3 Drivers of Change

GERD LUDWIG/CORBIS

He who foretells the future lies, even if he tells the truth.

Arabian proverb

California's water management systems have always had to accommodate changing conditions, such as population growth and major shifts in the state's economic structure, from mining in the 1800s to agriculture in the 1900s to today's predominantly urban economy. The most urgent and overarching challenge for water management in the modern era is to reconcile the demands of the environment with the large and evolving demands for water for human activities. Policymakers at all levels will need to address this task in the midst of shifting conditions. In the coming decades, California is likely to experience wide-ranging and simultaneous changes that will further complicate water management but that will also present new opportunities (Table 3.1).

- **Climate.** Sea level rise, warming land and water temperatures, and shifting precipitation will affect water supply, flood risk, and the environment.
- **Deterioration.** The physical conditions of the water system—including both infrastructure and water quality—will deteriorate as a result of wear and tear, earthquakes, accumulating contaminants, and other complications.
- **Economy and demography.** California will experience a growing urban population, ongoing shifts in its economic structure, and further state and federal financial constraints.
- **Ecosystems.** Natural systems and species will face additional pressures as a result of growing human populations, new invasive species, more variable climate, and other sources of stress.

Farmland and housing developments in the Coachella Valley.

- **Science and technology.** Innovation and advances in knowledge may create new problems (such as new chemicals in the environment) as well as new technical and management solutions that benefit ecosystems and the economy.

This chapter discusses these drivers of change and how they will affect water management in California. Although there is uncertainty regarding the magnitudes and rates of change to expect, the presence and importance of such changes are rather certain. Responding to competing demands for water is difficult enough with the natural vagaries of California's Mediterranean climate. Planning for these new conditions will tax the adaptive capacity of existing water management systems and institutions and require that institutions themselves change to keep pace.

Table 3.1
Drivers of change in California water management

Category	Driver	Major changes
Climate	Sea level rise	Submergence of western and central Delta and Suisun Marsh Movement of coastal estuaries inland Seawater intrusion into coastal aquifers Problems for coastal infrastructure and housing
	Warming	Decline in total runoff Decline in snowpack, more winter/less spring and summer runoff Higher stream temperatures Increased demand for cold water for fish
	Precipitation changes	More floods or droughts, or both
Deterioration	Aging infrastructure	Increasing expense for maintenance and upkeep Higher risk of dam, levee, and aqueduct failures
	Accumulating contaminants	Accumulating salts in western San Joaquin and Tulare Basin soils, with some agricultural land retirements Accumulating nitrates in groundwater basins (statewide) Accumulating emerging contaminants in surface and groundwater Tighter drinking water and wastewater discharge standards More polluted environmental water
	Mining legacies	Continued but diminishing mercury and other mine contaminants Episodic failures of mine drainage containment
	Accumulating groundwater overdraft	Long-term reduction in water supply from groundwater, in Tulare Basin especially

Table 3.1 *(continued)*

Category	Driver	Major changes
	Earthquakes	Episodic interruptions of water supply (statewide) Permanent flooding in western and central Delta and interrupted Delta water exports
	Sacramento–San Joaquin Delta	Permanent flooding of western and central Delta and Suisun Marsh Reductions or end of through-Delta water exports
Economy and demography	State and federal financial constraints	Less state and federal funding for water management More local financing of water management More state use of regulation instead of financial incentives
	Globalization	Continued reduction in agricultural share of economy Continued growth of service economy Shifts to higher-value and permanent crops
	Population growth and urbanization	Residential growth, especially in floodplains and hotter inland areas Higher housing densities with lower per-capita urban water use Urbanization of agricultural land, reducing agricultural water use
Ecosystems	New invasive species	Additional pressure on native species and infrastructure
	Accumulating degradation	Continued loss of desirable aquatic and riparian habitat Decline of native species and ecological regime shifts Extinctions plus more Endangered Species Act listings More and bigger wildfires, reducing water quality
Science and technology	New chemicals	New pesticides and chemicals in the environment
	Water use improvements	Improved agricultural yields Improved water conservation technologies
	Improved infrastructure and operations	New water treatment technologies (conventional, reuse, and desalination) Improved flood and climate forecasts Remote sensing of net water use
	Improved ecological science and technology	Better understanding of what is not working Improved emergency measures, such as hatcheries Potential to better integrate ecosystem and water system management

Climate Change

All major water projects in California were designed assuming that hydrologic conditions in the recent past represent future conditions. This approach has two limitations. First, hydrologic data are available only for about the last century, which severely limits the ability to gauge the size and frequencies of the largest droughts and floods. Second, this approach does not account for long-term observed and expected changes in climate (Milly et al. 2008; Palmer et al. 2008).

Many field and modeling studies of the western United States demonstrate long-term climate warming, increasingly early spring runoff, and potential variability and changes in precipitation patterns (Ellis, Goodrich, and Garfin 2010; Barnett et al. 2008). Many independent modeling efforts have examined global warming as a driver of these changes in California. Observed warming and changes in runoff during the late 20th century are due to both natural climate variability in California and global warming (Maurer et al. 2007; Hidalgo et al. 2009; Das et al. 2009; Cayan et al. 2001).

Changes in climate will drive water management in California through three primary channels: sea level rise, warming temperatures, and changes in precipitation. Some of these events are more certain than others, and uncertainty also exists in their timing and magnitude. But it is certain that climate change will affect water management, and it would be imprudent to ignore such threats in preparing infrastructure and institutions for managing California water over the long term.

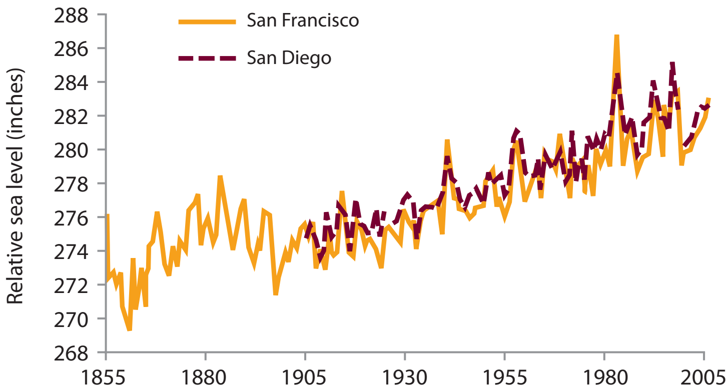
Rising Sea Level

Sea level rise is the most certain long-term environmental change. Sea levels throughout the world have been rising since the end of the last ice age. This rise stems from both an increased mass of water in the oceans from melting ice and snowpacks and an increase in water volume in the oceans as warmer water becomes less dense and takes up more space (Jevrejeva, Moore, and Grinsted 2008).

Mean sea level along California's coast has risen an average of 2.2 cm (0.87 inches) per decade over the past century and a half, roughly consistent with global sea level rise (Figure 3.1). Short-term rates of rise have fluctuated considerably in response to astronomical conditions and circulation changes in the Pacific Ocean (Bromirski, Flick, and Cayan 2003; Ryan and Noble 2007).

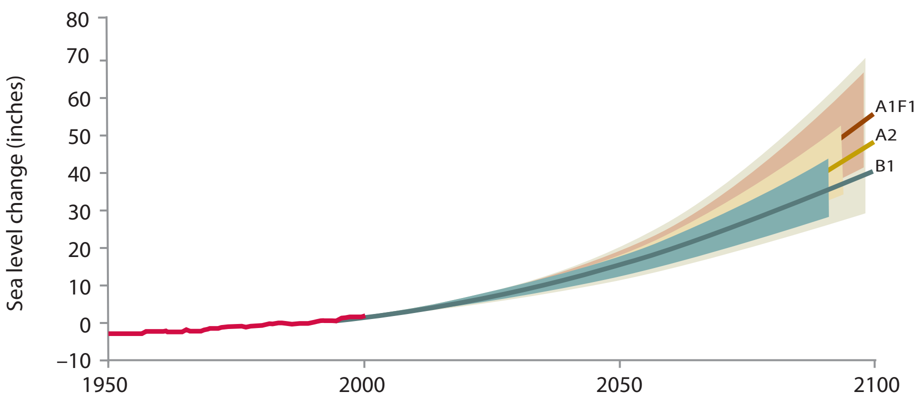
Projections of sea level rise vary widely. The Intergovernmental Panel on Climate Change (IPCC) (2007) projections are lower than recently observed sea level rise but do not account for melting of ice sheets. CALFED's Independent Science Board recommended using semi-empirical models—which take into account recent observed changes—for projecting future sea level rise for planning purposes (Mount 2007). For the range of greenhouse gas emission scenarios used by the IPCC, this approach projects from 1 to 1.4 meters (39 to 55 inches) above present levels by the end of this century (Figure 3.2).

Figure 3.1
Sea level along the California coast has risen nearly 12 inches since the mid-1800s



SOURCE: California Energy Commission (2009).

Figure 3.2
Sea level could rise another 39 to 55 inches by 2100



SOURCE: Based on Vermeer and Rahmstorf (2009), using emission scenarios from the IPCC.

NOTES: High emissions scenario is A1F1; low emissions scenario is B1. The red line shows historical data.

Table 3.2
Climate change: physical responses and management challenges

Climate event	Physical responses	Management challenges
Sea level rise	Higher average sea level Higher extreme high tides Higher estuarine salinities Greater seawater intrusion into aquifers	Lower Delta water export reliability and quality Larger estuarine and coastal floods Reduced coastal aquifer quality and yield
Warming climate	Reduced total runoff Changes in watershed vegetation Greater proportion of precipitation as rainfall Reduced snowpack Reduced spring and summer stream flow Higher stream temperatures; reduced cold-water habitat	Less water supply stored in snowpack Increased likelihood of flooding More demand for cold water releases for fish Reservoir operation changes needed Greater peak electricity and hydropower demands
Precipitation changes	Either a drier or wetter climate overall Potentially more variable and extreme weather	More floods and droughts Higher or lower demands for storage in reservoirs and aquifers

Rising sea level will have major effects on water management in California (Table 3.2). Coastal regions and estuarine areas such as the Delta will have to make the greatest adjustments, responding to increases in estuarine salinity, extreme high tides, and seawater intrusion into coastal aquifers.

Increasing difficulties in keeping Delta waters fresh

The Sacramento–San Joaquin Delta and San Francisco Bay (San Francisco Estuary) lie between the Pacific Ocean and Central Valley rivers. Water flows and quality in this region are driven largely by tides and sea level. Upstream reservoirs and export pumping are currently managed to keep the Delta fresh for Delta farming and for exports of fresh water to cities and farms in areas south and west of the Delta. Even modest rises in sea level will shift salinity landward enough to interfere with Delta water exports and agriculture in the western Delta (Fleenor et al. 2008; Chen et al. 2010). Failure of subsided islands in the western Delta—resulting from sea level rise and other factors (discussed below)—will further increase Delta salinity. Increased salinity is likely to be common in other California estuaries, such as Humboldt Bay, particularly during periods of low freshwater flow.

Increasing coastal flood risks

Beyond its effects on average sea level, sea level rise also increases the frequency of extreme sea level heights. Such sea level height "anomalies" occur when high astronomical tides, storm surges, low pressure systems, and warm ocean conditions coincide. Typically, they occur when El Niño events and major Pacific storms affect the coast simultaneously (Cayan et al. 2008). Extreme sea level anomalies have increased since 1915. For San Francisco during 1915–1969, extreme sea level anomalies occurred on average once in every four years. During 1969–2004 anomalies occurred roughly twice per year. In addition, the maximum anomaly recorded during the 1969–2004 interval was almost 40 cm (16 inches) higher than the pre-1969 period. Sea level anomalies could increase dramatically over the next century, perhaps going from a current average of one to two per year to roughly 17 per year by the end of the century in San Francisco Bay (Cayan et al. 2008).

