2. Geophysical Setting and Consequences of Management in the Bay-Delta

Steven Culberson,[1] Loren Bottorff,[2]
Mark Roberson,[3] Elizabeth Soderstrom[1]

At the heart of California is the four hundred mile-long Central Valley—a large, relatively flat, fertile valley between the coastal mountain ranges and the Sierra Nevada, running from Mount Shasta in the north to Fresno in the south. Its northern half is drained by the Sacramento River and is referred to as the Sacramento Valley, whereas its southern half is drained by the San Joaquin River and is the San Joaquin Valley.

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[1] CALFED Science Program

[2] URS Corporation

[3] CALFED Bay-Delta Program

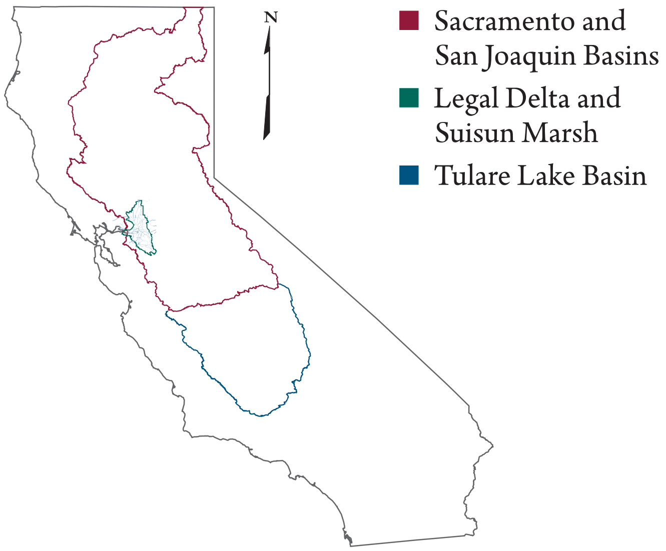

Figure 2.1. California's Central Valley, highlighting the location of the Sacramento-San Joaquin Delta. (Source: URS Corporation 2007)

The two valleys and their rivers meet in the area between Sacramento and Stockton and form the Sacramento-San Joaquin Delta, a geometrically complex network of interconnected canals, streambeds, sloughs, marshes, and peat islands, which drain into the Suisun and San Francisco Bays (see Figure 2.1). This unique estuarine resource is an integral part of California's water system, and assumes varied levels of importance when viewed from global, national, state and regional contexts.

The Delta is part of an estuary system. Like all estuaries, the ecological processes of the Bay-Delta are intricately linked to the coastal ocean and tidal influence, as well as inland rivers, resulting in high variability at many scales and across many linkages.[1] From a global context, the 1,315-square-mile Delta is one of a few dozen inland delta systems in the world. Before images from low Earth orbit were available, inland deltas or megafans were considered by geologists to be generated by large rivers, at major mountain fronts and most likely related to arid climates. We now know inland deltas exist worldwide, in all climates and that neither major mountain fronts nor large rivers are necessary for their development since they are often generated by relatively small rivers. California's Bay-Delta is unique among inland deltas because it is characterized by a wet winter and dry summer precipitation regime. The Mediterranean climate in California is important because it drives a crucial mismatch between the timing of California's water demands and water supplies. The Delta's climate is also unusual in its extreme variability (Cayan et al. 2003), which routinely yields extended periods of drought or periods of widespread flooding. Indeed, the year-to-year variations of the combined flows from the Central Valley are notably larger (relative to their long-term averages) than other large western rivers, the Columbia and Colorado, for example.

On a national scale, the Bay-Delta system is the largest estuary on the West Coast. The Delta includes fifty-seven islands, eleven-hundred miles of levees, and hundreds of thousands of acres of marshes, mudflats and farmland. Ecologically, the Delta is home to an array of ecosystems and more than seven hundred plant and animal species,

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[1] Discussed in greater detail in Chapter 7

including many unique to this estuary. The Bay-Delta eco-region is an important resting and feeding area on the Pacific Flyway, and an important breeding ground for many waterfowl species. From an economic perspective, the Bay-Delta plays an important role nationally—California has the estimated seventh-largest economy in the world, generating a Gross Domestic Product of about $1.5 trillion annually, and is the world's fifth-largest supplier of food and agricultural commodities (California Department of Finance 2005). Of the 8.5 million acres of irrigated farmland in California, about 3 million acres are irrigated from Delta-associated water supplies, resulting in at least $27 billion in agricultural income—45 percent of the nation's agricultural production.

From a state perspective, the Bay-Delta system is one of few estuaries in the world used as a major drinking water supply; the system provides some or all of the drinking water for two-thirds of the state's population (twenty-three million people). The Delta also provides estuarine habitat for many resident and migratory species, some state and/or federally listed as threatened or endangered, including winter- and spring-run Chinook salmon *(Oncorhynchus tshawytscha)*, Central Valley steelhead *(Oncorhynchus mykiss irideus)*, Delta smelt *(Hypomesus transpacificus)*, Sacramento splittail *(Pogonichthys macrolepidotus)*, Southern green sturgeon *(Acipenser medirostris)*, giant garter snake *(Thamnophis gigas)*, salt marsh harvest mouse *(Reithrodontomys raviventris)*, Suisun song sparrow *(Melospiza melodia maxillaries)*, California clapper rail *(Rallus longirostris obsoletus)*, Valley elderberry longhorn beetle *(Desmocerus californicus dimorphus)*, Delta green ground beetle *(Elaphrus viridis)*, Suisun thistle *(Cirsium hydrophilum* var. *hydrophilum)*, and soft bird's-beak *(Cordylanthus mollis* ssp. *mollis)*.[2]

Regionally, many islands in the Delta and adjacent lands sustain productive agriculture. Water supply is critical. In addition to the water exported through the Central Valley Project (CVP) and the State Water Project (SWP), nearly 90 percent of municipal water used in the East Bay is diverted from the Delta or transported across it in aqueducts. The cities of Sacramento and Stockton have seaports, and regularly maintained shipping channels cut through the Delta. The Delta also serves as a transportation corridor with roads, bridges and auto ferries connecting islands and tracts. A variety of utilities (electrical transmission, natural gas, petroleum and water pipelines) also cross islands, sloughs and tracts. With more than seven hundred miles of waterways, water-based recreation and tourism is increasing in the Delta. There are 191 hunting clubs in Suisun Marsh and the Delta, and boating accounts for more than 6.4 million visitor-days annually.

