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Adapting California's water management to climate change

Ellen Hanak · Jay R. Lund

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Abstract California faces significant water management challenges from climate change, affecting water supply, aquatic ecosystems, and flood risks. Fortunately, the state also possesses adaptation tools and institutional capabilities that can limit vulnerability to changing conditions. Water supply managers have begun using underground storage, water transfers, conservation, recycling, and desalination to meet changing demands. These same tools are promising options for responding to a wide range of climate changes. Likewise, many staples of flood management—including reservoir operations, levees, bypasses, insurance, and land-use regulation—are available for the challenges of increased floods. Yet actions are also needed to improve response capacity. For water supply, a central issue is the management of the Sacramento-San Joaquin Delta, where new conveyance, habitat investments, and regulations are needed to sustain water supplies and protect endangered fish species. For flood management, among the least-examined aspects of water management with climate change, needed reforms include forward-looking reservoir operation planning and floodplain mapping, less restrictive rules for raising local funds, and improved public information on flood risks. For water quality, an urgent priority is better science. Although local agencies are central players, adaptation will require strong-willed state leadership to shape institutions, incentives, and regulations capable of responding to change. Federal cooperation often will be essential.

1 Introduction

Californians have a history of adapting to different climates in a context of dynamic economic and population changes. The first settlers from the eastern United States arrived

E. Hanak (✉)
Public Policy Institute of California, San Francisco, CA, USA
e-mail: hanak@ppic.org
URL: www.ppic.org

J. R. Lund
Center for Watershed Sciences, University of California, Davis, CA, USA
e-mail: jrlund@ucdavis.edu
URL: http://watershed.ucdavis.edu

in a rapidly changing state with a significantly different and poorly understood climate. The sagas of how they adapted are part of California's early history, from the Donner Party to our history of irrigation and flood control (Pisani 1984; Kelley 1989). These early settlers had fewer intellectual, organizational, and economic resources to adapt than present-day Californians, and it required 50–100 years for them to adjust their water law, farming practices, infrastructure, and institutions to this new environment.

Today, water management in California concerns a wide array of activities, ranging from supply planning and delivery, to water quality protection for humans and ecosystems, to reducing flood risks, to generating hydropower. Although state and federal agencies have roles in all aspects of water management, local governments are generally on the front line. Roughly 400 large retail utilities (population >10,000) deliver water to most California homes and businesses. Hundreds of agricultural water districts manage water supplies for California's farmers. Nearly 600 local wastewater utilities must meet water quality standards for municipal wastewater discharge. Most county governments and numerous special districts oversee local flood management. City and county governments have become responsible for managing the quality of stormwater runoff. Local governments also oversee land development, with important implications for water demand, water quality management, and flood risk. Over 150 hydropower projects are managed by private power companies and local, state, and federal agencies.

This institutional diversity creates the potential for innovation and flexible responses to management challenges, but also challenges effective coordination (Bish 1982). California's water system often suffers from governmental fragmentation and an absence sustained of state and federal leadership, but it has benefited greatly from the local accountability, innovations, and financial base that stem from decentralization. These institutional traits will help shape adaptation to climate change in the coming decades.

Rising temperatures, sea level rise, and anticipated increases in extreme droughts and storms from climate change are likely to profoundly affect the range of water management activities, requiring adaptive responses. There is considerable variation in our current knowledge of climate impacts on water and water use, and different stages of thinking about adaptation strategies. Water supply planners have begun discussions about how best to adapt to changing supplies, as evidence mounts for a diminishing Sierra snowpack. In the areas of flood control and water quality, managers have been slower to react, either because information on climate impacts remains more speculative (the case with water quality), or because institutional obstacles (especially related to land use) have hindered preparations (the case with flood management). Effective response to climate change will require unprecedented integration, because water supply, water quality, floods, and other water concerns are all hydrologically related. The need for more integration will challenge existing water management institutions and require state leadership to re-align local, regional, and (where possible) federal interests, finance, and expertise to better address problems in a changed environment.[1] Climate change adds further uncertainty to water policy, planning, and management, on top of already formidable uncertainty in California's hydrology, institutions, and water demands.

This article reviews the adaptation challenges for water management in California. We begin by reviewing the state of the science on climate change impacts affecting this sector, and then look briefly at coincident changes in population, the economy, and technology that

[1] The California Energy Commission Public Interest Energy Research (PIER) program and the California Department of Water Resources have sponsored or conducted much pioneering research on climate change impacts and adaptation for California, particularly in the water sector.

may affect adaptation needs and capabilities. This is followed by a discussion of adaptation options and costs, drawing on a variety of modeling studies. We then turn to an assessment of the institutional capabilities and constraints to adaptation, taking into account the roles of local, state, and federal agencies, and discuss steps needed to enhance adaptive capacity in this sector.[2]

2 Concerns for climate change

Climate has many characteristics and can change in many ways. Each potential form and magnitude of change has different effects on water systems, societies, and economies, as well as implications for adaptation (Kundzewicz et al. 2007). For water management in California, several forms of climate change are of greatest current concern:

- Sea level rise
- Warmer temperatures shifting mountain runoff from spring to winter
- Changes in precipitation and temperature affecting average runoff volume
- Changes in drought persistence
- Higher water temperatures in streams and reservoirs
- Changes in water demands from higher air temperatures and CO_2 concentrations
- Increased flood flows and flood frequencies

2.1 Sea level rise

Rising sea level is the most certain aspect of how California's climate will change. Sea level has been rising for thousands of years and will continue to rise, probably at an increasing rate due to global climate warming (Luers and Mastrandrea 2011). Many of California's water managers are now working with projections of a 14 inch rise by mid-century and a 40 to 55 inches rise by 2100, slightly above the levels projected in the higher emissions scenarios of the Intergovernmental Panel on Climate Change (IPCC).[3]

Rising sea level has implications not only for coastal areas (Hanak and Moreno 2011) but also for the Sacramento-San Joaquin Delta. The Delta, at the eastern edge of the San Francisco Estuary, is a hub of California's water supply system, enabling northern California water to pass to the Bay Area and the southern half of the state (Lund et al. 2007, 2010). Sea level rise will raise salt water elevation at the Delta's western end and increase water depths throughout the Delta, potentially changing the amplitude of tides and storm surges in this region. The resulting increases in levee failures and seawater intrusion into the Delta, would disrupt water supply system slowly or catastrophically for several months to several years. Sea level rise also will likely affect some coastal aquifers and increase costs and difficulties for coastal drainage and wastewater systems (Heberger et al. 2009).

Sea level rise could also further reduce salt and brackish wetland areas in California, particularly if marsh sedimentation cannot keep up with rises in sea level and if upland urban or agricultural lands are prevented from converting to wetlands (Caldwell and Segal 2007).

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[2] Many of the topics presented here are assessed in greater depth in Hanak et al. 2011.

[3] This range was recently recommended for use for planning purposes by the California Ocean Protection Council (2011), based on projections by Vermeer and Rahmstorf (2009).

2.2 Shifting mountain runoff from spring to winter

Rising temperatures will reduce snowpack in California's mountains because more precipitation will fall as rain and snowmelt will occur earlier (Knowles et al. 2006; Null et al. 2010). Soot and other particles from urban and agricultural activities also may be increasing the albedo of snowpack, accelerating snowmelt (Qian et al. 2009; Jacobson 2007; Hadley, et al. 2007). If overall precipitation patterns do not change, these effects of warming will increase winter runoff and decrease spring runoff (Lettenmaier and Gan 1990). This form of climate change also is rather certain; a greater proportion of annual runoff is already flowing earlier in the water year (Aguado et al. 1992; Dettinger and Cayan 1995). For reservoirs downstream of significant mountain snowpacks, the shift in reservoir inflows could increase risks for floods and water supply, particularly if reservoir operations are not changed for these new conditions (California Department of Water Resources 2006; Medellin-Azuara et al. 2008; Fissekis 2008).

2.3 Changes in average precipitation and runoff volume

The effects of climate change on overall precipitation and runoff are less clear, but of great potential importance. The already substantial amount of surface reservoir storage on most major streams in California provides a fair amount of capacity to accommodate seasonal shifts in inflows for most years. However, any reduction of annual runoff volumes due to declines in precipitation or increases in reservoir and watershed evapotranspiration would directly reduce water and energy supplies. In modeling studies, the effects of reduced runoff due to decreased precipitation appear to be much more important than seasonal shifts, particularly for water supply and hydropower (Tanaka et al. 2006; Medellin-Azuara et al. 2008; Connell 2009). However, the net effects of climate warming on total runoff volumes remain unclear (Dettinger 2005, Cayan et al. 2009). It is likely to be decades before we know if and by how much precipitation and runoff volumes are changing (Klemes 1993, 2000a, b).

2.4 Changes in drought persistence

Droughts in the western U.S. are often persistent. Of three droughts in California since the 1920's, two were six years long. Droughts on the Colorado River, another significant source of water for California, also commonly last for several years or longer. Moreover, California and the Colorado Basin have experienced extremely severe and persistent droughts in the past two thousand years. Stine (1994) and others have found signs of two prolonged severe droughts in California about a thousand years ago, each lasting over 100 years with mean annual flows between 40 and 60% of recorded historical flows. These past droughts appear to have had less effect on runoff in the Sacramento basin (Meko et al. 2001). Such droughts could return in the future.

2.5 High stream and reservoir temperatures

Higher temperatures overall will increase water temperatures throughout the system, including inflows into reservoirs, water stored within reservoirs, and water flowing downstream. Such increases will affect ecosystem and human uses of the water system.