Large increases in coastal and estuarine high-water levels, will contribute to failures in the Delta's fragile levees (Mount and Twiss 2005; Lund et al. 2007, 2010). The combination of rise in sea level and increases in salinity could eventually render current Delta water export facilities obsolete (Lund et al. 2010).

Increasing magnitude and frequency of sea level anomalies are also likely to overwhelm some unprepared coastal flood defenses. Assuming year 2000 coastal population levels, as many as 480,000 California residents would be placed at risk by a 55 inch rise in sea level (Heberger et al. 2009). In addition, coastal lagoons and marshes, important habitats for rare species, from steelhead trout to marsh birds such as the California clapper rail, are likely to flood more frequently with seawater. In most watersheds, there is little room for these habitats to shift upstream or inland, either because of natural geologic restrictions or urbanization and the hardening of streambanks with levees.

Sea level rise also will affect wastewater treatment plants and stormwater systems in coastal California, which rely on gravity to collect water to wastewater treatment plants at low seashore locations. Twenty-eight existing wastewater treatment plants in California would be placed at high risk by a 55 inch sea level rise (Heberger et al. 2009). Mitigation would require extensive reengineering of these facilities.

Saltwater intrusion in coastal aquifers

Many large and heavily utilized aquifers are situated along California's coast. The seaward margin of these freshwater aquifers usually rests on top of denser salt water. One challenge to groundwater managers is preventing salt water from migrating landward as sea levels rise, reducing the ability to store and distribute fresh water (California Department of Water Resources 2009). Saltwater intrusion is already a common problem for coastal aquifers in the South Coast and the Central Coast regions, particularly in the aquifers that underlie coastal Orange County, Los Angeles, the Oxnard Plain (Ventura County), and the lower Salinas and Pajaro Valleys (Monterey and Santa Cruz Counties). Accelerating sea level rise will augment basin management challenges. Responses can include reducing aquifer pumping coupled with increased artificial recharge, both translating to lower yield (Nishikawa et al. 2009).

Warming Temperatures

Average annual temperatures in California have risen in the last century by roughly 0.1°C (0.18°F) per decade (Anderson et al. 2008). This warming has accelerated spring snowmelt, resulting in a larger share of stream flow occurring in winter than in spring in recent decades. Global Circulation Models (GCMs) used to simulate future climate changes for various greenhouse gas emission scenarios all point to continuing or accelerating warming for California and the western United States. (Intergovernmental Panel on Climate Change 2007).

Recent summaries of results from downscaled GCMs (which translate global results to the regional level) show a range of average annual temperature increases for California depending on model differences and policies adopted to slow greenhouse gas emissions (Cayan et al. 2007; Moser et al. 2009; Chung et al. 2009). Under optimistic assumptions, projected increases range from 3°F to 5.5°F by 2100. A more pessimistic view leads to projected increases between 8°F and 10.5°F. The current trend of warming seems likely to accelerate; uncertainty lies only in how much and how fast. Prudent water managers will want to prepare for such changes.

Increasing temperatures have broad implications for water management in California (Table 3.2). Primary changes include (1) direct reductions in the total amount of water available from precipitation (total runoff), as a result of increased consumption of water by natural vegetation; (2) reduced snowfall and a shift of stream flow timing from spring to winter; and (3) increases in stream temperatures.

Reductions in total available water

Under current climatic conditions, between one-half and two-thirds of the precipitation in California never becomes stream flow or groundwater (Table 2.1). Even if the average volume of precipitation remains unchanged, warming is likely to reduce overall water available to streams and aquifers, by increasing

Warming temperatures are diminishing the share of precipitation stored as snow in the Sierra Nevada and Cascade Mountains. Photo by Sarah Null.

the evapotranspiration rate and by lengthening the growing season (Hidalgo, Cayan, and Dettinger 2005).

Modeling studies of average annual increased temperatures in the western Sierra Nevada watersheds suggest that low- to mid-elevation locations (up to about 6,000 feet) will experience declines of 4 percent to 10 percent in annual runoff with temperature increases of 7.2°F (Null, Viers, and Mount 2010). Watersheds at higher elevations show comparable reductions with higher temperature gains (10.8°F), which may occur by the end of the century.

Warming also dries soils for longer periods, changing natural vegetative cover within watersheds. Streams, riparian lands, and soils at high altitudes may dry earlier in summer in semiarid regions where precipitation occurs only in narrow windows of time and where less snowmelt is available to fill streams and keep the ground moist. Irrigation water demand may also increase as soils dry, leading farmers to alter cropping patterns.

Less snow, earlier runoff

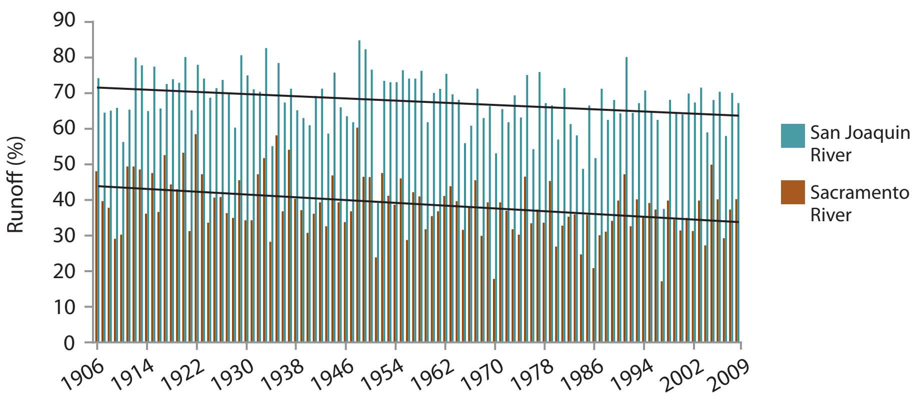
Climate warming also reduces the proportion of winter precipitation that falls as snow and accelerates the melting of snow in winter and early spring, with consequences for water storage, flooding potential, and the ability to maintain stored cold water needed for some native fish species.

Having less precipitation falling as snow reduces the accumulation of the mountain snowpack, an important form of seasonal water storage in California (Knowles, Dettinger, and Cayan 2006; Pierce et al. 2008; Das et al. 2009). In the northern Sierra Nevada, late season snowpack water storage has declined since the 1950s. However, snowpack water storage is not declining in the southern Sierra Nevada and may even be increasing slightly (Mote et al. 2005; Pierce et al. 2008). This difference may be due to higher elevations in the southern Sierra Nevada, where temperatures, although warmer, still remain cool enough for snow to form and accumulate.

Increases in temperature also accelerate the melting of snowpack. In most mountains of California, the historical peak in snow water storage occurred around April 1st. The timing of this peak is related to meteorological conditions, driven mostly by temperature, and the increasing intensity of solar radiation in the spring. Over the last century, declining snow water storage and warmer air temperatures have shifted spring snowmelt to earlier in the year (Barnett et al. 2008) (Figure 3.3).

Models that project future warming also project significant and, in some cases, dramatic decreases in snow water storage and shifts from spring to winter stream flows (Barnett et al. 2008; Knowles and Cayan 2004; Knowles, Dettinger,

Figure 3.3
Spring and summer runoff has been declining as a share of annual runoff on California's major rivers



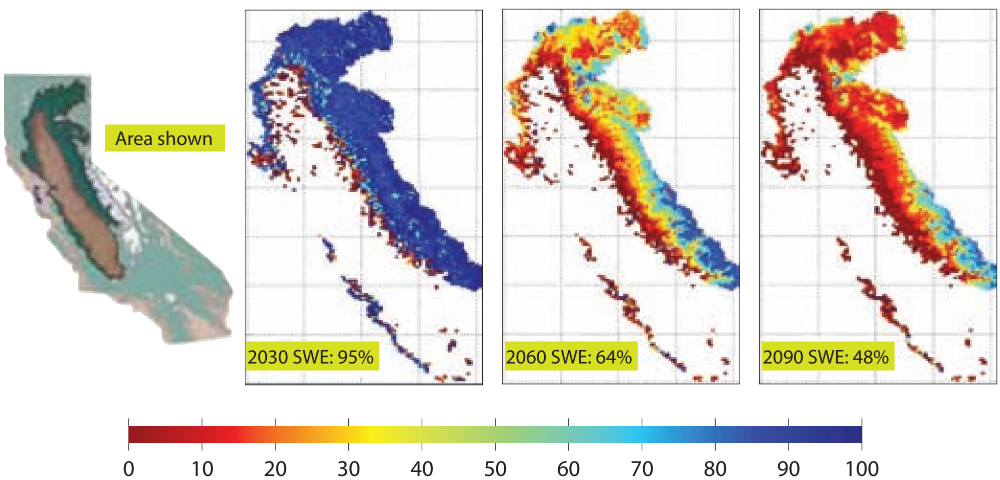
SOURCE: Authors' calculations using data from the California Department of Water Resources.

NOTES: The figure shows unimpaired spring and summer runoff (April 1–September 30) as a share of total annual runoff (October 1–September 30). The lines show trends over the period 1906–2009. Runoff shift from spring to winter has been 1 percent per decade ($R^2 = 0.12$) for the Sacramento River and 0.7 percent per decade ($R^2 = 0.07$) for the San Joaquin River.

and Cayan 2006). The magnitude of these changes differs with watershed elevation and latitude. Moderate warming could decrease April snow water content by more than one-third in the Sierra Nevada (Knowles, Dettinger, and Cayan 2006). The shifts in runoff from spring to winter begin with mid-altitude watersheds, moving to higher watersheds as warming progresses, with spring ultimately arriving more than a month earlier than today (Null, Viers, and Mount 2010). Figure 3.4 illustrates the declines in snowpack projected over this century with a relatively modest increase in temperatures; at higher temperatures, reductions could exceed 80 percent by the end of the century (Maurer et al. 2007).

This change will complicate water supply management, because the snowpack now provides a “free” source of seasonal storage. In a typical year, about one-third of annual supplies are conveniently stored as snowpack. Water managers can make up for much of this lost storage by using downstream reservoirs and, at some additional cost, by storing more water in aquifers, thereby freeing up space in surface reservoirs for more seasonal storage (Tanaka et al. 2006;

Figure 3.4
Rising temperatures will reduce the role of snowpack for water storage



SOURCE: Knowles and Cayan (2002).

NOTES: SWE is snow water equivalent. The scenarios are based on projected temperature increases: 0.6°C (1.1°F) (2020–2039), 1.6°C (2.9°F) (2050–2069), and 2.1°C (3.8°F) (2080–2099), expressed as an increase over present conditions (1995–2005). These are modest increases in temperature relative to some model projections (see the text). With higher temperature increases, the snowpack would be commensurately smaller.

Connell 2009; Madani and Lund 2010). Expanding this type of "conjunctive use" of groundwater and surface water will require changes in reservoir operations and strong groundwater basin management systems, often lacking today. New surface storage facilities are likely to be a more costly way to make up for the lost snowpack, particularly if climate change also reduces average precipitation and runoff, as discussed below.