California's statewide physiographic setting, climate, ecology, water flows and water resource infrastructure is context for the challenges facing California's water resource managers. This chapter focuses on the climate, hydrology and history of watershed modifications and water resources development. The chapter concludes with a discussion of major drivers or forces that have shaped and will continue to shape this waterscape into the future.

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[2] See Chapter 1 and United States Fish and Wildlife Service 2007 for a full list of threatened and endangered species, see http://ecos.fws.gov/tess_public

California's Mediterranean Climate

California has a Mediterranean climate, characterized by hot, dry summers and mild, wet winters. One important feature of this climate is that precipitation patterns are highly variable from year to year (inter-annually) and within years (seasonally) (see Figure 2.2). For example, although the average December precipitation for the period is about eight inches, the maximum December precipitation is over thirty inches, and minimum December precipitation is near zero. It is difficult to find any year that can be truly classified as average. Another feature of California hydrology is that more rain and snow fall in the northern part of the state than in the southern portion.

The variability of precipitation and runoff has important implications for the ecology of the state's watersheds, rivers and adjacent floodplains. For example, many native fishes use temperature and flow cues in rivers and streams to begin migration, spawning, or other life-stage activities (Williams 2006; Moyle 2002). The timing of spring snowmelt runoff in the Sierra Nevada or warming in the Delta in the summertime have important consequences for environmentally tuned ecosystem processes and functions, such as species shifts in aquatic communities or emergence of seedlings or flowering structures (Cayan et al. 2001; Sickman, Leydecker, and Melack 2001; Kondolf 2000), and may be partly responsible for patterns in occurrence and abundance for many species (Cronk and Fennessy 2001; Western 2001).

> "It is a mistake […] to think of California in terms of averages and regular cycles of precipitation. The evidence, both recent and in tree rings dating from prehistoric times, reveals great variation. [….] The long-term record reveals a similar pattern of alternating cycles of severe drought and heavy precipitation (Hundley 2001, p.10).

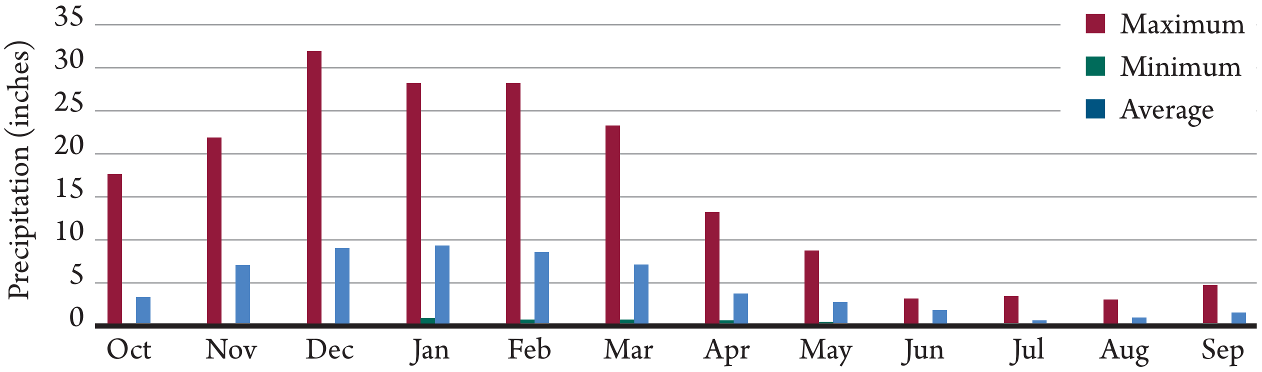
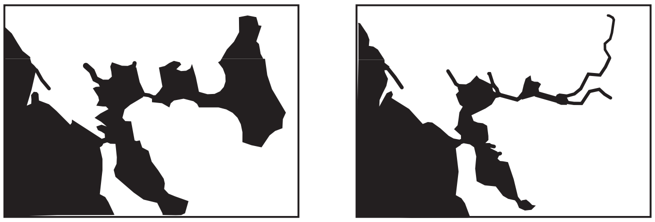


Figure 2.2. Northern Sierra monthly precipitation from 1921 to 2006 (averaged across precipitation measurements at Mt. Shasta City, Shasta Dam, Mineral, Brush Creek RS, Quincy, Sierraville RS, Pacific House and Blue Canyon). A year that produces the average precipitation values for each month would be extremely rare. (Source: California Data Exchange Center 2007)

15,000 Years Ago
(End of last Ice Age—sea level approximately 400 feet below present level; rivers not shown)

10,000 Years Ago
(Formation of Farallon Islands and intrusion into the "Golden Gate")

5,000 Years Ago
(Formation of Bay and Delta Basins)



125 Years Ago
(Landward edge of undiked tidal marsh)

Today
(Includes changes due to hydraulic mining sediment deposition, land reclamation, and filling of wetland areas)

Figure 2.3. Marine water intrusion into the Central Valley created the estuary we find today. (Source: The Bay Institute 1998)

These important relationships are further complicated when a given species also shows life-stage dependencies on Delta water quality (temperature, turbidity and salinity) patterns. Ecologists and hydrologists are increasingly finding evidence that many such complicated relationships are at the root of population abundance patterns (Nobriga et al. 2008; Feyrer, Nobriga, and Sommer 2007; Monsen, Cloern, and Burau 2007). It is also likely that invasive species exploit changes in local or regional water quality conditions to acquire or increase relative competitiveness over native and endemic species (Spalding and Hester 2007; Byers 2002). Indeed, longer-term (interdecadal) relationships between estuarine and coastal ocean processes have been shown to alter the biotic community structure found in the inland estuary of the Bay-Delta (Cloern et al. 2007).

