affect the well-being of native species. Some of these factors are well understood, but their interactions and cumulative consequences are not, making it impossible to make definitive statements about what is causing native species to decline. As a result, predicting the outcome when water operations, land forms, or the levees are changed is uncertain, at best. Nevertheless, opportunities exist to conserve and restore aspects of the native system and to structure the rest of the Delta to make it more hospitable to native species. Realizing those opportunities without jeopardizing water supply is the ultimate challenge in managing the Delta.

Many of the approaches used in water-scarce environments elsewhere are under-utilized in the Delta. While adjustments to the infrastructure as it ages are essential, opportunities exist to simultaneously redefine bold action as we pursue proven (although not always initially popular) ways to work more effectively with what we have (www.energy.ca.gov/wet/). Examples include the following:

- Groundwater recharge and conjunctive use offer storage potential beyond that available for surface waters (CIWR 2015).
- Initiatives to promote water reuse, water recycling, and desalination in selected circumstances are under-utilized and can help address the imbalance between demand and supply (ACWA 2015).
- Priorities for maintenance and upgrades of the levees can be built from growing understanding of physical vulnerabilities, climate change, economics, and water transit needs (DSC 2015).
- Making water conservation a continual, long-term, statewide investment is a necessary part of accepting water scarcity (USEPA 2015; NatGeo 2014).
- Greater attention to both the tributaries and the Bay in Delta planning, including wetlands restoration, offer opportunities for both protection from sea level rise and ecosystem restoration (Save the Bay 2015).
- Continuing the precedent of improving water quality from tributary inputs and within Delta sources can help counter the expansion of exotic species (Brown and Caldwell 2015).

- Risk reduction for catastrophic Delta infrastructure failure can include investing in targeted levee improvements, addressing additional stresses from sea-level rise and planning for climatic extremes such as atmospheric rivers and long-term droughts.
- Making the "One Delta, One Science" concept a reality will improve the underpinning for political actions in the face of uncertainty (DSP 2013).

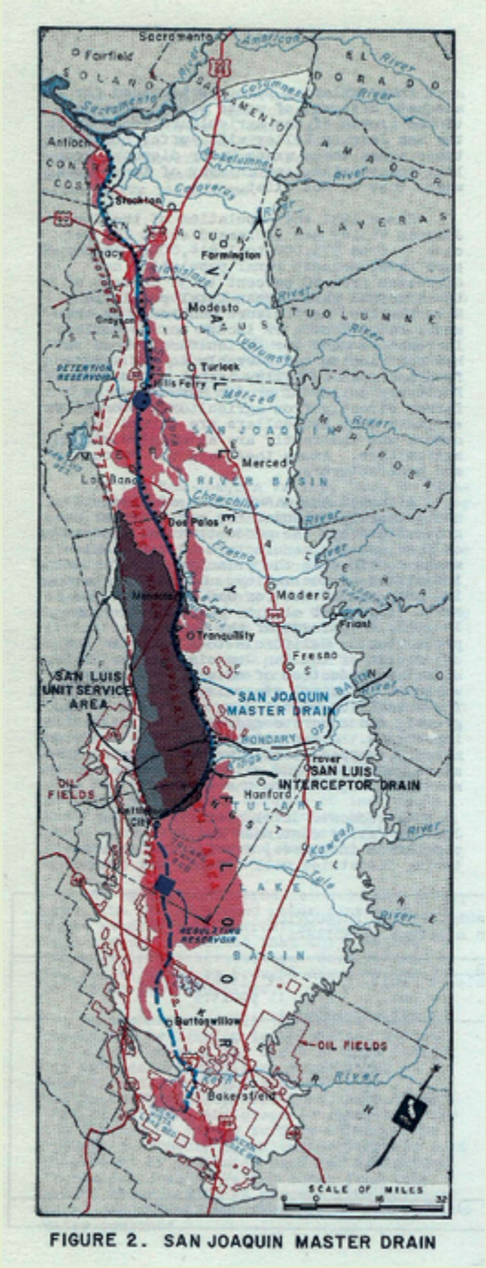
Complex, wicked problems like the Delta rarely yield to the simplistic solutions directed at only one dimension of the problem. The lack of flexibility resulting from the already complete allocation of a shrinking water supply, combined with the serious deterioration of the native ecosystem, will reduce the effectiveness of many traditional engineering solutions in the Delta. History shows that large-scale, irreversible, physical changes in the water system are particularly risky (see *San Luis Drain* opposite) unless they promote flexibility and are implemented incrementally (see *South Florida Example* p. 28). Incremental, as used here, does not imply "small," but "implementation in stages" such that lessons learned from early increments can be used to improve design of later increments. While economics alone may not always support such an approach, it is time to recognize that other dimensions of the issue also must carry weight.