Declining snowpacks and more precipitation falling as rain will also affect future flooding potential. During large winter storms, the proportion of precipitation that falls as snow is retained in mountains, reducing potential flood peaks. The greater proportion of precipitation falling as rain as a consequence of warming increases storm runoff. The loss of snowpack accentuates this effect because snowpack itself can dampen flood peaks (Dettinger et al. 2009). The extent to which these changes will increase flood damage depends on California's ability to respond effectively. Fissekis (2008) finds, for instance, that flood-operating policies that consider real-time watershed snow, precipitation, and soil moisture conditions would generally be adequate to handle anticipated increases in runoff volumes and peak flows for the largest winter storms experienced in California over the last 50 years. In addition to operational changes (for instance, making more reservoir storage available for flood flows in winter), there is likely to be an increased demand for larger flood defenses such as levees to protect homes and businesses in vulnerable areas (Zhu et al. 2007). This demand will be influenced, in part, by the requirement under current federal policy that urban areas have flood defenses adequate to pass a flow having a 1 percent probability of occurring in any year (Chapter 2). With changing conditions and new flow information, that 1 percent probability flow will increase (Mount 1995; Das et al. submitted).

Increasing water temperatures

Higher water temperatures are likely to affect a wide range of aquatic organisms. In the Delta, higher overall temperatures are likely to threaten some native species, such as delta smelt, which traditionally spawn in a fairly narrow range of water temperatures (Moyle and Bennett 2008).

Warming also is likely to significantly complicate the management of water to maintain adequate habitat for such fish as salmon and steelhead, now confined to the lower-elevation portions of rivers and streams because of dams. Releases of cold water from deeper parts of reservoirs are currently needed in summer to maintain this habitat. Managers of large reservoirs often rely on the stratification of water layers to preserve denser cold water at the bottom of the reservoir, with warmer, lower-density water resting on top. Where reservoirs can tap water from various levels, they often blend warm and cold water to keep downstream temperatures for fish within optimal ranges. Management of this cold water pool over the course of the summer can be complicated. The reservoir operator must retain sufficient cold water for the season while drawing down the reservoir to meet temperature and other requirements downstream, including irrigation demands.

Warming temperatures have several implications for cold water pool management. First, to offset higher air temperatures downstream, more of the cold water pool must be released for a longer period, increasing the likelihood of exhausting the cold water supply by late summer. Second, if water flowing into the reservoir during winter is warmer, then the temperature of the cold water pool will be higher the following summer, requiring more cold water to be blended with warmer waters to meet temperature standards. Third, when the difference in temperature between the bottom cold water and top warm water decreases, the reservoir is more likely to destratify and mix, losing the cold water pool entirely. Finally, with warmer air temperatures, the release of cold water from a reservoir preserves fish temperatures for a shorter distance downstream. These effects have occurred in the state's reservoirs historically during warm drought periods.

In sum, the frequency of releases of warm water from reservoirs is likely to increase as conditions warm, increasing the temperatures of rivers and worsening conditions for many species of fish. To mitigate these problems, reservoir operators are likely to be required to reserve more water for cold water releases for fish, raising the potential for competition and conflicts between water management for environmental and direct human uses. For areas further downstream, beyond the temperature influence of cold water from reservoirs, warmer temperatures will permanently and increasingly stress some fish and other organisms.

Changing Precipitation

Precipitation drives water availability. Three aspects of precipitation are most relevant for water management: (1) total precipitation, usually expressed as a long-term average; (2) interannual variability, reflecting the length and intensity of dry and wet years; and (3) precipitation intensity during individual storms, which drives floods. Compared with sea level rise and warming, there is generally less certainty about what will happen to precipitation with climate change.

Changes in total precipitation

About a century of detailed precipitation records are available for California. They reveal no statistically significant trend in precipitation statewide. The GCMs used to estimate future temperatures also predict future precipitation patterns, but there is less consensus on precipitation results for California (Cayan et al. 2007; Chung et al. 2009). Projections vary widely, and the average precipitation levels across all models differ little from the historical average (Cayan et al. 2007).

Thus, average precipitation in California could change little over this century, or the future could be significantly wetter or much drier. A drier climate would increase water supply and environmental problems, while decreasing flooding problems and the effectiveness of new surface storage. A wetter climate would decrease water supply and environmental water quantity problems but probably increase flooding. Modeling studies have examined management adaptation to a wide range of warmer and drier or wetter climate scenarios in California.[1] These studies tend to show that California's water supply and flood control system are more affected by precipitation changes than by temperature changes alone. In Chapter 6, we present the results of some management scenarios with a drier future, which has been the focus of much of the state's recent attention.[2]

Interannual variability

Although average precipitation appears not to have changed in California over the past century, interannual variability may be increasing, with longer, more intense wet and dry periods (Anderson et al. 2008). This phenomenon has been noted throughout the American West (Barnett et al. 2008). Overall, climate simulation models for California do not agree on significant shifts in the frequency of dry and wet periods. However, model results evaluated by Cayan et al. (2007) indicate increased intensity of dry years, particularly in the latter

1. See Tanaka et al. (2006); Medellin-Azuara et al. (2008b); Connell (2009); Fissekis (2008); Ragatz (2011); Lettenmaier and Sheer (1991); Vicuna et al. (2008); Madani and Lund (2009, 2010); and California Department of Water Resources (2006).

2. In particular, the second biennial assessment of California climate effects, organized by the California Energy Commission (2009), focused on a dry-warm form of climate change.

half of the 21st century. These simulation results deserve some caution, however. The GCMs are calibrated to the weather of the past 100 years. During this time, no droughts lasted more than six years without significant intervening periods of above-average precipitation. The water systems of California and much of the West are constructed around this range of variability. However, evidence from a wide range of studies demonstrates that the past century had exceptionally low climatic variability compared with the previous 3,000 years (Box 3.1).

3.1

The past may *yet* be a predictor of the future

Broad concern exists in the scientific community over using the past 100–150 years of climate record to design water resource and flood management infrastructure and to guide operations, particularly in the face of climate change (Milly et al. 2008; Intergovernmental Panel on Climate Change 2007).

Reconstructions of past climate conditions are based on many sources of information, including tree rings, fossil pollen, rodent middens, lake and marine sediments, cave speleothems (mineral deposits), and ice cores, leading to extensive information on California's and the western U.S. climate over the past 3,000 years, a period known as the Late Holocene.

All information available about the Late Holocene points to significant past changes in precipitation and runoff. Studies of the climate of the Sierra Nevada and adjacent areas of the Great Basin indicate that long-term droughts, vastly exceeding current six-year droughts, were quite common. Studies by Benson et al. (2002) of lakes that drain the Sierra Nevada show that Late Holocene droughts lasting from 20 to 100 years recurred in intervals of 80 to 230 years. Two droughts during the Medieval Warm Period (from AD 890–1110 and AD 1210–1350) may be the longest and most severe droughts of the entire 12,000-year Holocene epoch (Stine 1994). What is striking about these droughts is not the reduction in amount of runoff (25 percent reduction at the centennial scale, 40 percent at the decadal scale [Graham and Hughes 2007]) but their extreme duration without intervening wet periods. Modeling studies have examined how California's water system might respond to such extreme changes in climate (Harou et al. 2010; Brekke et al. 2009).

The Late Holocene was not particularly warm compared to the earlier Holocene, except for the Medieval Warm Period; temperatures were roughly equivalent to Northern Hemisphere temperatures during the 1980s (Mann et al. 2008). These are, in turn, lower than the temperatures of the 1990s. The current warming trend exceeds anything found in the past 3,000 years. The climate of the past 150 years may have been benign compared to earlier climates (MacDonald 2007) and future climates.

Precipitation intensity

Intense precipitation during winter storms causes the most damaging floods in California. In concept, warming should increase precipitation intensity, and this appears in some model results (Cayan et al. 2007). However, this is difficult to model with confidence because of the short timescale of most storms.

Much climate modeling of California for the next century does not show a great increase in the frequency of winter storms. However, a recent study indicates greater storm intensity and frequency with warming (Das et al. submitted). A particular concern is unusual meteorological phenomena known as *atmospheric rivers*. These storms occur when narrow bands of moisture in the upper atmosphere flow directly from the subtropics near Hawaii into California, producing warm, intense precipitation (the so-called "Pineapple Express"). These storms can produce high rainfall intensities for several days and are responsible for most of the major floods California has experienced over the past 100 years (Dettinger et al. 2004; Dettinger 2005).

Conditions necessary for winter storms to become atmospheric rivers may become more frequent over time (Dettinger et al. 2009). On average, models predict an increase of roughly 30 percent in the number of winter days in which atmospheric river conditions occur by the end of the century, and most predict that the largest events will have storm intensities exceeding anything recorded in the last century.[3] Greater frequency and intensity of large, flood-generating storms could further stress water management, if reservoirs must make room for additional flood storage capacity.

These various aspects of climate change will impose many changes on water management, from the Delta to reservoir operations to management for native species (Hanak and Lund 2008). The uncertainties of climate change for planning and design purposes are great, particularly for flood frequency estimation (Klemes 2000a, 2000b). The estimation of extreme floods, necessary for proper risk analysis, becomes still more approximate when the climate is changing. Although these changes are substantial and profound, many management options and directions are available to adapt, as we discuss in later chapters.

Deterioration of the Water System

California is now a well-settled state, with water and land having been employed intensely in the interest of its population for over a century. This intense use

3. Atmospheric river conditions do not always create atmospheric river-type storms.

of land and water, as well as various naturally occurring events such as earthquakes, are contributing to a continual deterioration of the state's water system, resulting in a dated and aging infrastructure, accumulating contaminants, groundwater overdraft, toxic drainage from old mines, earthquake damage, changes in estuaries, and the sinking and likely ultimate disappearance of many low-lying islands in the Sacramento–San Joaquin Delta. Although serious, this deterioration need not prove fatal to the operation of the state's water system. Indeed, given capable and timely management, it may provide opportunities for modernization and improvement.

Aging Infrastructure

California's extensive water and wastewater management infrastructure is largely established and is now aging. Aging infrastructure has three problems: obsolete design and operation, increasing maintenance costs, and increasing likelihood of some components failing.

First, existing infrastructure was often designed for conditions that have changed and will further change in the future. For example, increases in water quality standards often have required costly increases in water and wastewater treatment. Similarly, urban water conservation efforts reduce dry-season flows in sewers designed to support higher-volume toilets and summer flows. These older sewers required less slope and trenching to achieve required scouring, but with lower wastewater flows resulting from water conservation, more maintenance may be required, such as periodic sewer flushing.

Second, aging itself can increase maintenance costs. After construction, water and wastewater facilities commonly have several decades of low-cost operations. But with time, aging pipes, pumps, and other components need to be replaced. Replacement of aging or obsolete components is often more expensive than the original costs (after inflation), because replacement often lacks the economies of scale present in original construction; it also becomes necessary to accommodate transportation infrastructure, houses, and other activities that have grown around the original water infrastructure (notably, underground pipes). Failure to keep up with deteriorating infrastructure can increase the risks of failure and contamination and increase ultimate replacement costs.

Third, failure of major infrastructure components—including dams, levees, and aqueducts—becomes more likely with time. California's geologic and climatic setting makes the state prone to rare but significant natural disasters with a high potential to disrupt water supply and flood management. California has a long history of overconfidence in efforts to manage these forces (Kelley 1989; McPhee 1989). If they were to fail, roughly half of the 1,400 state-regulated dams pose a high potential hazard to downstream populations.[4] But annual funding for state dam safety programs averages only about $6,000 for each regulated dam (Association of State Dam Safety Officials 2005). The biggest threats to most dams involve insufficient spillway capacity for very large floods. But as discussed below, earthquake risks are a particular concern for some dams; similarly, the elaborate levee systems of the Delta, Central Valley, and Southern California are all at risk from large earthquakes and floods.