Central Valley Hydrography, Past and Present

Approximately twenty thousand years ago, sea surface level was about four hundred feet lower than today, and the Delta did not exist in its current location until sea level began to rise about ten thousand years ago (see Figure 2.3). Aquatic species have used the ten thousand-year history of the incursion of tidal coastal ocean water into the Central Valley to fine-tune their use of the San Francisco Estuary's water resources to their particular life-history requirements. The variability of the Californian Mediterranean climate and regional and local environmental conditions is increasingly understood as being important to how endemic and native species have adapted and thrived over this history (Moyle 2002). Anadromous fish have passed through the Central Valley and into its tributaries for much longer than the Delta has existed.

In addition to precipitation-derived runoff, the Bay-Delta is influenced by the Pacific Ocean in the form of twice-daily tides that deliver a large amount of coastal ocean water and tidal energy to the Delta's hydraulic network. Tidal rise and fall varies with location, from less than one foot in the eastern Delta to more than five feet in the western Delta. The direction and magnitude of flows in Delta channels also vary during the tidal cycle, from 330,000 cubic feet per second (cfs) in the upstream (landward) direction to 340,000 cfs in the downstream (seaward) direction during a typical summer tidal cycle at Chipps Island (Hoffard 1980). The magnitudes of the tidal flows diminish at locations farther into the Delta, but nonetheless, for most of the Bay-Delta, twice-daily tides and varying inputs from rivers and streams result in highly dynamic conditions within a single day. Hydrodynamic conditions change continuously in the Delta, from one tide to the next, one day to the next, and one year to the next. Management of Delta water resources and ecosystems that depend on Delta water must contend explicitly with this inherent variability.

Estimates of unimpaired runoff—the flows that would have occurred without upstream dams and water diversions—provide an approximation of the range of annual flows into the Delta under natural (non-managed) conditions (see Figure 2.4). The period of record for the Central Valley (1906 to the present) illustrates the degree of variability in the unimpaired outflow from the Bay-Delta watersheds to San Pablo Bay. In 197, the outflow was five million acre-feet (MAF) and in 1983 it was about sixty MAF. This is an unusual degree of variability in outflow from a western North American river basin and poses unique challenges for water management (Cayan et al. 2003).

On a seasonal basis, flow variation has been greatly reduced as a result of storage dams. Winter and spring flows below dams are much reduced, whereas summer and autumn flows are increased (see Figure 2.5).

The modulation of the discharge curve indicates a general effect water project management has had on freshwater discharges throughout the Bay-Delta. This effect is more pronounced during drought years than in average or wet years but is present regardless of water-year type. However, even in the era of pronounced water development in California, the variability in Delta inflows is remarkable (see Figure 2.6; Lund et al. 2007).

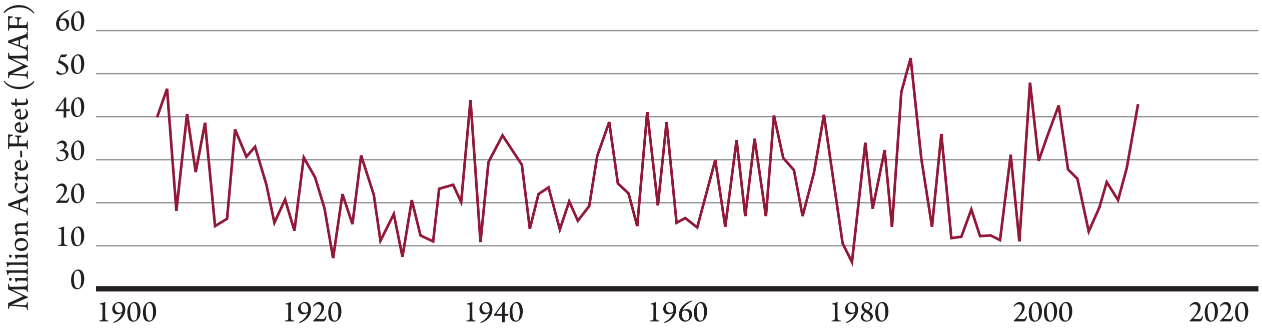


Figure 2.4. Combined Sacramento-San Joaquin River average annual unimpaired runoff for water years 1906 to 2006. The unimpaired runoff—an estimate of flows without upstream dams or diversions—shows the highly variable flow conditions from year to year. (Source: California Data Exchange Center 2007)

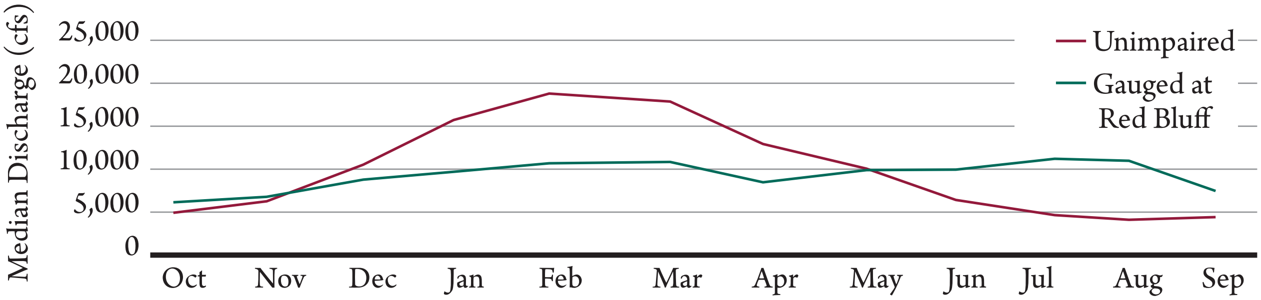


Figure 2.5. Seasonal distribution of observed versus unimpaired flow in the upper Sacramento River. (Source: The Bay Institute 1998)