New approaches to scenario-building and modeling can help managers explore the potential outcome of major management initiatives and anticipate problems before they arise. Modeling and scenario-building needs to be a collaborative, multi-institutional activity. As we enter an era of increasing uncertainty about climate, water supply, the fate of the Delta's native ecosystem, and institutional complexity, multi-institutional collaborative approaches will become increasingly important.

IMPLEMENTING INADEQUATELY UNDERSTOOD ENGINEERING SOLUTIONS: THE SAN LUIS DRAIN EXAMPLE

An example of implementing a simple solution to a complex problem is the issue of irrigation drainage in the Central Valley.

- As a part of the Central Valley Water project in the 1950s, governments were obligated to deal with the return drainage that resulted from the export of water from the Delta.
- The simplest solution was to build drainage infrastructure under the agricultural fields and a canal (the San Luis Drain) to take the drainage to San Francisco Bay.
- The first increment of that system was completed in the 1980s with the drainage canal temporarily terminating near Kesterson Wildlife Refuge.
- Soon after the drainage disposal began, severe deformities were observed in birds, including birds that were part of the international Pacific Flyway. Later studies showed a massive ecological disaster, which was eventually attributed to heretofore unknown selenium contamination in the drainage (Presser 1994).
- Later studies showed that a similar, if not worse outcome was likely if the drain was extended to the Bay (Presser and Luoma 2000).
- Dealing with this problem has been much more expensive than the San Luis Drain itself. Adverse effects of irrigation drainage products such as selenium will always be an important consideration in any plans that change water redistribution systems. The selenium problem cannot be solved, but it is being incrementally managed by land retirement and multiple, local in-valley treatment systems. The San Luis Drain was a multi-million dollar "stranded investment" that resulted from a poorly understood, simplistic engineering "solution" to a complex problem with many dimensions.



San Joaquin Valley master drain plan circa 1965. Map: DWR

INCREMENTALLY APPROACHING A COMPLEX PROBLEM: A SOUTH FLORIDA EXAMPLE

Most Delta restoration projects have not been in place long enough to draw conclusions about the approaches being used. But the Kissimmee River in south Florida provides an example of how an incremental approach to restoration can work. Key elements of this widely proclaimed restoration success are listed here (see Dahm et al. 1995):

- River channelized for flood control from 1962-1971 at a cost of $38 million
- Collapse of key bird and fish communities
- Mounting interest and public pressure for restoration
- Pilot project to reroute some canal water back onto floodplain from 1984-1988 with positive responses from birds and fish
- Design phase for a large-scale restoration in the early 1990s with a rigorous evaluation program
- Testing sediment plug from old spoils piles to see if the channelized river could be rerouted onto the old floodplain in 1996; plug functioned as designed
- Construction of Phase One restoration 2000-2001 for about 30 kilometers of river and 3,200 hectares of wetland
- Initial restoration largely successful
- Currently carrying out Phase Two of restoration
- Restoration costs to date approaching one billion dollars

Water scarcity has defined and will continue to define the future of the Delta and all that is linked to it. California has risen to the challenge of water scarcity in the past to build an economy and a society that is, in many ways, the envy of the world. The present problem of water scarcity seems more complex and less amenable to traditional engineering solutions than in the past. But California has the tools and the intellectual resources to manage the problem and to achieve the twin goals of a reliable water supply and an ecologically diverse Delta ecosystem.