Replacement of aging infrastructure sometimes provides opportunities to modernize and update for both contemporary and anticipated conditions. For instance, new wastewater treatment plants can be designed to facilitate the delivery of highly treated recycled wastewater to end users, something more difficult for older facilities. For some dams, deterioration can facilitate removal. As discussed in Chapter 5, retirement of dams that no longer serve their original water supply and hydroelectric functions well can support important environmental improvements. Dam removal is likely to increase with time, as even some large dams become unsafe, fill with sediments, or are ill-suited to changing conditions.

The replacement and updating of local water and wastewater infrastructure are typically funded by local ratepayers, who directly benefit from these services. As shown in Chapter 2, California's utilities appear to be on track for making the capital investments needed to maintain their systems, thanks largely to local utilities' abilities to adjust charges to customers. These investments will cause significant rate increases, however. For instance, the major seismic repair and upgrade work under way for San Francisco's Hetch Hetchy 80-year-old system, which supplies roughly 2.5 million Bay Area residents, is costing over $4.5 billion and will more than double wholesale water rates by 2016.[5] Such rate increases will create additional incentives to conserve water.

Significant gaps in funding capacity exist for maintaining and upgrading flood management infrastructure, which is largely funded by federal and state agencies and which requires direct voter approval for local funding. Dam

4. The dams regulated by the state are either at least six feet high with more than 50 acre-feet of water storage capacity or over 25 feet high with more than 15 acre-feet of storage capacity.

5. Wholesale rates in early 2009 were approximately $600/af, and they are projected to increase to $1,400/af by 2016 (Palo Alto Utilities Department 2010).

removal is another area where the current funding system is inadequate. In later chapters, we discuss some options for funding system reform.

Accumulating Contaminants

Accumulating contaminants in both surface and groundwater—including salts and residues from fertilizers, pesticides, and other chemicals—are raising the costs of farming, spoiling some farmland entirely, raising the costs of drinking water and wastewater treatment, and posing as yet largely unknown risks to public health, fish, and other wildlife.

Salinization of farmland

The accumulation of salts in some large agricultural areas south of the Delta has long been noted (Orlob 1991). For decades, approximately half a million tons of salt annually have accumulated in the San Joaquin and Tulare Basins. For the San Joaquin Basin, more salt enters the basin through irrigation water than leaves via drainage into the San Joaquin River. The Tulare Basin drains to the San Joaquin River only in rare wet years and so retains almost all the salt entering the basin. This accumulation of salts has already led to the retirement of 70,000 acres of agricultural land and has diminished productivity on some remaining farmland (Medellin-Azuara et al. 2008a; Shoups et al. 2005). Further reductions in agricultural acreage can be expected as salts continue to accumulate. Roughly a million acres of irrigated farmland are susceptible to this problem (Letey 2000; U.S. Department of the Interior 1990).

The productive life of much of this area has already been extended by improvements in agricultural water use efficiency (which results in not only less water, but also less salt, being applied to the soils), set-asides of some local areas for salt disposal, improved leaching methods, and retirement of some lands with high natural soil salinity (Letey et al. in press). Maintaining a sustainable salt balance in remaining areas requires the development of drains from the basin, reductions in salt loads entering the basin, or further reductions in irrigated area (Orlob 1991). Drainage solutions can be particularly difficult where the salts themselves are highly toxic. This is the case with selenium on the west side of the San Joaquin Valley, which can accumulate and harm wildlife at even moderate concentrations. For instance, an attempt to establish drainage in the western San Joaquin Valley in the early 1980s, in which selenium-laced water was out in the open, led to bird mutations and die-offs (Chapter 1). One advantage of a new water conveyance system around or under the Delta would be to significantly reduce salt loads entering the basin, as Delta water is roughly three times saltier than water diverted upstream from the Sacramento River (Lund et al. 2010).

Even if these various efforts can help extend the productive life of salinity-affected farmland, it will also be necessary to have a better plan for retiring some of these lands before they become too toxic for alternative uses. Current economic incentives encourage farmers to farm the land to the point where it becomes unsuitable as native dryland habitat. From an ecosystem management standpoint, it might be better to stop farming such lands sooner, so that they could be converted to wildlife-friendly dryland habitat or at least be able to support enough natural vegetation to reduce dust clouds. Such a solution would require a regional land management plan with incentives to encourage farmers to manage the lands for conservation purposes instead of farming them intensively.

In addition to impairing local farmland, San Joaquin Basin salinity is a major source of surface water pollution on the lower San Joaquin River and the southern Delta. These salts contribute to an environment in the southern Delta that favors nonnative fish species and is a major impediment to ecological restoration in the Delta (Brown 2000).

Finally, salinity also raises the costs of drinking water and poses some still uncertain public health risks. The costs of treating water from the Sacramento/San Joaquin Delta for urban uses, for example, could increase by $400/af with increased salinity driven by sea level rise (Chen et al. 2010). Moreover, these treatment technologies may not fully remove potentially harmful by-products of the treatment process.

Contamination of groundwater basins

Salts and a range of other contaminants such as nitrates (largely from fertilizers and livestock wastes) and some pesticides are also accumulating in California's groundwater basins. Nitrate accumulations are especially widespread, affecting most groundwater basins underlying agricultural areas (e.g., the Chino Basin and the San Joaquin Basin: Harter et al. 2002; Dubrovsky et al. 1998). Nitrates can have adverse health effects, particularly on infants and young children. Because water can remain in aquifers for a very long time, it will often take centuries to decrease contamination. The slow percolation of contaminants from irrigation water laced with agro-chemicals also means that the full weight of contaminant loads often has yet to arrive in the main bodies of aquifers (Fogg and LaBolle 2006).

Groundwater basins also contain some naturally occurring contaminants. Arsenic, present in many groundwater basins in the southern Central Valley, is a highly carcinogenic contaminant for which regulatory standards have recently been tightened.[6] The primary solution for addressing groundwater contamination—wellhead treatment—is usually too costly for agricultural uses and small rural drinking water systems.[7]

Emerging contaminants

The number of chemicals and biological contaminants in drinking water subject to federal and state regulation has been rising. In 1977, the first set of maximum concentration levels (MCLs) for drinking water in California included 20 chemicals; as of 2010, this number had jumped more than fourfold, to 84.[8] Increases in the number of MCLs reflect increased understanding of the public health consequences of these constituents, improvements in detection capability, and increasing use of poorer quality water sources.

The current number of drinking water MCLs pales, however, compared to the immense and growing number of new chemicals entering the environment. According to the Environmental Protection Agency (EPA), more than 80,000 known chemicals are used for industrial and household applications, with more than 700 new chemicals registered each year.[9] In California, there are more than 12,500 registered pesticide products.[10] Only some of these are monitored, with guidelines limiting what constitutes safe exposure. The number, magnitudes, and uncertainties of these chemicals pose significant challenges for proper public health and environmental regulation.

Although chemical regulation issues go well beyond the water sector, they are important for both drinking water quality and the quality of water for the environment. Recent advances in detection technologies and environmental toxicology are making it possible to identify previously neglected chemicals from wastewater treatment plants and urban and agricultural runoff. These

6. See http://water.epa.gov/lawsregs/rulesregs/sdwa/arsenic/index.cfm. See also Welch et al. (2000).

7. A recent study of domestic wells in Tulare County found that 40 percent of 181 domestic wells tested for nitrates exceeded the public water supply standard of 10 mg/l (State Water Resources Control Board 2010a). There are 600,000 domestic wells in California serving over 1.6 million people not connected to regulated public water supply systems.

8. These 84 chemicals include inorganic elements (e.g., copper, lead, mercury, nitrate), radionucleids (e.g., uranium, radium), volatile organic compounds (paints, benzene, MTBE [methyl tertiary butyl ether]), synthetic organic compounds (mostly pesticides and fungicides), and disinfection by-products (e.g., trihalomethanes, bromate).

9. This figure refers to chemical substances as defined under the Toxic Substances Control Act. See www.epa.gov/oppt/newchems/pubs/invntory.htm.

10. See http://state.ceris.purdue.edu/htbin/stweb.com.

compounds, known as "emerging environmental contaminants" or "chemicals of emerging concern," include ingredients in pharmaceuticals, sunscreens, flame retardants, and artificial sweeteners, among others. The health and environmental effects of such seemingly innocuous products, found in surface water and groundwater throughout California, are just beginning to be understood (la Farré et al. 2008; Richardson 2009; U.S. Environmental Protection Agency undated (f)). They are often difficult to remove using conventional wastewater treatment methods.

In the future, drinking water regulators are likely to establish MCLs for some, perhaps many, additional contaminants. The EPA currently has 104 contaminants on its watch list, and more are likely to be added as toxicology improves.[11] This growing list will raise the costs of treating both drinking water and wastewater and increase the value of water sources with low contamination such as high mountain streams (e.g., San Francisco's Hetch Hetchy Reservoir) and spring systems in volcanic areas.

Emerging contaminants are likely to significantly affect water treatment and quality for wastewater recycling as well. At present, California recycles approximately 200–300 taf [thousand acre-feet] per year (Figure 2.4), and efforts are under way to expand this supply option considerably, to as much as 2 million acre-feet. Depending on the number of cycles of reuse and the treatments applied each time, recycled water can develop high concentrations of urban and agricultural chemicals (most notoriously, salt). A State Water Resources Control Board Science Advisory Panel report (Anderson et al. 2010; National Water Research Institute 2009) illustrates the complexity of this issue and highlights some challenges for expanding recycled water use.

Treatment to remove contaminants from drinking water is, at best, a partial solution to the problems posed by chemicals in California's waterways. It raises the costs of water for urban users and does nothing to address the negative effects of these contaminants on fish and other wildlife. A more comprehensive approach, focusing on source protection and pollution discharge control (to prevent harmful chemicals from entering water in the first place), is urgently needed. As described in Chapter 6, federal and state agencies have had difficulty regulating the use of chemicals under existing authority, and there are weaknesses in the control of polluted agricultural and urban runoff.

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11. The current "contaminant candidate list" includes 11 microbiological and 93 chemical contaminants (www.epa.gov/ogwdw000/ccl/ccl3.html).

Mine Pollution

Water quality management in the future will also be affected by the legacies of pollution from California's early mining economy. California has more than 47,000 abandoned mines, and more than 5,200 of these have the potential to significantly degrade water quality for human use and wildlife (www.consrv.ca.gov). One hundred and fifty of these mines are currently considered dangerous and in need of immediate attention, mostly because they produce acidic solutions laced with a complex mix of toxic chemicals. These mines are most dangerous following intense storms, when runoff overwhelms discharge capture and treatment programs. The state's abandoned mines are a chronic problem that requires extensive investments to manage. Federal regulations in recent decades have greatly reduced the potential for new mine drainage problems, so new mines are unlikely to be a major driver of change in the future in California, although the U.S. General Mining Law of 1872 is still unchanged and thus new mines are always a possibility (Woody et al. 2010).