With regard to the coupling of hydrology and species-specific life-history requirements, there is evidence that native species may be having difficulty persisting in the face of these hydrologic changes. Flood and floodplain-dependent species like the Sacramento splittail, migratory species like the various runs of Central Valley salmon, and pelagic species dependent upon Delta habitat like the Delta smelt are showing long-term declines in abundance, possibly due in part to alteration of the natural hydrograph of the Delta (Feyrer, Nobriga, and Sommer 2007; Williams 2006).[3]

Groundwater hydrology has also changed as a consequence of water development within the Central Valley (Alley 1993). Prior to about 1940, groundwater moved toward valley stream channels, and much of the valley was a discharge area. By 1970, pumping for agriculture and other uses had drawn groundwater reservoirs down hundreds of feet. Importation of irrigation water (from rivers or from the CVP) together with continued overuse of groundwater means the Central Valley is now primarily a groundwater recharge area, and most groundwater discharge is a result of pumping rather than natural seepage. As a result, salts and selenium accrete in Central Valley soils, poisoning agricultural runoff water. The storage capacity of Central Valley aquifers may also be substantially reduced as a result of compaction resulting from overdrafting and water table drawdown (Ireland, Poland, and Riley 1984).

Despite California's extensive system of water storage and flow management, there is growing evidence that our capacity to manage water supply and water quality is limited. For example, there is no getting around the fact that natural patterns of precipitation and runoff drive Central Valley hydrology, and that the salinities found in the Bay-Delta are driven as much by natural climate variability as they are by freshwater management (Knowles 2002). In addition, in spite of the billions of dollars invested in levees and flood control, a 150-year record of levee breaks in the Central Valley reveals that: (1) the frequency of levee breaks has not declined, and (2) the relationship between peak flows and the likelihood of levee failure has not changed (Florsheim and Dettinger 2007).[4]

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[3] Discussed in greater detail in Chapter 4

[4] Discussed in greater detail in Chapter 5

History of Watershed Modification and Water Resource Development

Several descriptions of California water resources development and watershed modification (Hundley 2001; The Bay Institute 1998; Kelley 1989; Reisner 1986) bear witness to the extent and degree to which humans have altered California's waterscape from its original natural condition and ecology. The contemporary Delta cannot be thought of as a natural system—it is a highly managed water supply and flood control system, with total upstream storage capacity roughly equal to the average annual total runoff from the watershed (see Figure 2.7). Many of the conflicts in California water management trace their origin to the difficulty of providing both ecological water and water for human uses from the common Delta water resource base.

An understanding of how human use of the land has changed through time, and how those uses have transformed physical and biological processes within the watershed, is fundamental to understanding how the Bay-Delta provides, or fails to provide, ecological services today. Reviewing land use change helps to assess how riverine and landscape function and quality have changed in relation to human influences.

Significant diversion and modification of stream flows in Sierra watersheds began during the Gold Rush (1850 through 1880) to facilitate gold mining (Hundley 2001; The Bay Institute 1998; Kelley 1989). Upstream mining operations had serious impacts on the Delta region. Hydraulic

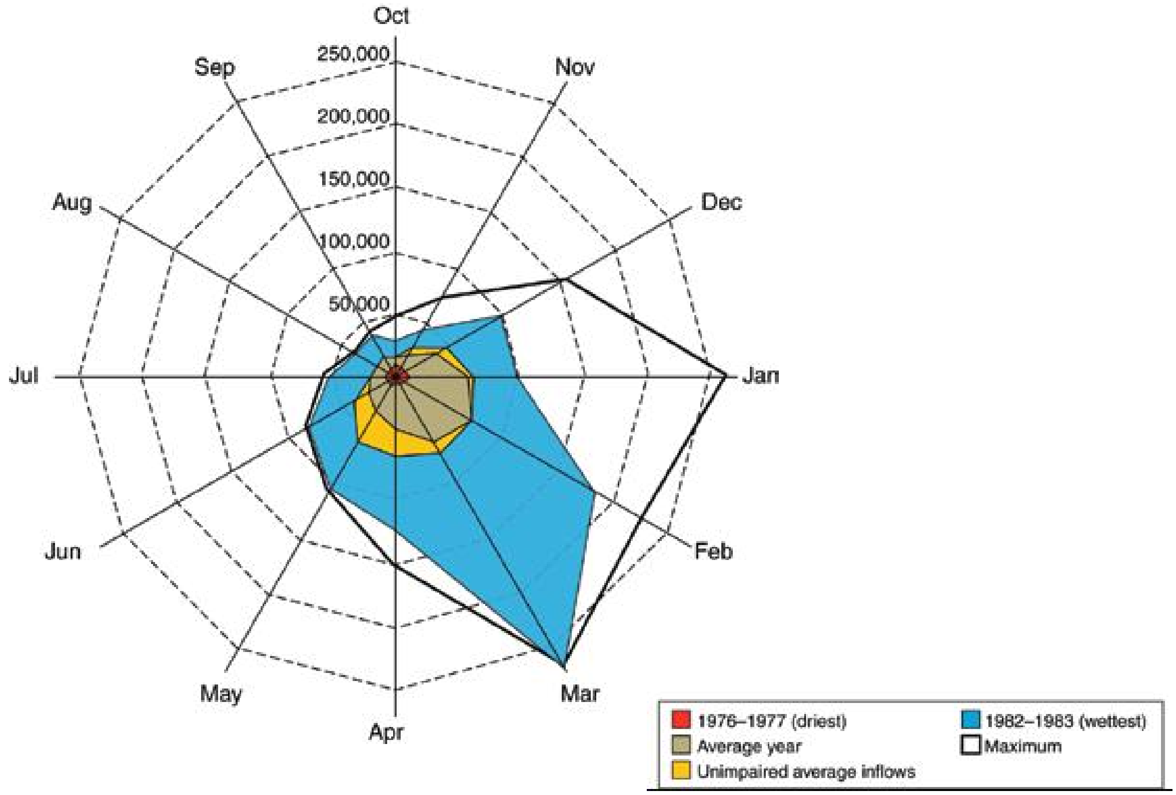

Figure 2.6. Seasonal and annual variability of Delta inflows, from 1956 to 2005 in cubic feet per second(cfs). (Source: Lund et al. 2007)