Kissimmee River restoration, showing flood control channel filled in so river meanders could be restored.
Photo: South Florida Water Management District

REFERENCES

Yolo Bypass floodplain during drought.
Photo: Bird's Eye View

As we enter an era of increasing uncertainty about climate, water supply, the fate of the Delta's native ecosystem, and institutional complexity, multi-institutional collaborative approaches will become increasingly important. California has the tools and the intellectual resources to manage these problems and, as difficult as they are, achieve the twin goals of reliable water supply and an ecologically diverse Delta ecosystem.

Footnotes

1 Widening demands for water are expected from projected population growth, economic growth, and demands to use water for the environment. The Delta Reform Act of 2009 states its "coequal" goals as "providing a more reliable water supply for California and protecting, restoring, and enhancing the Delta ecosystem. The coequal goals shall be achieved in a manner that protects and enhances the unique cultural, recreational, natural resource, and agricultural values of the Delta as an evolving place" (CA Water Code 85054). "Widening" means overall demand, not necessarily increasing demand per capita.

2 The El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) phenomena are two examples of ocean climate influences (http://www.pmel.noaa.gov/tao/elnino/el-nino-story.html).

3 http://www.bloomberg.com/news/articles/2015-01-16/brown-s-california-overtakes-brazil-with-companies-leading-world
http://ajed.assembly.ca.gov/keyinsightsintoinnovation and https://www.census.gov/foreign-trade/statistics/state/data/ca.html
http://www.ppic.org/content/pubs/report/R_512EHR.pdf
https://watershed.ucdavis.edu/files/biblio/R_314EHR_Paying_for_Water.pdf
http://en.wikipedia.org/wiki/Economy_of_California
http://www.delta.ca.gov/res/docs/ESP/ESP_ES_FINAL.pdf
Howitt et al. 2014 https://watershed.ucdavis.edu/files/biblio/DroughtReport_23July2014_0.pdf
http://www.delta.ca.gov/res/docs/ESP/ESP_ES_FINAL.pdf
http://www.washingtonpost.com/wp-srv/inatl/longterm/mia/part1.htm

References

[ACWA] Association of California Water Agencies. 2015. Local agencies find innovative ways to reduce use [Internet]. Sacramento (CA): ACWA; [accessed 2015 Sep 21]. Available from: *http://www.acwa.com/content/local-agencies-find-innovative-ways-reduce-use*

Austin C. 2015. Pat Mulroy to California: Fix the Bay Delta [Internet]; Maven's Notebook. [accessed 2015 Sep 21]. March 24, 2015. Available from: *http://mavensnotebook.com/2015/03/24/pat-mulroy-to-california-fix-the-bay-delta/*

Bates ME, Lund JR. 2013. Delta subsidence reversal, levee failure and aquatic habitat: a cautionary tale. San Franc Estuary and Watershed Sci [Internet] [accessed 2015 Sep 21];11(1). Available from: *http://escholarship.org/uc/item/9pp3n639* doi: *http://dx.doi.org/10.15447/sfews.2013v11iss1art1*

Baxter R, Breuer R, Brown L, Conrad L, Feyrer F, Fong S, Gehrts K, Grimaldo L, Herbold B, Hrodey P, Müeller–Solger A, Sommer T, Souza K. 2010. Interagency Ecological Program 2010 pelagic organism decline work plan and synthesis of results. Available from: *http://www.water.ca.gov/iep/docs/ FinalPOD2010Workplan12610.pdf*

Bredehoeft JD, Alley WM. 2014. Mining groundwater for sustained yield. The Bridge 44(1):33–41. Available from: *http://www.researchgate.net/profile/William_Alley2/publication/269872295_Mining_Groundwater_for_Sustained_Yield/links/54982bf80cf2519f5a1dc84b.pdf*

Brown and Caldwell. 2015. Sacramento Regional County sanitation district: pilot study [Internet]. Sacramento (CA): Brown and Caldwell; [accessed 2015 Sep 21]. Available from: *http://www.brownandcaldwell.com/pilotStudy/*