A larger legacy of California's gold mining era is large amounts of mercury in Central Valley and Delta sediments. The Gold Rush in the Sierra Nevada created a mercury rush in the nearby Coast Ranges. Mercury was used to separate gold from ore. More than 10 million pounds of mercury were released into the Sierras' streams (Churchill 2000). Mines of the Coast Ranges also discharged large quantities of mercury into Central Valley tributaries. Mercury is stored in and transported with the sediments that historically moved from the Coast Ranges and the Sierra Nevada. Hydraulic mining from 1852 to 1884 moved vast quantities of mercury-laden sediment into the Central Valley, the Delta, and San Francisco Bay (Bouse et al. 2010).

Mercury is a powerful neurotoxin at high concentrations. In many environmental settings rich in organic material, elemental mercury can undergo methylation, making it available for assimilation into food webs (Morel, Kraepiel, and Amyot 1998). As this mercury moves up the food web, it concentrates in higher-order predators such as predatory fish, fish-eating birds, and humans (Alpers et al. 2005), although effects on health and reproduction of organisms may nevertheless be less than expected (Suchanek et al. 2008). Mercury poisoning health warnings are common against consuming large numbers of resident wild fish from the Sierra Nevada, Clear Lake, the Coast Ranges, the Delta, and San Francisco Bay.

Many water and environmental management activities will have to address potential releases of additional mercury into the environment. Mercury is trapped in sediments behind dams, creating a concern for dam removal efforts

(James 2005). Riverfront levees in the Sacramento Valley now isolate floodplain sediments deposited during the Hydraulic Era, so levee setbacks could reintroduce this stored mercury into the environment. Restoration of riparian and tidal wetlands to support fish will also have to consider the potential that disturbing the existing landscapes will reintroduce mercury and increase its methylation (Marvin-DiPasquale 2000).

However, agencies and organizations often use mercury as an excuse to do nothing. Indeed, regulatory agencies commonly cite mercury as a reason *not* to restore habitat, to the detriment of the species they are charged with recovering. There are rational reasons for a conservative approach. Yet, decades of research in California show no indication that habitat restoration efforts create a significant problem regarding mercury, harming either aquatic organisms or humans. Regardless, mercury will remain a fundamental issue in future water management in California, particularly for restoring wetland and tidal marsh habitats.

Accumulating Groundwater Overdraft

As noted in Chapter 2, chronic overdraft—or groundwater mining—accounts for as much as 2 million acre-feet, or 5 percent of gross agricultural and urban water use. The two major basins affected by persistent overdraft are the Tulare and Salinas Basins (Faunt 2009). Long-term overdraft in the Tulare Basin is estimated to be about 1.4 million acre-feet (maf)/year. For the smaller Salinas Basin, overdraft is about 19 taf per year. More localized overdraft occurs in other smaller Central Coast basins (Pajaro Valley, Santa Paula, Nipomo).

In some historically overdrafted basins in Southern California and Silicon Valley, active aquifer recharge programs, supplied by imported surface water, have helped to stabilize groundwater levels (Walker and Williams 1982; Blomquist 1992). In some heavily used basins in wetter parts of the state, groundwater levels have been stabilized by local surface supplies. In these cases, pumping induces faster recharge from local rainfall and adjacent rivers and streams—reducing local surface water flows. The Cosumnes River is an example of this tradeoff (Fleckenstein et al. 2004). Even where groundwater levels are now stabilized, the water table remains low enough that stream flow and native vegetation are reduced (Howard and Merrifield 2010).

Groundwater overdraft often causes land subsidence, as has occurred particularly in the San Joaquin Valley (Galloway, Jones, and Ingebritsen 1999; Poland et al. 1975). This subsidence has implications for flood management (since lands are lower and more susceptible to flooding) as well as the functioning of roads and long canal systems (which can break down when the ground sinks too much).[12] The acceleration of pumping during the drought occurring in the late 2000s has created instabilities in the concrete lining of the California Aqueduct, for instance.

Like many mining operations, overdraft also provides economic benefits, at least for a period. However, ultimately, overdraft must end, and it will end either by diverting more surface water to current groundwater uses or by reducing net use of groundwater (Harou and Lund 2008).

Earthquakes

Given California's geologic setting, large earthquakes will episodically and abruptly affect all facets of life. The Uniform California Earthquake Rupture Forecast (Field et al. 2008) estimates a 99 percent probability of a major quake (magnitude 6.7 or greater) in California over the next 30 years, with Southern California at slightly higher risk than Northern California.

The design of most water supply structures in California is significantly driven by the expectation of earthquakes. This is especially pertinent to the roughly 1,400 state-regulated dams and to the complex system of canals and pumping stations that make up regional, state, and federal water projects. Although these structures must meet basic design criteria for earthquakes, almost no structure is entirely earthquake-proof. And because standards and methods of analysis for earthquakes are constantly changing, many older structures in California can be expected to need costly upgrades or else be retired.

Although most water supply structures in the state have reasonably high resistance to earthquakes, several large dams are considered at high risk of failure during an earthquake.[13] In addition, California's network of levees is at risk. Earthquake vulnerability is particularly acute in the levees of the Delta, whose design does not incorporate significant earthquake risk (Mount and Twiss 2005). Levee failure from earthquakes has a high potential for disrupting water supply operations in the Delta, with profound economic and social

12. The initial lowering of a groundwater table usually implies some irreversible subsidence from compaction of the aquifer. This implies some unavoidable mining of groundwater from the compacted aquifer material but also creates depletion in the groundwater basin which can later be used for water storage (Galloway, Jones, and Ingebritsen 1999).

13. Several large dams, including Success Dam on the Tule River, Lake Perris Dam in Riverside County (part of the State Water Project), Isabella Dam on the Kern River, and numerous smaller structures have been deemed by state and federal dam safety regulators to be insufficiently safe and in need of significant upgrades.

consequences statewide (Chapter 6).[14] Less appreciated, but no less significant, earthquakes also increase the risk of catastrophic flooding in existing and proposed urban areas protected by Delta levees. Advances in technical understanding and regulatory responses should drive change in the design and maintenance of levees and will likely increase costs.

Converging Pressures on the Sacramento–San Joaquin Delta

One persistent theme in this review of deteriorating water system assets concerns conditions in the Delta. This hub of California's water supply system, which supplies about 15 percent of California's urban and agricultural water use, is undergoing profound change (Lund et al. 2010). Change in the Delta is likely from earthquakes, as well as from other fundamental geological and climate processes. Subsidence of Delta islands from oxidation and erosion of their peat soils has long been recognized as an eventual cause for the demise of many western and central Delta islands (Figure 3.5).[15] Unavoidable sea level rise and permanent failure of the most subsided Delta islands will reduce the quality of water available for export. State policy for Delta levees and water supply management will need to change as earthquakes and floods make existing policies untenable or irrelevant.

The accumulating number of endangered fish species in the Delta, and resulting restrictions on Delta pumping operations, also will drive continued changes in Delta water exports. The immediate costs to water users of a catastrophic failure of Delta levees, which would draw seawater into the Delta and shut down the export pumps for many months, could amount to more than $15 billion (Lund et al. 2010). The costs of eliminating, reducing, or replumbing Delta water exports over the longer term will involve billions in up-front investments and up to several billion dollars per year of expenses statewide (Chapter 6). But these inevitable changes will also provide opportunities to improve water quality for agricultural and urban users, create better habitat for native species, and shift the Delta's economy to more sustainable foundations. The changes in the Delta's ecosystem and inevitable landscape changes in the central and western Delta are among the most fundamental changes that will drive water management in California in the coming decades.

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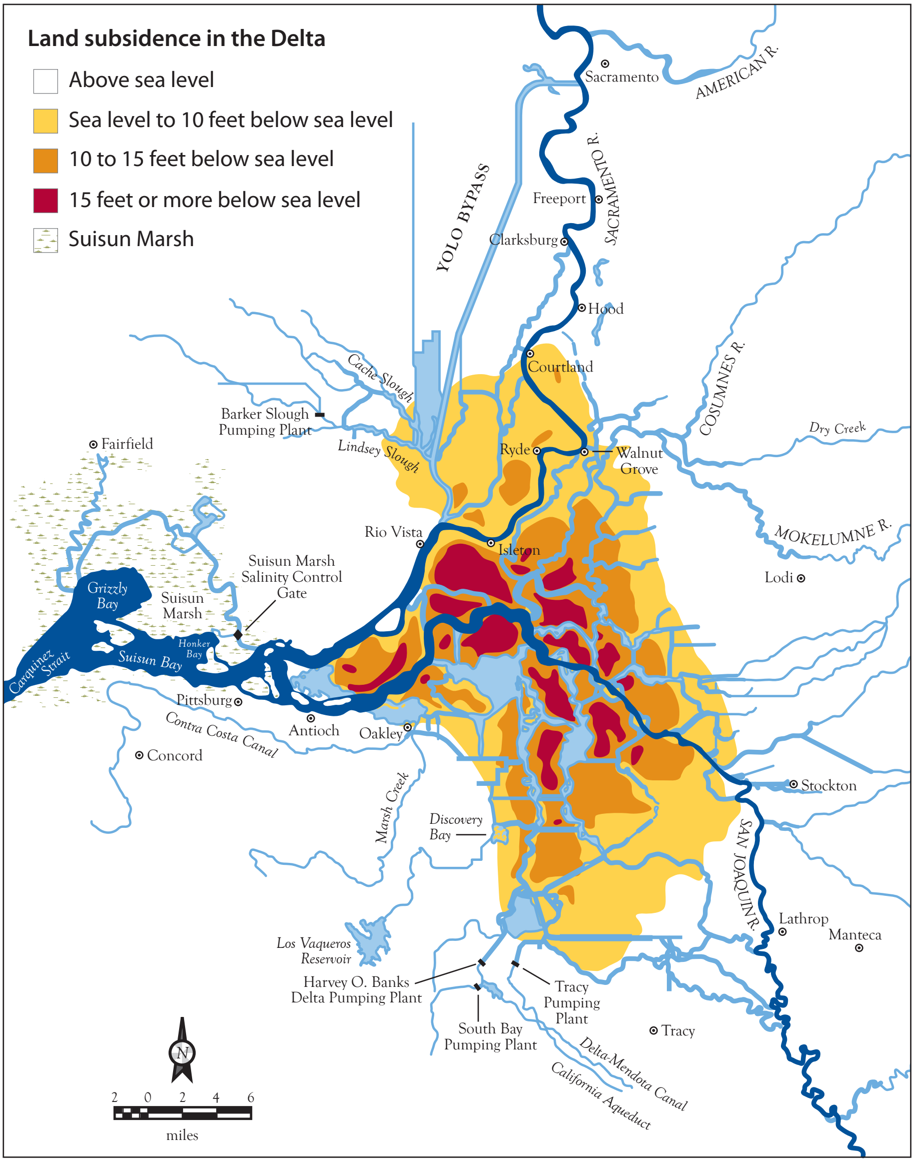
14. See Lund et al. (2010) and recent technical reports (URS Corporation and J. R. Benjamin and Associates, 2009a, 2009b).

15. For a historical analysis, see Thompson (1957); for recent analyses of levee problems, see Suddeth, Mount, and Lund (2010) and Lund et al. (2010).

Figure 3.5
Many Delta islands are well below sea level, heightening vulnerability to floods and earthquakes



SOURCE: California Department of Water Resources (1995b).

Economic and Demographic Conditions

Economic and demographic factors have always driven water use and management in California, and several trends already under way will strongly influence the future of the state's water delivery system: the financial constraints on state and federal governments, continued strong population growth and urbanization, and the growing globalization of the California economy.