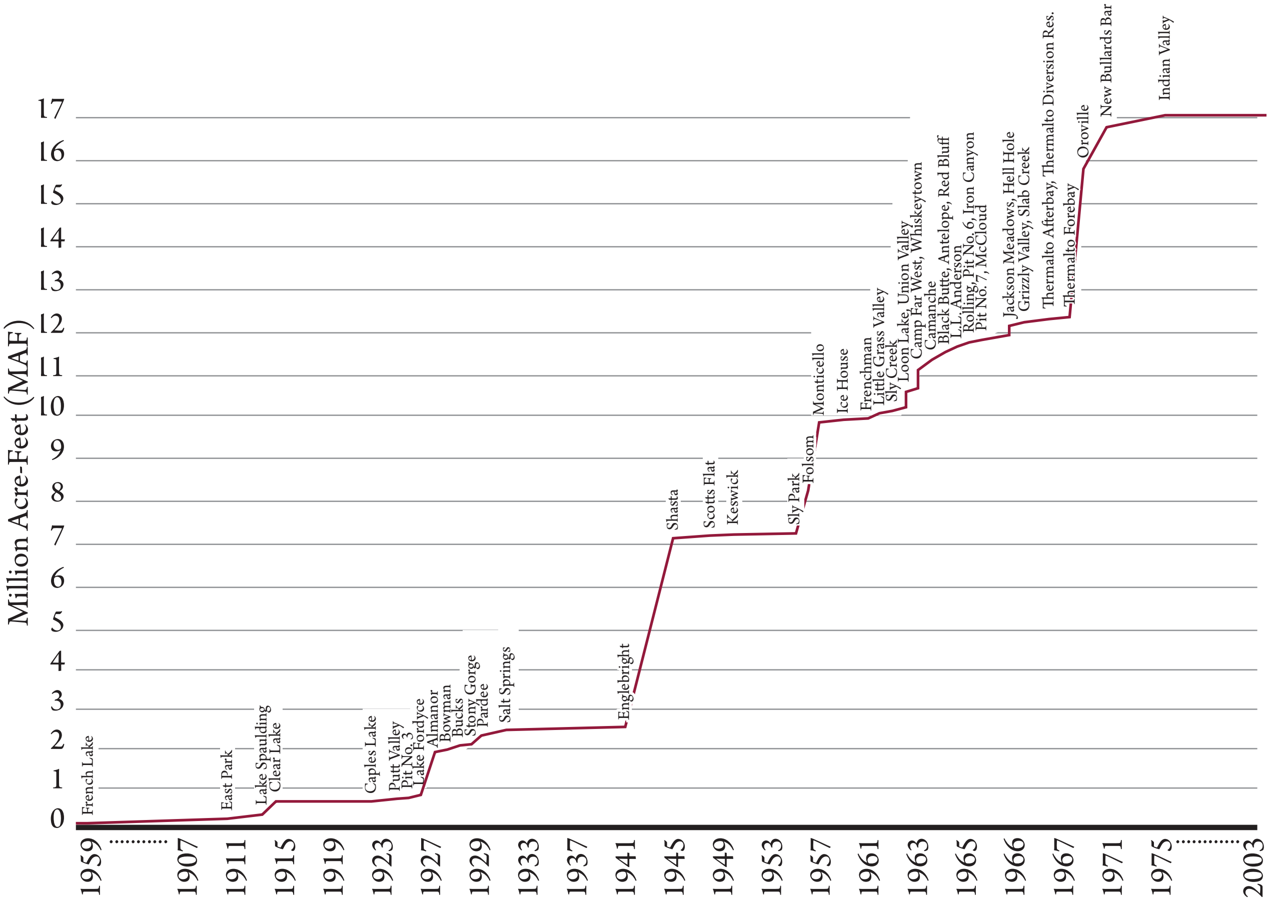

Figure 2.7. History of the development of Sacramento River water storage capacity, shown as million acre-feet (MAF) versus year, with each data point representing the indicated added storage reservoir. (Source: Chung 2007)

mining washed more than eight hundred million cubic yards of mining debris through the Delta. This is enough sediment to bury the whole 1,315-square-mile Delta area to a depth of about ten inches. Concentrated in the channels, the depth of sediment would be as much as five and one half feet! When washed down into the Central Valley this sediment raised streambeds and elevated water levels in upstream rivers and the Delta, causing frequent floods. Levees were built higher to protect surrounding homes and farmlands, and rivers were progressively disconnected from their floodplains. Shortly thereafter, major upstream water diversions for crop irrigation in the Central Valley began as local and regional markets for agricultural products grew. Water diversions from rivers and streams upstream of the Delta are now estimated at approximately four to ten MAF per year.

Alteration of sloughs and reclamation of lands within the Delta itself began for agricultural purposes, but became increasingly important as settlement of low-lying areas near Sacramento and other new centers of commerce and shipping developed. Levee construction for flood management within the Delta and along tributary rivers and streams isolated the floodplains from the periodic flooding. As many as 297,000 acres (460 square miles) of historic Central Valley floodplains have been separated from their parent rivers and streams.