Cayan DR, Dettinger MD, Diaz HF, Graham NE. 1998. Decadal variability of precipitation over Western North America. J Climatol 11:3148–3166. doi: *http://dx.doi.org/10.1175/1520-0442(1998)011<3148:DVOPOW>2.0.CO;2*

[CDWR] California Department of Water Resources. 2014. Groundwater sustainability program draft strategic plan. March 2015. Available from: *http://www.water.ca.gov/groundwater/sgm/pdfs/DWR_GSP_DraftStrategicPlanMarch2015.pdf*

[CDWR] California Department of Water Resources. 2015. Where rivers meet—the Sacramento–San Joaquin Delta [Internet]. Sacramento (CA): CDWR; [updated 2008 Jul 18; accessed 2015 Sep 21] Available from: *http://www.water.ca.gov/swp/delta.cfm*

[CIWR] California Institute of Water Resources. 2015. Improving groundwater recharge [Internet]. Oakland (CA): University of California, Division of Agriculture and Natural Resources; [accessed 2015 Sep 21] Available from: *http://ciwr.ucanr.edu/CIWR_Making_a_difference/Completed_projects/Improving_groundwater_recharge_/*

Cloern, JE, Jassby A. 2012. Drivers of change in estuarine-coastal ecosystems: discoveries from four decades of study in San Francisco Bay. Rev Geophys 50,RG4001. 33 p. doi: *http://dx.doi.org/10.1029/2012RG000397*

Cloern JE, Knowles N, Brown LR, Cayan D, Dettinger MD, Morgan TL, Schoellhamer DH, Stacey MT, van der Wegen M, Wagner RW, Jassby AD. 2011. Projected evolution of California's San Francisco Bay–Delta river system in a century of climate change. PLoS ONE 6(9)e24465. doi: *http://dx.doi.org/10.1371/journal.pone. 0024465*

Cohen AN, Carlton JT. 1998. Accelerating invasion rate in a highly-invaded estuary. Science 279:555–558. doi: *http://dx.doi.org/10.1126/science.279.5350.555*

[CSA] California State Assembly. 2010. Fast facts on California's innovation economy [Internet]. Sacramento (CA): CSA; [accessed 2015 Sep 21]. Available from: *http://ajed.assembly.ca.gov/keyinsightsintoinnovation*

Dahm, CN, Cummins KW, Valett HM, Coleman RL. 1995. An ecosystem view of the restoration of the Kissimmee River. Rest Ecol 3(3):225–238. doi: *http://dx.doi.org/10.1111/j.1526-100X.1995.tb00172.x*

del Rosario RB, Redler YJ, Newman K, Brandes PL, Sommer T, Reece K, Vincik R. 2013. Migration patterns of juvenile winter-run-sized Chinook salmon (*Oncorhynchus tshawytscha*) through the Sacramento–San Joaquin Delta. San Franc Estuary and Watershed Sci [Internet] [accessed 2015 Sep 21];11(1). Available from: *https://escholarship.org/uc/item/36d88128*. doi: *http://dx.doi.org/10.15447/sfews.2013v11iss1art3*

Dettinger MD. 2015. Sturm und drang: California's remarkable storm–drought connection. Hydrolink [Internet]. [accessed 2015 Sep 21];(1):21–22. Madrid and Bejing (Spain and China): International Association for Hydro-Environment Engineering and Research (IAHR). Available from: *http://tenaya.ucsd.edu/~dettinge/hydrolink5_2015.pdf*

Dettinger MD, Cayan DR. 2015. Drought and the California Delta—a matter of extremes: San Franc Estuary and Watershed Sci [Internet] [accessed 2015 Sep 21];12(2). Available from: *http://escholarship.org/uc/item/88f1j5ht* doi: *http://dx.doi.org/10.15447/sfews.2015v13iss2art1*

Dettinger MD, Ralph FM, Das T, Neiman PJ, Cayan DR. 2011. Atmospheric rivers, floods, and the water resources of California. Water 3:445–478. doi: *http://dx.doi.org/10.3390/w3020445*