State and Federal Financial Distress

The 2010–2011 California budget year began with the prospect of a $20 billion shortfall for a total budget of about $120 billion (Gordon 2010). The federal budget, for its part, has a $1.4 trillion deficit of a roughly $3.6 trillion budget total. Although California's budget woes have been exacerbated by the economic recession, the state has suffered structural financial shortfalls throughout the past decade. Each year, these shortfalls require additional spending cuts or revenue increases, because adopted state budgets cannot legally include a deficit. Economic recovery is likely to eventually improve the state's revenue picture, but long-term liabilities, including undercapitalized pension funds, rapidly escalating costs for Medicaid, and underfunded retiree health benefits, will maintain pressure on state resources. At the federal level, where deficit finance is possible, similar cost uncertainties loom large, and there is widespread concern about the long-term economic effects of sustaining such large deficits. Large-scale increases in taxes—the alternative to reduced spending—are unpopular at both state and federal levels. These trends imply long-term reductions in state and federal support for California water investments, as well as other investments.

As shown in Chapter 2, a primary source of state funding for the water sector in recent decades has been general obligation (GO) bonds, which are funded by general state tax revenues.[16] These bonds have been used not only to finance infrastructure construction but also to support a wide range of operating expenses, from science to conservation to environmental mitigation. In a tight state budget without new tax revenues, repayment of GO bonds takes priority over other major state expenditures, making it likely that education

16. One exception was the initial general obligation bond supporting the construction of the State Water Project (SWP), passed by voters in 1960, which is being repaid by water users who receive SWP water, not taxpayers. Subsequent SWP extensions to the Central Coast have been funded through revenue bonds, directly backed by revenues from ratepayers, rather than the general fund.

and other sectors relying on state general funds will oppose continued reliance on GO bonds to fund water projects.[17]

In recent decades, federal contributions for California water have declined in real terms, following the winding down of large grant programs for wastewater treatment facilities in the late 1970s and 1980s and real reductions in flood control spending since the 1970s. Despite a recent, short-term boost from stimulus spending, the large and likely long-lived federal budget deficit can be expected to preclude major long-term increases in federal funds for California water.

These financial woes at the state and federal levels imply that local governments and water users will have no choice but to take more direct financial responsibility for California's water system. This shift also implies less ability for state and federal government to provide financial incentives to induce behavioral shifts by local and regional entities. The "carrot" approach has been a focus of much of the recent state bond funding, to encourage cooperation among local groundwater users and among regional water entities. As we discuss in Chapter 7, this constraint might be mitigated if California were to create a water trust fund by levying a surcharge on water use. Parallels include the federal highway trust fund, which is supported by a transportation fuel tax, and the public goods charge on energy use in California. These revenues fund local transportation and energy efficiency investments as well as research and development.

Population Growth

California's population today is nearly 39 million.[18] Mid-range projections put the state's population at nearly 60 million by 2050 and perhaps as high as 85 million by 2100.[19] This growth will bring large increases in housing, commerce, and employment and major changes in land use. Growth in the number of households will expand urban land areas, with much of this expansion replacing

17. For instance, the California Teachers' Association opposed the $11.14 billion general obligation bond that was part of the 2009 legislative water package, on the grounds that it would encumber general fund resources available for schools (Buchanan 2010).

18. As of July 2009, the California Department of Finance estimated the state's population at 38,477,000. The U.S. Census had a somewhat lower estimate, at 36,962,000.

19. The California Department of Finance (2007) projects the 2050 population at 59.5 million. Using projections developed by Hans Johnson, Sanstad et al. (2009) project a similar level for their mid-range estimates and 85.3 million by 2100. Earlier in the decade, Landis and Reilly (2002) projected even higher growth by the end of the century, to 92 million. Sanstad et al. (2009) also project low and high growth scenarios that place a wide band around these levels, with 44.2 to 69.4 million residents by 2050 and 43.8 to 147.7 million by 2100. This wide range highlights the difficulties inherent in long-run population projections. For the purposes of assessing the ranges of urban water demand in Figure 3.8 (see below), we use a more moderate, slower growth scenario of 51.7 million residents in 2050 and 64.6 million residents in 2100 (personal communication from Hans Johnson).

agricultural land on the urban fringe, reducing agricultural water use. Some of this growth will occur on floodplains and fire-prone hills.

Land use policies can significantly affect these factors, however. For instance, Figure 3.6 presents two alternative scenarios of urban growth by mid-century. In a compact vision of new development (shown in red), population increases to 65 million inhabitants, displacing roughly 1 million acres of farmland. In contrast, a more sprawling vision of new development (largely covering the red areas as well as the area shown in yellow) projects a loss of nearly 2 million acres of farmland, despite more modest population growth (59.2 million).[20]

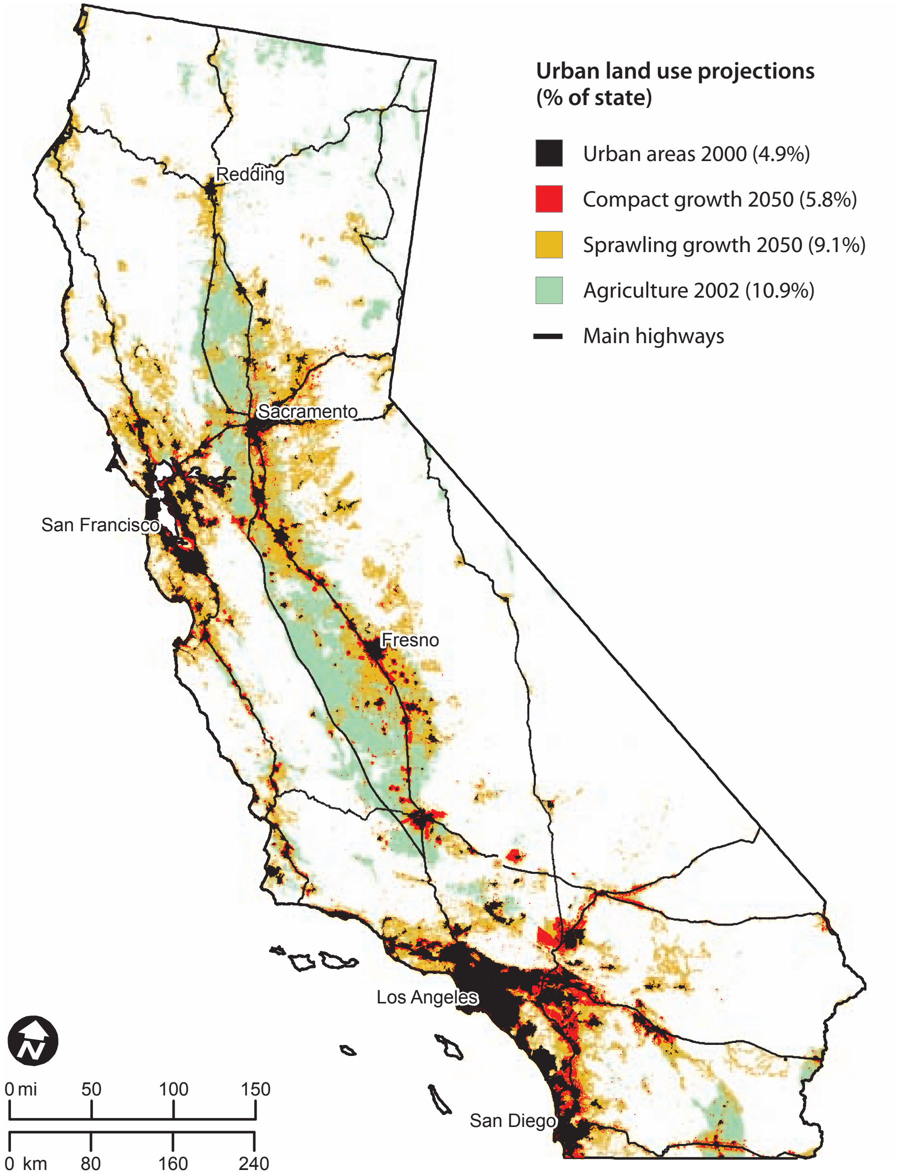
Generally, new urban development can be expected to use less water per capita than existing homes within the same regions: It will generally contain newer, more efficient appliances and plumbing fixtures, and it will require less landscape irrigation because of smaller lots and higher residential densities. However, a larger proportion of growth will occur in hotter inland areas, where housing densities tend to be lower and landscape evaporation is higher than in the coastal metropolitan areas (Hanak and Davis 2006). Growth in these inland areas also increases peak electricity demands for summer air conditioning, much of which is provided by hydropower (Vine 2008). Urbanization also will increase discharges of urban runoff and treated wastewater, while decreasing agricultural runoff from urbanized agricultural lands.

It is commonly assumed that population growth and the accompanying shift from urban to agricultural land uses will increase overall water use. But this is not entirely certain. If land and water resources are well managed, new urbanization can have a smaller per capita water use rate and can replace relatively water-intensive agricultural water uses. Urban water use efficiency efforts, the urbanization of some agricultural lands, and the retirement of agricultural lands in saline areas could combine to decrease overall human water use and particularly net water use.

Although California's population will also change in other ways, such as its ethnic composition, age structure, and income, growth in population is likely to be the most important demographic change from a water management perspective. Other studies have found that the effects of growth in population and water demands are likely to be important for water management worldwide, with global effects on water use greater than those likely from climate change (Vörösmarty et al. 2000).

20. See Teitz, Dietzel, and Fulton (2005) for an examination of multiple scenarios for the San Joaquin Valley.

Figure 3.6
Urban growth will displace farmland



SOURCES: Authors' calculations using 2002 agricultural land use data from the California Department of Water Resources; 2000 urban land use and compact growth scenario data from Landis and Reilly (2002); and sprawling growth scenario data from Sanstad et al. (2009).

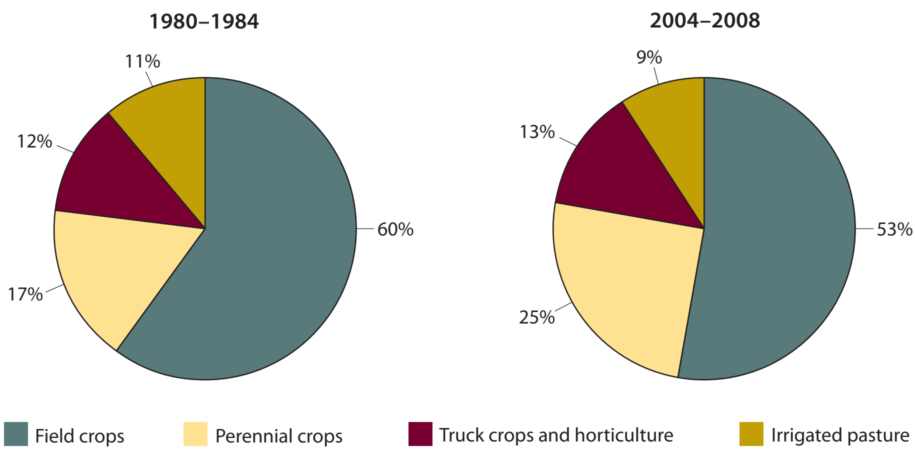
NOTE: Urban areas in 2000 would remain urban in the two growth scenarios, which largely overlap, with greater overall land use by urbanization in the sprawling growth scenario.