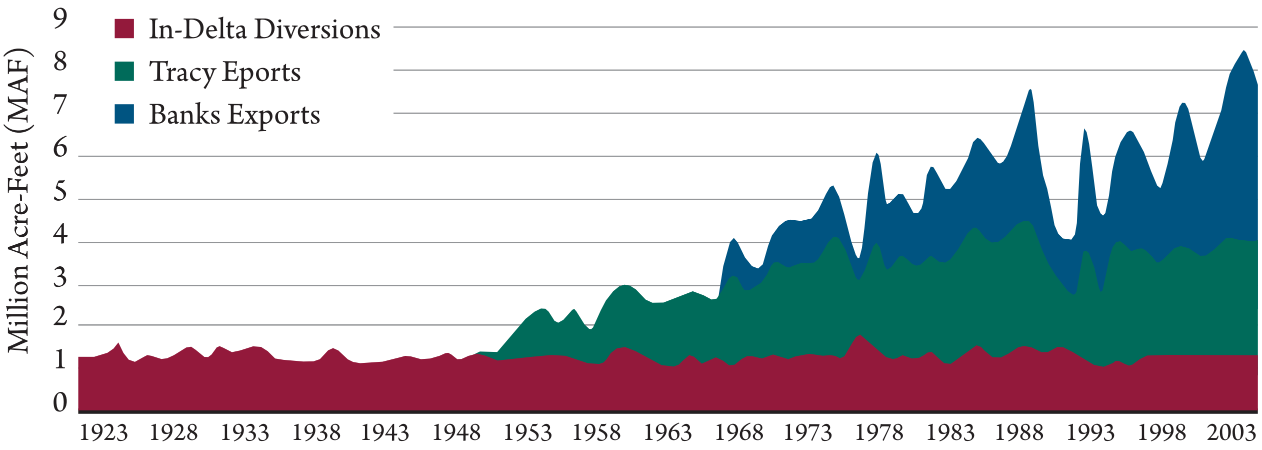

Figure 2.8. Delta Water Diversions and Exports. Delta diversions and exports have grown over time. In-Delta diversions for irrigation have been about the same since the early 1900s. Federal exports (Tracy) began in the early 1950s, and state exports (Banks) began in the late 1960s. (Source: URS Corporation 2007)

Historically, periodic flooding of these areas provided valuable habitat for many species and reduced flood stage farther downstream. The Delta itself absorbed flood flows to become a vast shallow lake. At its greatest extent prior to reclamation, the Delta covered 1,931 square miles of tidally influenced open water, mud flat and marsh. Today the network of Delta levees has substantially reduced the area exposed to the tides to about 618 square miles.

Water project construction occurred most aggressively between 1930 and 1980, a period of rapid urbanization and agricultural development throughout California. Large-scale water management was achieved through construction of dams for water supply, flood control, hydroelectric development, and through the establishment of several regional and statewide aqueducts. The Delta was incorporated into this water management system as the means by which to convey Sacramento River water to the export pumping facilities in the South Delta, where currently about eight MAF is exported annually (see Figure 2.8). The thriving state economy is closely tied to these water development projects. Collectively, the storage capacity of the reservoirs within the Delta's watershed is about thirty-two MAF, or about 1.3 times the average annual flow to the Delta. These reservoirs allow water managers flexibility for moving water in time and place by capturing water during high-flow periods and releasing it during low-flow periods. Reservoir management is complicated by the fact that most serve the dual purposes of flood control and water storage. To achieve these dual purposes, managers maintain free (flood control) space in reservoirs during the season of heavy storms, then capture as much flow as possible (mostly from snowmelt in some basins) from late-season (springtime) high flows. The stored water is released later during low-flow periods when water demand for agriculture is high.

California has less storage capacity than the two other large western United States river systems—the Columbia and Colorado Rivers (California storage capacity is thirty-two MAF; Columbia River storage capacity is fifty MAF; Colorado River storage capacity is sixty MAF). Whereas California's storage capacity is a bit more than one year's average runoff, compared with the Columbia (much lower at 30 percent of annual runoff) and the Colorado (much higher at four times annual runoff), the volumes are much different. The Columbia has relatively little year-to-year flow variability and relatively little storage; the Colorado has moderate year-to-year flow variability and a large storage capacity; the Central Valley has high flow variability, medium storage relative to runoff, and the lowest volume storage capacity (Cayan et al. 2003).

There are approximately two thousand water diversions for irrigated agriculture in the Delta. These diversions are capable of diverting up to 5,000 cfs during peak periods of water use, and amount to additional withdrawal of about 1.7 MAF per year from the Delta.[5]

Delta water management occurs primarily by manipulating water project infrastructure (dams, gates and pumps). The geometry and alignment of some Delta channels have been modified to increase the flow of freshwater from the Sacramento River to the export facilities in the southern Delta, and to facilitate shipping to the ports of Stockton and Sacramento. In some channels, gates and barriers were added. Channel cuts made through some Delta islands have connected previously isolated sloughs. Delta hydrologists speculate that a consequence of these modifications has been an increase in hydrodynamic mixing within the Delta, and decreases in the variability of salinity, temperature, water clarity, residence time, nutrient loads and primary productivity (Enright, Culberson, and Burau 2006), with potentially large implications for the Delta ecosystem (Monsen, Cloern, and Burau 2007).

Bay-Delta water quality depends on tides, freshwater inflow, state and federal water quality regulation and natural and engineered structures. There is only limited and localized management or regulation of tides: what is managed is the location of the salinity gradient where marine and freshwater mix. This is done through the management of Delta inflows and export pumping. Freshwater inflow to the Delta depends on natural runoff, upstream diversions, return flows and storage or releases from upstream reservoirs that alter the natural runoff. The CVP and SWP use the Sacramento and San Joaquin Rivers and Delta channels to transport natural river flows to the South Delta export facilities, which changes the natural flow direction in some channels.