DiGennaro B, Reed D, Swanson C, Hastings L, Hymanson Z, Healey M, Siegel S, Cantrell S, Herbold B. 2012. Using conceptual models and decision-support tools to guide ecosystem restoration planning and adaptive management: an example from the Sacramento–San Joaquin Delta, California. San Franc Estuary and Watershed Sci [Internet] [accessed 2015 Sep 21];10(3). Available from: *http://escholarship.org/uc/item/3j95x7vt* doi: *http://dx.doi.org/10.15447/sfews.2012v10iss3art1*

[DPC] Delta Protection Commission. 2012. Economic sustainability plan for the Sacramento–San Joaquin River Delta: executive summary. Available from: *http://www.delta.ca.gov/res/docs/ESP/ESP_ES_FINAL.pdf*

Dryzek J, Norgaard R, Schlosberg D. 2013. Climate-challenged society. [London (UK)]: Oxford University Press. Available from: *http://global.oup.com/academic/product/climate-challenged-society-9780199660117?cc=us&lang=en&*

[DSC] Delta Stewardship Council. 2013. Delta plan. Sacramento (CA): Delta Stewardship Council. Available from: *http://deltacouncil.ca.gov/sites/default/files/documents/files/DeltaPlan_2013_ CHAPTERS_COMBINED.pdf*

[DSC] Delta Stewardship Council. 2015. State investments in Delta levees: key issues for updating priorities. Sacramento (CA): Delta Stewardship Council. Available from: *http://deltacouncil.ca.gov/sites/default/files/2015/01/15-0109_Levee_Investment_Strategy_Issue_Paper.pdf*

[DSP] Delta Science Program. 2013. Delta science plan: one Delta, one science. Sacramento (CA): Delta Stewardship Council, Delta Science Program. Available from: *http://deltacouncil.ca.gov/science-program/delta-science-plan-0*

[USEPA] U.S. Environmental Protection Agency. 2015. How to conserve water and use it effectively [Internet]. San Francisco (CA): EPA. [updated 2012 Mar 06; accessed 2015 Sep 21] Available from: *http://water.epa.gov/polwaste/nps/chap3.cfm*

Famiglietti JS, Lo M, Lo SL, Bethune J, Anderson KJ, Syed TH, Swenson SC, de Linage CR, Rodell M. 2011. Satellites measure recent rates of groundwater depletion in California's Central Valley. Geophys Res Lett 38(3):L03403. doi: *http://dx.doi.org/10.1029/2010GL046442*

Farhi P, Rosenfeld M. 1998. American pop penetrates worldwide: first of three articles [Internet]; The Washington Post, Made in America, October 25, 1998, page A1. [accessed 2015 Sep 21]. Available from: *http://www.washingtonpost.com/wp-srv/inatl/longterm/mia/part1.htm*

Faunt C, Sneed M. 2015. Climatic variability and land-use changes and their effect on water availability and subsidence in California's Central Valley. San Franc Estuary and Watershed Sci [Internet] [accessed 2015 Sep 21];13(3). doi: *http://dx.doi.org/10.15447/sfews.2015v13iss3art3*

Ferner M. 2012. Conclusion to the special issue: ecology and regional context of tidal wetlands in the San Francisco Bay National Estuarine Research Reserve. San Franc Estuary and Watershed Sci [Internet] [accessed 2015 Sep 21];10(2). Available from: *http://escholarship.org/uc/item/91815085* doi: *http://dx.doi.org/10.15447/sfews.2012v10iss2art1*

Fleck J. 2011. N.M. tied to water questions in California [Internet]; Albuquerque Journal; page A1. [updated 2011 Jun 28; accessed 2015 Sep 21]. Available from: *http://www.abqjournal.com/39401/upfront/nm-tied-to-water-questions-in-california.html*

Fleck J. 2012. What seven states can agree to do: deal-making on the Colorado [Internet]; Rural West Initiative. Stanford (CA): Bill Lane Center for the American West, Stanford University. [updated 2012 Aug 03; accessed 2015 Sep 21]. Available from: *http://web.stanford.edu/group/ruralwest/cgi-bin/drupal/content/what-seven-states-can-agree-do-deal-making-colorado-river*