Globalization and Continuing Shifts in California's Economy

Along with population growth, globalization of the world's economy is likely to reinforce some trends already under way in California's economy (Figure 1.3), including the increasing share of service-sector employment and the declining shares of manufacturing and agricultural employment. Global market forces are also likely to continue the shift in California's agriculture toward more permanent and higher-value tree and vine crops. Since the early 1980s, these crops have already increased substantially as a share of total acreage (Figure 3.7). In the water-short San Joaquin Valley, perennials now constitute 32 percent of all cropland.[21]

California agriculture already serves a largely global market. The state's favorable climate and the increasing demand for higher-value agricultural products worldwide is likely to foster demand growth for fruits, nuts, and other high-value agricultural commodities (Howitt, Medellin-Azuara, and MacEwan 2009; Hanak et al. 2010). This shift toward perennial crops will increase agricultural revenues. But by reducing the flexibility of the agricultural sector to fallow crops during droughts, this shift will also increase the costs of farm water shortages.

Figure 3.7
Acreage shifts toward higher-value perennial crops have reduced flexibility to cope with droughts



SOURCE: Authors' calculations using data from County Agricultural Commissioner Reports (various years).

NOTES: Acreage includes nonirrigated cropland. Average acreage totals: 10.6 million in 1980–1984 and 10.4 million in 2004–2008.

21. Authors' calculations using data from County Agricultural Commissioner Reports. These data include nonirrigated crop land; the share of perennials in irrigated acreage is likely somewhat higher.

Changing Ecosystems

Changes in the size, structure, and species-composition of California's aquatic ecosystems will also drive changes in water management. Major ecological drivers include the growing problem of new invasive species and the degradation of habitats for native species, both of which will lead to additional organisms becoming threatened or endangered, and thus increasing the conflicts over water uses.

Invasive Species

California's intensive commerce with the rest of the world brings many new species of plants, animals, and microorganisms to the state. At the same time, changing environments create conditions that increasingly favor established alien (nonnative) species over native species. Most rivers and estuaries in California already contain a mix of native and alien species. The San Francisco Estuary and Sacramento–San Joaquin Delta are dominated by alien species, from plants to invertebrates to fish (Cohen and Carlton 1998), making it one of the most invaded estuaries in the world. Large populations of alien species alter ecosystem function and community dynamics and complicate management efforts to maintain native species (Lund et al. 2010; Moyle and Marchetti 2006). Alien species at this stage are usually labeled as invasive species, or as alien invaders, because many alien species, if not most, do not cause significant harm.

The dominance of aliens in many of California's streams, lakes, estuaries, and riparian areas stems largely from human alterations of physical habitat, combined with introductions of new organisms into the system either by individuals and agencies or as by-products of water-based transportation systems. Examples of sources include dumping of ship ballast water, disposal of aquarium fish into water bodies, transport of organisms such as mussels on recreational boats, and the spread of fish and other organisms through aqueducts. In rivers, the "homogenization" of habitat through flow regulation, reservoir creation, and levee construction provides conditions favoring widespread aliens at the expense of natives (Moyle and Mount 2007).

Most reservoirs in California, for example, contain alien fish (e.g., bass, sunfish, shad, catfish, minnows, carp), crayfish, Asian clams, and aquatic weeds, with very few native species. These organisms are then transported elsewhere with the water. Other alien species, once introduced, spread well both on their own and with assistance from humans (e.g., anglers, aquarists, fish farmers) into more natural systems. As a result, brook trout (*Salvelinus fontinalis*) from the eastern United States have displaced native trout and amphibians in lakes and streams throughout the Sierra Nevada and Cascade Mountains, and redeye bass (*Micropterus coosae*) have eliminated most native fishes from the Cosumnes and Santa Margarita Rivers (Moyle 2002; Moyle et al. 2003). Lake Tahoe has been invaded by so many species of fish and invertebrates that the aquatic ecosystem today bares scant resemblance to the one that existed before European settlement, and new species continue to arrive (Moyle 2002).

Although the displacement of native species by alien invaders is perhaps the most studied problem in aquatic systems, the direct effects of these species on water management are of concern as well. For example, dense beds of aquatic plants known as macrophytes (e.g., *Egeria densa* or Brazilian waterweed) can impede navigation and therefore require application of herbicides to water supply systems. Likewise, dense growths of some macrophytes (e.g., *Hydrilla*) can clog irrigation canals, reducing delivery capacity. The dense growth of invasive clams (*Corbicula fluminea*) in aqueducts can reduce water-carrying capacity, a problem likely to worsen as zebra and quagga mussels (*Dreissena* spp.) invade the water supply system (Stokstad 2007). These mussel invasions are both predictable and preventable (Lund et al. 2007).

Current management efforts are unlikely to resolve the alien invader issue, particularly under changing climatic conditions, although plans are in place (California Department of Fish and Game 2008). At best, careful management can reduce the frequencies of new invasions, conduct eradication programs before invaders are well established, and provide conditions that allow native species to thrive, recognizing they will be coexisting with aliens already established in much of their habitat (Chapter 5).

Habitat Degradation

Alien species are just one of many factors contributing to the decline in California's native aquatic and riparian species. California's aquatic ecosystems have been fundamentally changed by 150 years of water and land management. Today's river, lake, riparian, and wetland ecosystems reflect an interweaving of pre-development natural systems and the accumulated effects of human uses and management of water and land. Indeed, no completely pristine ecosystems remain in California; all are affected by human uses, which have resulted in habitat loss and fragmentation, unfavorable changes in flow conditions and quality, and invasions of alien plants and animals. Climate change will exacerbate many already unfavorable trends.

For example, wildfires are increasing in frequency and severity in California as a consequence of increased human presence in wild areas and failure to recognize that wildfires of low to moderate severity are important for ecosystem functioning (Sugihara et al. 2006). Warming temperatures are likely to be contributing to this trend, which favors conditions for invasive insects that kill various tree species (Miller et al. 2009). By allowing fuels to accumulate, fire-suppression policies have contributed to more severe fires, with numerous negative effects on aquatic systems: direct kills of organisms, destruction of riparian systems, increased siltation from erosion, increased nutrients from burned materials, and altered stream flows as the burned landscapes are less able to retain water. These factors imperil more species, especially in Southern California (e.g., southern steelhead).

Likewise, the anticipated changes in stream flow timing and magnitude with warming, outlined above, will harm freshwater ecosystems, particularly in mountain rivers and in streams that depend on seasonal snowpacks. These shifts are likely to affect a wide range of fishes, amphibians, and riparian plants whose life-history strategies depend on the spring snowmelt pulse—previously the most predictable flow event of the year (Yarnell, Viers, and Mount 2010). This pulse provides an extended period of abundant, low-temperature flow that occurs around the same time almost every year, providing an ideal cue and habitat for the reproductive cycle of these species. Reproduction, both egg-laying and release of seeds, is highly sensitive to changes in the timing, magnitude, and rate of change in this critical flow. These conditions are likely to change significantly in mountain watersheds as a result of climate warming (Null, Deas, and Lund 2010), threatening the survival of native species such as the foothill yellow-legged frog and the hardhead minnow.

Changes in the timing and amount of flow also will harm native species in lowland river systems. As discussed in Chapter 5, conditions of large riverine and estuarine ecosystems in California are already increasingly unfavorable to native fishes. Systems such as the Klamath, Sacramento, San Joaquin, and Colorado Rivers have witnessed significant declines in native fish populations because of harmful flow regulation, flood management, invasive species, and discharge of agricultural and urban waste (Moyle et al. 2010). If present trends in altered flows and degraded habitat continue, California's rivers will be increasingly dominated by alien species, from bass to clams, with many fewer desirable natives, such as salmon and river mussels.

Declining aquatic ecosystems and native species will increasingly affect water management. Changing social values, reflected in state and federal endangered species and clean water legislation, have become embedded in all water management activities. But continued declines in native biodiversity are a stark indicator that current laws, regulations, and management are simply not working well. Fish, amphibians, and other aquatic organisms are losing the contest for water and habitat.

Additional native species will almost certainly be listed as threatened or endangered under the federal or state Endangered Species Acts. Moyle, Katz, and Quiñones (2010), for example, indicate that 17 unprotected species of fish should qualify for immediate listing as threatened or endangered, with others rapidly approaching that condition. Agencies responsible for water management will become increasingly bound to act to prevent extinction and promote recovery of listed species. Future necessary actions, under a changing climate, cannot be known today with high confidence but have potential to disrupt water management operations at all scales, particularly when cold water is necessary for maintaining fish populations. Although more water is not always better for fish, especially if not accompanied with habitat restoration (Hanak et al. 2010), increased environmental demands for flow are likely, simply to keep up with or compensate for changing conditions.

Scientific and Technological Progress

Advances in scientific knowledge and technological innovation will surely occur over the coming decades, as they have in the past. Some innovations—such as the ongoing introduction of new chemicals, discussed above—are likely to heighten water management challenges for human and environmental health. Others will help California cope with its water-related supply and demand problems, including reductions in water availability. Scientific advances should also lead to better understanding and tools for improving the health and functioning of the ecosystem. However, technology also has its limitations and is unlikely to provide a "silver bullet" solution for all of California's water problems (Hanak et al. 2010).

In this section, we briefly explore four areas where advances are likely: (1) treatment technologies for expanding potable water sources; (2) technologies and management approaches for improving efficiencies in water use; (3) technologies for measuring water use; and (4) advances in ecosystem management.

Treatment Technologies

Water treatment makes it possible today to safely and affordably supply drinking water from a wide range of previously disparaged water sources. Reuse of treated wastewater for nonpotable uses such as landscaping is now common in many parts of California, several Southern California agencies have indirect potable reuse by recharging groundwater with highly treated wastewater, and discussions continue regarding more direct potable reuse of water (California Department of Water Resources 2009). Desalination of brackish water is now affordable and is used by urban agencies in inland Southern California. Desalination of seawater, while still very costly, is becoming potentially affordable as an incremental urban water supply in California (California Department of Water Resources 2009; Hanak et al. 2010).

However, new treatment technologies are likely to have limits. As noted above, even as new wastewater and reuse technologies are developed, new chemicals of environmental and public health concerns arise to challenge these technologies. Water treatment also has fundamental physical and economic limits. For example, the most efficient large seawater desalination plants currently use about 4.5 kilowatt hour/cubic meter ($670/acre-foot for energy alone at recent industrial sector energy prices in California), and it seems unlikely that these plants will be able to reduce their energy use by more than 20 percent.[22] Real energy prices are likely to rise in the future. Capital and siting costs of these facilities are also substantial, as well as the sometimes significant costs of environmentally safe disposal of "waste" salt and brine.

Efficiency in Water Use

As discussed in Chapter 2, agricultural water use in California continues to become more efficient, primarily through increases in crop yields. Yields are likely to continue to progress in the decades to come.

Irrigation technology and management tools can help improve water quality, and this will become increasingly important as California works to reduce the flow of polluted agricultural runoff into streams and groundwater basins (Letey

22. See Semiat (2008) on desalination energy use. Energy prices are from the U.S. Energy Information Administration (www.eia.doe.gov/electricity/epm/table5_6_a.html). Recent industrial rates in California are on the order of $0.12 per kilowatt hour. Commercial sector rates are higher (over $0.16 per kilowatt hour).