Human-caused changes in land-use patterns and the hydraulic geometry of river and Delta channels, have had lasting and variable impacts on water quality and the hydrodynamics (how water transport through Delta channels varies over time and with location) of the Bay-Delta as a whole (Enright, Culberson, and Burau 2006; Grossinger and Striplen 2006). As the watershed is increasingly altered, the water chemistry and temperature of the runoff will resemble the historical conditions less and less. There is evidence that changes to date have significantly altered pelagic and shallow water aquatic habitats to the detriment of native or otherwise-desirable Delta species (Sommer et al. 2007; Williams 2006).

Consequences of Water Development in California

Urbanization, industrialization and irrigated agriculture realized more-or-less directly via the development and management of California's water resources contribute substantially to the state economy. Irrigated agriculture alone contributes an estimated $27 billion annually to California's $1.5 trillion economy (California Department of Finance 2005). The indirect economic contribution of Delta-based water resources management

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[5] See Figure 1.3 in Introduction: New Perspectives on Science and Policy in the Bay-Delta

could amount to tens of billions of dollars more per year. In short, the state economy is fueled to a large degree by its Delta-based water management infrastructure. Urban development and population growth since about 1950 have largely been a function of the availability of water to urban users and agricultural producers in Southern California, the San Francisco Bay Area and in the Sacramento and San Joaquin Valleys. Additional land has been made available through flood control and reclamation of tidal and riparian areas throughout the state, including the Delta.

Environmental impacts of state economic and population growth and water resources development have presented policy challenges since environmental resources were first exploited (hydraulic mining debris impacts in the Central Valley during the 1880s, or over-fishing of salmon in the Sacramento River by the 1920s, for example), and these impacts have received enhanced attention since the adoption of national and state protection of endangered species and ecosystems beginning in the 1970s (Endangered Species Act, California Endangered Species Act). Recent examination of the impacts of water project development in the state has documented species population losses due to destruction of habitat, alteration of flow timing and changes in water chemistry, water velocities and runoff quantities (Healey 2007). As the Delta watershed becomes increasingly urbanized, toxic storm water runoff becomes more difficult to manage. Cheap and dependable water supplies throughout the state have created the expectation that affordable water supplies will expand in conjunction with an expanding economy, regardless of any natural limits on supply. Under-appreciation of levee failure risk has contributed to questionable building practices that leave entire communities vulnerable to catastrophic flooding (Lund et al. 2007). Sacramento, Stockton and adjacent areas including the Delta remain vulnerable to flooding similar to that experienced in New Orleans following Hurricane Katrina in 2005 (Seed 2005; URS Corporation and Jack R. Benjamin and Associates, Inc. 2007).

Future Changing Conditions and Drivers of Change

Lund et al. (2007) list the drivers of change affecting the current and future ecosystem, landscape and water project infrastructure of the Delta (not to mention human populations dependent upon these resources): subsidence; sea-level rise; seismicity; regional climate change; alien species; and urbanization. The Millennium Ecosystem Project[6] identifies a broader list of direct and indirect drivers of ecological change in nine categories that encompass the list by Lund et al. (2007), but also includes economic and sociopolitical drivers as well as science and technology drivers (Nelson et al. 2006). Under the umbrellas of sociopolitical drivers and science and technology drivers are legal instruments, such as listing species for protection under state and federal Endangered Species Acts, and declarations that certain water bodies are impaired or regulated under the Porter-Cologne Water Quality Control Act and the federal Clean Water Act. Adherence to regulations under these laws requires changes to water resource management perhaps equal in magnitude to any recent environmental or ecological changes in the Delta. Indeed, a shutdown of the SWP pumps in the winter of 2007 was due to endangered species (Delta smelt) concerns from a federal judge adjudicating state authority in pumping Delta water under state and federal Endangered Species Acts.

From a strictly hydrological viewpoint, we may be experiencing unprecedented change in climate and regional precipitation patterns that have not been

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[6] See: www.millenniumassessment.org/en/index.aspx

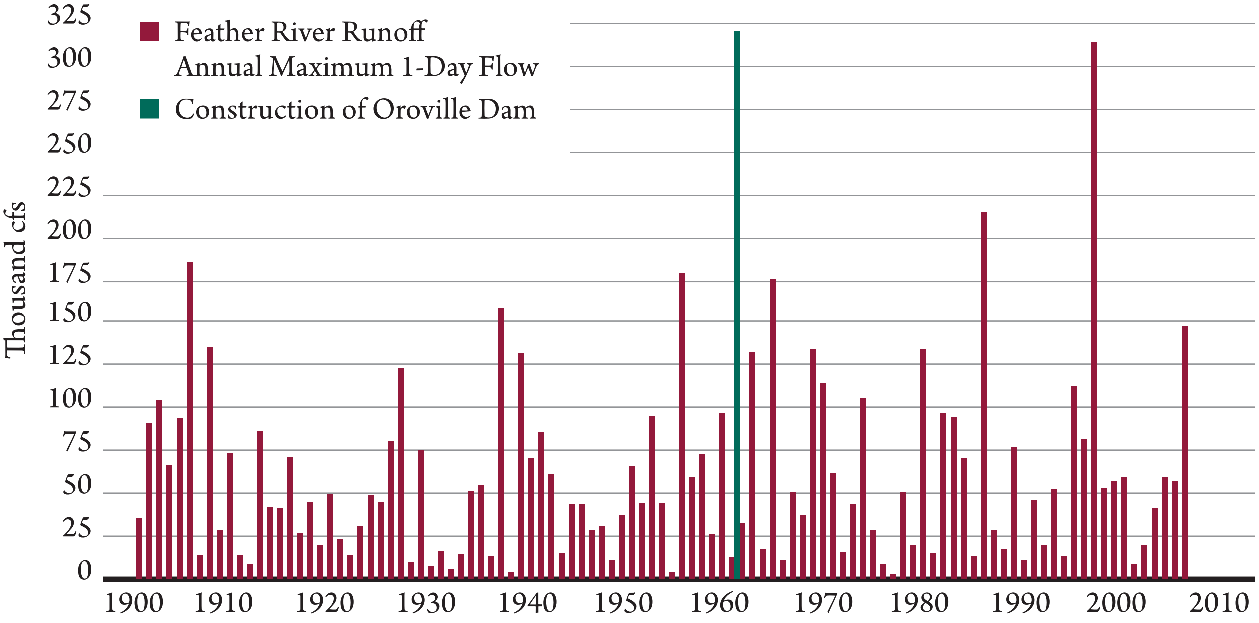

Figure 2.9. Changes in peak runoff flows (in thousand cfs) in the Feather River, from 1902 to 2006. (Source: Snow 2007)