Fox J. 2015. Greedy environment steals California's water. Bloomberg View [Internet]; [accessed 2015 Sep 21]. May 5, 2015. Available from: *http://www.bloombergview.com/articles/2015-05-05/greedy-environment-keeps-stealing-california-s-water*

Grantham TE, Viers JH. 2014. 100 years of California's water rights system: patterns, trends and uncertainty. Environ Res Lett 9:084012. doi: *http://dx.doi.org/10.1088/1748-9326/9/8/084012*

Hanak E, Gray B, Lund J, Mitchell D, Chappelle C, Fahlund A, Jessoe K, Medellin–Azuara, J, Misczynski D, Nachbaur J, Suddeth R. 2014. Paying for water in Calfornia. San Francisco (CA): Public Policy Institute of California. Available from: *https://watershed.ucdavis.edu/files/biblio/R_314EHR_Paying_for_Water.pdf*

Hanak E, Lund J, Dinar A, Gray B, Howitt R, Mount J, Moyle P, Thompson B. 2011. Reconciling ecosystems: reversing declines in native species. Chapter 5. In: Managing California's water: from conflict to reconciliation. San Francisco (CA): Public Policy Institute of California. *http://www.ppic.org/content/pubs/report/R_211EHChapter5R.pdf*

Hanak E, Lund J, Thompson B, Cutter WB, Gray B, Houston D, Howitt R, Jessoe K, Libecap G, Medellín–Azuara J, Olmstead S, Sumner D, Sunding D, Thomas B, Wilkinson R. 2012. Water and the California economy. San Francisco (CA): Public Policy Institute of California. Available from: *http://www.ppic.org/content/pubs/report/R_512EHR.pdf*

Healey MC. 2008. Science in policy development for the bay–delta. In: Healey MC, Dettinger MD, Norgaard RB, editors. The state of bay–delta science, 2008. Sacramento (CA): Delta Science Program. p. 155–169. Available from: *http://www.science.calwater.ca.gov/pdf/publications/sbds/sbds_final_update_122408.pdf*

Healey MC, Dettinger MD, Norgaard RB. 2008. New perspectives on science and policy in the bay–delta. In: Healey MC, Dettinger MD, Norgaard RB, editors. The state of bay–delta science, 2008. Sacramento (CA): Delta Science Program. p. 1–18. Available from: *http://www.science.calwater.ca.gov/pdf/publications/sbds/sbds_final_update_122408.pdf*

Hornberger MI, Luoma SN, van Geen A, Fuller CC, Anima R. 1999. Historical trends of metals in the sediments of San Francisco Bay, CA. Mar Chem 64:39–55. doi: *http://dx.doi.org/10.1016/S0304-4203(98)80083-2*

Howitt RE, Medellín–Azuara J, MacEwan D, Lund JR, Sumner DA. 2014. Economic analysis of the 2014 drought for California agriculture. Davis (CA): Center for Watershed Sciences, University of California, Davis. 20 p. Available from: *https://watershed.ucdavis.edu/files/biblio/DroughtReport_23July2014_0.pdf*

[IEP MAST] Interagency Ecological Program Management, Analysis, and Synthesis Team. 2015. An updated conceptual model of Delta Smelt biology: our evolving understanding of an estuarine fish [Internet]; [accessed 2015 Sep 22]. IEP technical report 90. Sacramento (CA): California Department of Water Resources. 200 p. Available from: *http://www.water.ca.gov/iep/docs/Delta_Smelt_MAST_Synthesis_Report_January%202015.pdf*

Janssen EML, Thompson JK, Luoma SN, Luthy RG. 2011. PCB-induced changes of a benthic community and expected ecosystem recovery following in situ sorbent amendment. Environ Toxicol Chem 30(8):1819e1826. doi: *http://dx.doi.org/10.1002/etc.574*

Jassby AD, Cloern JE, Cole BE. 2002. Annual primary production: patterns and mechanisms of change in a nutrient-rich tidal ecosystem. Limnol Oceanog 47:698–712. Available from: *http://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/docs/cmnt081712/sldmwa/jassbyetal2002.pdf*. doi: *http://dx.doi.org/10.4319/lo.2002.47.3.0698*