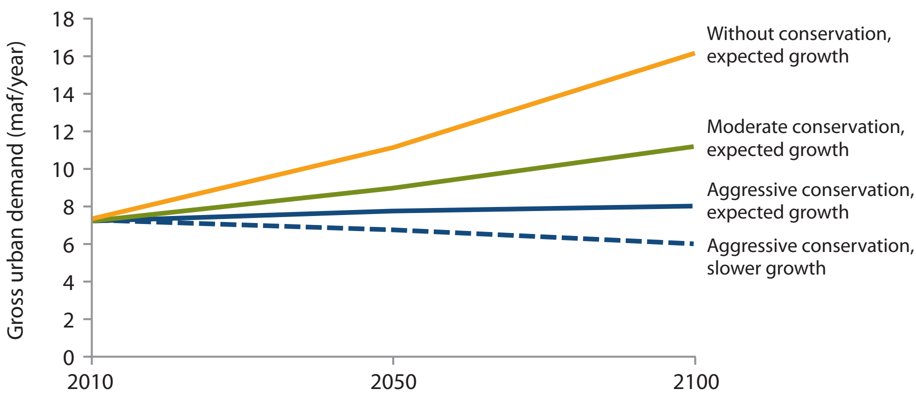
et al. in press). In areas prone to soil salinization, such as the west side of the San Joaquin Valley, reductions in drainage from irrigation efficiency improvements have already greatly reduced salt loads in local soils and receiving waters (Wichelns, Jouston, and Cone 1997; Wichelns and Cone 2006; Shoups et al. 2005).

However, irrigation technology has less potential to create net water savings, because it generally does not reduce net agricultural water use (Box 2.1). Irrigation improvements can actually *increase* net water use by crops, by allowing either more intensive use of irrigation water on a given field (which raises both yields per acre and net water use per acre) or more extensive use of "saved" water on nearby fields that were previously less irrigated. Net water savings are more likely in areas where drainage water cannot be reused, such as where fields drain to brackish or saline aquifers or water bodies. Such savings have been the basis of water transfer agreements between the Imperial Irrigation District, whose crop runoff drains into the Salton Sea, and urban agencies in Southern California. Irrigation technology also can provide solutions to environmental water problems. But to create net water savings from farming in many parts of the state, reductions in crop acreage will be required. Some of this will happen naturally, as farmland is displaced by urban growth. Water marketing also provides an opportunity to compensate farmers and the local economy for reductions in acreage of low-value crops.

As in agriculture, improvements in urban water use efficiency can have water quality benefits. Inefficient landscape irrigation (generally less efficient than on-farm irrigation) is an important factor in polluted urban runoff. And even though the urban sector uses far less water than agriculture, urban water use efficiency actions—both indoors and outdoors—have a greater potential for net water savings. In the state's heavily populated coastal areas, most indoor water use savings result in net water savings, because most treated wastewater is discharged into the ocean. Improvements in outdoor water use efficiency, such as shifting from thirsty lawns to more drought-tolerant plants, can significantly reduce outdoor water use, especially in the hotter inland areas. Technological advancements in irrigation technology, including the use of "smart" irrigation control systems that use weather information to determine when plants need water, have the potential to significantly improve irrigation efficiency and reduce runoff from urban landscaping (Hanak and Davis 2006).

The introduction of more efficient indoor plumbing devices, such as low-flow toilets and showers, have already significantly reduced per capita urban use since the early 1990s (Chapter 2). Additional improvements in indoor plumbing (including more efficient appliances) as well as landscape planting changes, higher urban densities, and improvements in landscape irrigation have the potential to considerably slow growth in urban water use (California Department of Water Resources 2009; Gleick et al. 2003; Hanak and Davis 2006; CALFED 2006). With the mid-range population projections noted above at today's use rate (roughly 200 gallons per person per day [gpcd]), gross urban water demand would roughly double by the end of the century (Figure 3.8). A moderate conservation effort (20 percent by 2050 and 30 percent by 2100) would significantly lessen demand growth, and a more aggressive conservation effort (30 percent by 2050 and 40 percent by 2100) would keep gross urban demands roughly constant. These efforts would result in water use levels falling to 140–160 gpcd by 2050, and 100–140 gpcd by 2100. Lest this seem unreasonable, it is worth recalling that urban water use in the early 2000s in other developed economies with similar climates was 80–130 gpcd in Australia, 84 gpcd in Israel, and 76 gpcd in Spain (Food and Agricultural Organization of the United Nations, undated).[23] In Chapter 6, we explore the potential for aggressive urban conservation efforts to reduce pressures on the Delta and facilitate adaptation to climate change.

Figure 3.8
Successful conservation efforts could significantly slow urban water demand growth



NOTES: Expected population growth scenarios are from Sanstad et al. (2009): 59.2 million in 2050 and 85.3 million in 2100. Slower growth projections are 51.7 million and 64.6 million, respectively (unpublished estimates from Hans Johnson 2009). Moderate conservation assumes 20 percent reduction by 2050 (160 gpcd) and 30 percent by 2100 (140 gpcd). Aggressive conservation assumes 30 percent reduction by 2050 (140 gpcd) and 50 percent reduction by 2100 (100 gpcd).

23. The low estimate for Australia is from www.nwc.gov.au/www/html/2765-national-performance-report-2008-09---urban-water-utilities.asp?intSiteID=1. Urban water use in Australia has been further reduced in recent years in response to prolonged drought.

Measurement of Water Use

Advances in the use of remote sensing technologies are likely to be useful both for raising farm water use efficiency and for improving water accounting. Federal satellite data show promise for accurately estimating crop evapotranspiration on the scale of a farmer's field. This method has the potential to inform farmers and water managers about water use accurately, at relatively little cost compared to metering and on-farm measurement techniques currently available (Allen et al. 2005, 2007). From a regional and statewide water accounting perspective, this method could help improve water use estimates in areas where data collection is hampered by the lack of reporting requirements for some categories of water use. For areas not served by surface water, remote sensing of crop water use gives a direct estimate of net groundwater use as well.

Ecosystem Management

In recent decades, California has seen remarkable improvements in understanding of the state's aquatic ecosystems, compared with the Hydraulic Era when most of the state's water management infrastructure and institutions were designed and constructed. As described in Chapter 5, this knowledge provides an improving basis for shifting the focus of ecosystem management toward approaches that aim to restore ecosystem function at fairly large scales, using concepts such as the "natural flow regime" (which aims to mimic natural conditions, albeit with lower flow volumes). However, there is still much to learn about how ecosystems and species will respond to improved water management actions, particularly with rapidly changing conditions.

New approaches to ecosystem management under changing conditions will require continued, large-scale experimentation aided by computer modeling. This task is complex, because experiments, especially on a large scale, often yield ambiguous results.[24] Also, as with hydrology, the past is not always a good predictor of the future with many ecosystems. Linking human and natural systems, combined with changes in climate and influxes of alien species, creates novel, dynamic ecosystems with no historical analog. Thus, efforts to restore ecosystem functions and attributes involve hitting a moving, only partially visible target. Finally, ecosystem changes are often nonlinear and interrelated. Declines in habitat quality or abundance reduce ecosystem resiliency, with the result that even small changes in conditions can lead to abrupt system collapse

24. An example is the decline of delta smelt and the somewhat chaotic efforts for its recovery (Bennett 2005).

and reorganization to a new state (Walker and Salt 2006).[25] Such thresholds or tipping points are difficult to predict. Taken together, these factors suggest that efforts to improve conditions for California's native aquatic species will necessarily involve trial and error, and that success is far from guaranteed.

Seemingly Inevitable Changes

One of life's charms and curses is that the future is inherently uncertain. We find the drivers of change discussed above compelling, but it is likely that some will be less important than we envision and that others might more than take their place. Other potential influences include changes in social preferences among water management objectives, including a tightening—or radical loosening—of endangered species regulations; major changes in energy policy or costs; and destructive geologic events, such as proximate or global volcanic eruptions that alter climate conditions or devastate regional landscapes.

Predicting changes with certainty is clearly impossible, although change itself is certain. California has always been changing, often quite dramatically, and water management in California is no exception. A list of the dozen most likely changes affecting California water, in order of their likely importance, would include:

1. Greatly expanded efforts to maintain "natural" ecosystems and native species as a water management goal, given increased numbers of both endangered and alien species, placing increasing pressure on providing water for human consumption;
2. Transformation of the Delta and water management as a result of sea level rise, earthquakes, and permanent flooding of western and central islands, reducing the viability of the Delta as an urban and agricultural water source;
3. Population growth and expansion of the urban footprint, displacing portions of agricultural land, altering water use, and raising floodplain risks, particularly in the Central Valley;

25. For instance, the Delta's ecosystem seems to have abruptly shifted in the 1980s, driven by increasing water exports from an already highly altered system, exacerbated by invasive species and pollutants (Moyle and Bennett 2008). Likewise, the Eel River ecosystem shifted from a shaded cold water system to a more exposed cool water ecosystem, less friendly to salmon and steelhead, as the consequence of massive human-caused erosion and introduction of an alien predator (Yoshiyama and Moyle 2010).

4. Declining financial support for water management from traditional state and federal sources;
5. Degradation of infrastructure, including levees, dams, and water treatment facilities, with increasing replacement costs;
6. Increasing average air and water temperatures, leading to decreasing snowpack, declining available water, changing natural vegetation, and increasing environmental water demands in reservoirs to maintain cold water for salmon and steelhead habitat below dams;
7. Rising expenses for water and wastewater treatment as water quality standards continue to diversify and become more exacting and as understanding of the negative effects of increasingly diverse and abundant contaminants increases;
8. Reductions in per capita urban water use (gross and net);
9. Reductions in irrigated agriculture as a result of urbanization, the flooding of Delta farmlands, salinization, increasingly costly groundwater overdraft, and cutbacks in Delta water exports in the western San Joaquin and Tulare Basins;
10. Globalization of California's economy, with continued growth in its service economy and continued shifts to higher-value perennial crops;
11. Increasingly compromised groundwater basins, as a result of overdraft and declining groundwater quality; and
12. Increased investments in (or retreat from) current shorelines and reexamination of coastal management as a result of sea level rise.

Other changes are likely but less certain. One possibility is that, despite population growth, total human water use in California might decline over time through the combined effects of lower per capita urban water use and reductions of irrigated agricultural land. Other changes, perhaps more significant, are likely to arise with little warning or to be evident only in retrospect. Thirty years ago, few could have predicted the ubiquity of information now available through the Internet. Two years ago, few preparations were in place to manage European air travel in the event of volcanic eruptions in Iceland.

A major uncertainty for water management is what will happen to overall precipitation levels with climate change. In contrast to most other drivers examined here, there is uncertainty about not only the magnitude but also the direction of change. A drier climate will exacerbate water scarcity arising from reductions in the snowpack, and a wetter climate will lessen scarcity but exacerbate flood risks.

Decisionmaking in the face of uncertainty about the future is inevitable for California water management. But the challenge is not new: Water managers have always faced uncertainty, often with less sophisticated technical tools than are available today. For those decisions whose usefulness depends greatly on uncertain outcomes (such as new surface storage to accommodate changes in precipitation), it would be wise to wait for greater certainty (Chapter 6). However, for many decisions, awaiting certainty can become an excuse for maintaining a deteriorating status quo. Such procrastination can turn the "precautionary principle" into a potentially dangerous "inaction principle" when maintaining the status quo means continued loss of environmental services, biodiversity, and other water management benefits. Fortunately, sufficient certainty often exists to make better choices.

Some changes reviewed in this chapter can be addressed individually, but many will require more integrated and comprehensive solutions. Part II of this book describes several approaches for managing simultaneous changes and increasing the adaptive capacity of water management systems to achieve multiple goals.