adequately incorporated into our water resources management or infrastructure. By some accounts, peak runoff volumes have increased since the development of the state and federal water projects (see Figure 2.9).[7]

Historic hydrographs for Delta tributaries, developed during the twentieth century, may not reveal the full variability of peak flows that current or proposed dams are likely to encounter during their lifespans (Florsheim and Dettinger 2007; Snow 2007). Higher peak runoffs and diminishing snowpack will challenge our current water infrastructure and regulatory practices (California Department of Water Resources 2005; California Energy Commission 2006).[8] Even the most conservative (coolest) projections of twenty-first-century warming are expected to result in 30 percent declines in snowpack water content; more extreme projections would result in declines of 70 percent or more (California Energy Commission 2006).

Environmental conditions over the next several decades may change quickly, prompting movements in habitats, species communities and available resources throughout the Central Valley (Millar et al. 2006). Some species already at risk may face environmental conditions, such as warming of water beyond their physiological capability (Bennett 2005). Trends in peak runoff indicate earlier warming of streams in the spring that may lead to changes in timing of spring salmon migration patterns (Williams 2006). Changes in fish migration timing and distribution throughout the year may conflict with current water operation strategies and may affect future water deliveries, storage, or water quality. Sea-level rise will change Delta hydrodynamics, increase salinity levels and challenge our aging levee systems. A further future complication may be the occurrence of persistent long-term droughts (droughts of ten to twenty years or more), unknown in the recent past, but fairly regular when examining the paleodrought record of the inter-American west (Stahle et al. 2000; Stine 1994).

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[7] Discussed in greater detail in Chapter 6

[8] Discussed in greater detail in Chapter 6

Table 2.1. Paradigm Shifts Identified in *Envisioning Futures*

New Paradigm	Old Paradigm
The San Francisco Estuary is unique in many attributes, especially its complex tidal hydrodynamics and hydrology	The San Francisco Estuary works on the simple predictable model of East Coast estuaries with linear gradients of temperature and salinity controlled by outflow and edging marshes, both salt and fresh water, supporting biotic productivity and diversity
Alien species are a major and growing problem that significantly inhibits our ability to manage for desirable species	Alien (non-native) species are a minor problem or provide more benefits than problems
Changes in the management of one part of the entire estuary system affect other parts	The major parts of the San Francisco Estuary can be managed independently
Delta landscapes will undergo dramatic changes as the result of natural and human-caused forces such as sea-level rise, flooding, climate, and subsidence	The Delta is a stable geographic entity in its present configuration
The big pumps in the southern Delta are one of several causes of fish declines and their effect depends on species, export volume and timing of water diversions	The SWP and CVP pumps in the southern Delta are the biggest cause of fish declines in the estuary

(Source: Lund et al. 2007, pp. 219-222.)

Accumulation of Scientific Knowledge and Changing Ecological Understanding

Inasmuch as the “state of the science” leads us to focus on details, there is a danger that we will lose sight of the larger picture. Contentious water development and allocation issues have frequently been treated as arguments over specific contract or regulatory requirements, over specific measures of compliance or achievement, or over whose expert opinion is to be believed. When the atmosphere is adversarial, it is easy to lose sight of the degree to which our foundational scientific knowledge has changed over time. Moyle (Lund et al. 2007) describes a number of paradigm shifts in the way we understand the Delta and its ecosystem that have occurred over the past decade. These paradigm shifts express very clearly how much our understanding of the Delta has evolved and grown as a result of CALFED and other science: Table 2.1.

To these we add five paradigm shifts: Table 2.2. Not only does the Bay-Delta evolve and change with time, so too does our understanding evolve and change. What we may have valued about

Table 2.2. Additional Paradigm Shifts

New Paradigm	Old Paradigm
Coastal ocean influences and species are an important source of variability in the Bay-Delta	The Delta is primarily driven by riverine influences, species and outflow magnitude
Tidal channel geometry is a major factor contributing to hydrodynamic mixing within the Delta, as well as ecosystem viability and water quality, throughout large parts of the Delta	Reconfiguring a Delta slough is best considered a local operational concern
Sediment supplies to the Delta are changing and are having important ecological implications	The Delta is a cloudy and muddy mixing zone; the legacy of hydraulic mining is the source of any problems
Delta wetlands can be an important source of flood control and water quality maintenance	Wetlands are of little value but can be reclaimed for economic benefit
Restored wetlands can in some cases become sources of recycled contaminants so that wetland restoration needs to be designed and located to minimize any negative consequences	Restoration of wetlands always has multiple positive benefits for species, flood control and water quality

the Bay-Delta fifty years ago may not be what we value today, and may not be what we value fifty years hence. The suite of species driving restoration and protection programs today are not those which drove these programs twenty years ago and are not likely to be those which will drive such programs twenty years from now. Our state of knowledge, and the state of our science, is constantly being updated. Management practices will improve to the extent that we update them to reflect our growing understanding. *The State of Bay-Delta Science, 2008* summarizes the new knowledge available to inform debate about future management practices to sustain the Bay-Delta as a key component of California's water supply system and as a living, working ecosystem.

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