Knowles N, Dettinger MD, Cayan DR. 2006. Trends in snowfall versus rainfall in the western United States. J Climatol 19:4545–4559. doi: *http://dx.doi.org/10.1175/JCLI3850.1*

KTLA 5 News. 2015. Gov. Brown orders 25 percent cut in urban water use in 1st ever mandatory statewide reductions [Internet]; KTLA 5 News. [updated 2015 Apr 01; accessed 2015 Sep 21]. Available from: *http://ktla.com/2015/04/01/water-restrictions-in-california-ordered-by-gov-brown/*

Lehman PW, Boyer G, Hall C, Waller S, Gehrts K. 2005. Distribution and toxicity of a new colonial *Microcystis aeruginosa* bloom in the San Francisco Bay Estuary, California. Hydrobiologia 541:87–99. doi: *http://dx.doi.org/10.1007/s10750-004-4670-0*

Lubell M, Robins G, Wang P. 2014. Network structure and institutional complexity in an ecology of water management games. Ecol Soc 19(4):23. doi: *http://dx.doi.org/10.5751/ES-06880-190423*

Lund J, Hanak E, Fleenor W, Bennett W, Howitt R, Mount J, Moyle P. 2010. Comparing futures for the Sacramento–San Joaquin Delta. San Francisco (CA): Public Policy Institute of California. Available from: *http://www.ppic.org/content/pubs/report/R_708EHR.pdf*

Lund J, Hanak E, Fleenor W, Howitt R, Mount J, Moyle P. 2007. Envisioning futures for the Sacramento–San Joaquin Delta. Joaquin Delta. San Francisco (CA): Public Policy Institute of California. Available from: *http://www.ppic.org/content/pubs/report/R_207JLR.pdf*.

Marois MB, Pei S. 2015. Brown's California overtakes Brazil with companies leading world [Internet]. Bloomberg Business; [updated 2015 Aug 05; accessed 2015 Sep 21]. *http://www.bloomberg.com/news/articles/2015-01-16/brown-s-california-overtakes-brazil-with-companies-leading-world*

Moore J, Shlemon R. 2008. Levee system fragility. In: Healey MC, Dettinger MD, Norgaard RB, editors. The state of bay–delta science, 2008. Sacramento (CA): Delta Science Program. p. 103–120. Available from: *http://www.science.calwater.ca.gov/pdf/publications/sbds/sbds_final_update_122408.pdf*

Mount J. 2011. Water—who uses how much? California WaterBlog [Internet]; [accessed 2015 Sep 21]. May 5, 2011. Available from: *http://californiawaterblog.com/2011/05/05/water%E2%80%94who-uses-how-much/*

Moyle P, Bennett W, Durand J, Fleenor W, Gray B, Hanak E, Lund J, Mount J. 2012. Where the wild things aren't: making the Delta a better place for native species. San Francisco (CA): Public Policy Institute of California. Available from: *http://www.ppic.org/content/pubs/report/R_612PMR.pdf*

Muir WD, Smith SG, Williams JG, Hockersmith EE, Skalski JR. 2001. Survival estimates for migrant yearling Chinook salmon and steelhead tagged with passive integrated transponders in the Lower Snake and Lower Columbia rivers, 1993–1998. N Am J Fish Manage 21(2):269–282. doi: *http://dx.doi.org/10.1577/1548-8675(2001)021<0269:SEFMYC>2.0.CO;2*

Myers N, Mittermeier RA, Mittermeier CG, da Fonseca GAB, Kent J. 2000. Biodiversity hotspots for conservation priorities. Nature 403:853–858. doi: *http://dx.doi.org/10.1038/35002501*

[NatGeo] National Geographic. 2015. 5 dramatic ways California is tackling drought [Internet]; [accessed 2015 Sep 21]. May 09, 2014. Available from: *http://news.nationalgeographic.com/news/2014/05/140508-drought-california-water-shortage-conservation/*

[NRC] National Research Council. 2012. Sustainable water and environmental management in the California Bay–Delta. Washington, D.C.: The National Academies Press. 260 p.

Rubissow–Okamoto A. 2014. Keeping the salt field at bay. Estuary News [Internet]. [accessed 2015 Sep 21];23(1). Oakland (CA): San Francisco Estuary Partnership. Available from: *http://www.sfestuary.org/salt-field/*

Presser TS. 1994. The Kesterson effect. Environ Manage 18(3):437–454. Available from: *http://wwwrcamnl.wr.usgs.gov/Selenium/Library_articles/presser_kesterson_eff_1994.pdf* doi: *http://dx.doi.org/10.1007/BF02393872*

Presser TS, Luoma SN. 2000. Forecasting selenium discharges to the San Francisco Bay–Delta estuary: ecological effects of a proposed San Luis Drain extension. U.S. Geological Survey Open-File Report 00-416. 358 p. Available from: *http://pubs.usgs.gov/of/2000/ofr00-416/*

Richardson SD, Postigo C. 2012. Drinking water disinfection by-products. In: Barceló D, Kostianoy AG, editors. Emerging organic contaminants and human health. The handbook of environmental chemistry, vol. 20 p. 93–137. doi: *http://dx.doi.org/10.1007/698_2011_125*

Rittel H, Webber M. 1973. Dilemmas in a general theory of planning. Policy Sci 4(2):155–169.

Santos MJ, Khanna S, Hestir EL, Andrew ME, Rajapakse SS, Greenberg JA, Anderson LWJ, Ustin SL. 2009. Use of hyperspectral remote sensing to evaluate efficacy of aquatic plant management. Invasive Plant Sci Manage 2:216–229. doi: *http://dx.doi.org/10.1614/IPSM-08-115.1*

Save the Bay. 2015. Why wetland restoration [Internet]. Oakland (CA): Save the Bay; [accessed 2015 Sep 21]. Available from: *http://www.savesfbay.org/why-wetland-restoration*

Sommer T, Armor C, Baxter R, Breuer R, Brown L, Chotkowski M, Culberson S, Feyrer F, Gingras M, Herbold B, Kimmerer W, Müeller–Solger A, Nobriga M, Souza K. 2007. The collapse of pelagic fishes in the upper San Francisco Estuary. Fisheries 32:270–277. doi: *http://dx.doi.org/10.1577/1548-8446(2007)32[270:TCOPFI]2.0.CO;2*

Stewart AR, Luoma SN, Elrick KA, Carter JL, van der Wegen M. 2013. Influence of estuarine processes on spatiotemporal variation of bioavailable selenium. Mar Ecol Prog Ser 492:41–56. doi: *http://dx.doi.org/10.3354/meps10503*

[USDC] U.S. Department of Commerce. 2015. State exports from California [Internet]. U.S. Census Bureau, Foreign Trade; [updated 2015 Aug 5; accessed 2015 Sep 10]. Available from: *https://www.census.gov/foreign-trade/statistics/state/data/ca.html*

van Geen A, Luoma SN. 1999. A record of estuarine water contamination from the Cd content of foraminiferal tests in San Francisco Bay, CA. Mar Chem 64(1–2):57–69. doi: *http://dx.doi.org/10.1016/S0304-4203(98)00084-X*

Weston DP, Lydy MJ. 2010. Urban and agricultural sources of pyrethroid insecticides to the Sacramento–San Joaquin Delta of California. Environ Sci Technol 44(5):1833–1840. doi: *http://dx.doi.org/10.1021/es9035573*

Whipple A, Grossinger RM, Rankin D, Stanford B, Askevold RA. 2012. Sacramento–San Joaquin Delta historical ecology investigation: exploring pattern and process. Richmond (CA): San Francisco Estuary Institute, Aquatic Science Center. 408 p. Available from: *http://www.sfei.org/documents/sacramento-san-joaquin-delta-historical-ecology-investigation-exploring-pattern-and-proces*

[Wiki] Wikipedia contributors. 2015. Economy of California [Internet]. Wikipedia, The Free Encyclopedia; [updated 2015 Aug 5; accessed 2015 Sep 21]. Available from: *https://en.wikipedia.org/w/index.php?title=Economy_of_California&oldid=674682502*