Most species have a range of temperatures in which they thrive. Chinook salmon, in particular, generally prefer temperatures less than 20°C (68°F). Before the advent of dams, migratory fish had some ability to spawn and rear at different elevations as temperatures changed. Naturally, salmon spawning and rearing would be restricted to higher elevations as water warms at lower elevations. However today, on many streams dams block fish access to higher elevations and releases of stored cold water are made for spawning and rearing at unnaturally low elevations for some salmon runs. It will become more difficult to provide this largely artificial habitat as average water temperatures rise.

Downstream species also are likely to suffer from a general rise in water temperatures. The delta smelt—an endemic species whose plummeting population has focused attention on the environmental woes of the Sacramento-San Joaquin Delta—may be particularly vulnerable to temperature changes. The smelt are thought to require temperatures below 20°C to spawn (Bennett 2005). Rising temperatures are likely to reduce the spawning season, and perhaps eliminate spawning entirely.

To date, little research exists on other impacts of water temperature increases, although such changes are likely to affect drinking water quality and habitats for native species. Higher temperatures increase the rates of chemical reactions and algal growth and decay. Several drinking water treatment processes are affected by water temperature.

2.6 Increased water demands

Higher temperatures and increases in CO_2 are also likely to change water demands. Several direct physical effects are worth noting. As discussed below, the ultimate impacts will depend on other changes in the regional and global economy, population, and land use. The most important effect is likely to be on agricultural water demands, if only because agricultural water use is by far the largest water demand in California (about 80% of all human uses). Higher temperatures generally increase evapotranspiration (ET) rates, but higher temperatures and CO_2 concentrations also increase rates of plant growth and can shorten the time to plant maturity. Hopmanns and Maurer (2008) found that this increased productivity effect would reduce overall plant water use (ET) in the San Joaquin Valley, partially compensating for potential reductions in agricultural water supply. However, longer growing seasons with more rapid crop maturity could also increase demands from double-cropping. Climate change's interaction with other agronomic and economic factors affecting cropping and water use will vary by crop type (Jackson et al. 2009; Lee 2009; Lobell et al. 2009).

Urban water demands may also be affected by climate warming. Indoor water demand could rise with greater use of evaporative cooling of buildings and residences, as is common in some hot, dry areas in the southwestern United States.[4] Increases in evapotranspiration and growing season could increase outdoor water consumption for landscaping, which is half or more of residential water use in the hot, inland areas (Hanak and Davis 2006).

Energy demands are likely to increase from higher temperatures, since much power demand, particularly for peaking power, is for air conditioning (Vine 2011). Hydropower is particularly valuable for peaking power; it is one of the few large forms of storable power, and it can respond quickly to fluctuations in power demand. If daily peaks for power demand increase and broaden from additional air conditioning, this will raise the value of hydropower. Higher temperatures are also likely to lengthen the air conditioning season,

[4] In Phoenix, almost half of homes use evaporative cooling, which accounts for almost 15 percent of summer water use (Phoenix 2007). Such cooling systems are also in use in rapidly growing southern California desert areas, such as the Coachella Valley.

increasing hydropower demands earlier in the spring and later in the fall. Alternatively, warming would also reduce energy demands for heating during winter.

2.7 Increased flood flows and flood frequencies

In California, most major floods in the last century occurred in the last 50 years, after most dams were built. While this might not be a statistically significant indicator of climate change, California's flood control system provides significantly less protection than had been thought when these investments were made (National Research Council 1999).[5] Reductions in snowpack and shifts from snowfall to rainfall seem likely to increase flood peak flows and flood volumes (Miller et al. 2003; Fissekis 2008). For reservoirs downstream of significant mountain snowpacks, higher temperatures, even with decreases in precipitation, can increase flood volumes and pose major risks for flood control, particularly if reservoir operating policies are not modified to accommodate new conditions (Fissekis 2008).

Increased intensity and frequency of major storms, another anticipated effect of climate change, would worsen flood problems in California (Knox 1993; Florsheim and Dettinger 2007). With continued increases in floodplain urbanization and the associated increase in damage potential, flooding costs from climate change could exceed those of water supply. The effects of changes in flood flows on ecosystems are less well studied, but could be significant (both positive and negative). Habitat in many streams relies on periodic floods to reshape channels and re-establish habitat, but human responses to floods can disrupt ecosystems and threaten ecosystems already weakened by other stressors.

2.8 The difficulty of predicting impacts

Thus, a variety of forms of climate change have the potential to affect water supplies, floods, and ecosystems in California, ranging from rather certain effects of sea level rise and rising temperatures to less certain, but perhaps more important changes in storm intensity, average precipitation, runoff timing, and persistence of droughts. Most of these changes will occur against a noisy backdrop of natural variability. Accurately characterizing the magnitude and variety of climate change is likely to take many decades. Most large climate models predict major changes in 50–100 years (Barnett et al. 2008). However, for water management and operational purposes, particularly for flood frequency estimation, we will be able to quantify most climate changes only long after these changes have occurred (Klemes 1993, 2000a, b). Moreover, these changes will not occur in isolation. California will adapt to a changing climate in concert with a host of other major changes and challenges.

3 Coincident changes in California

Other changes in California over the coming decades include population growth, changes in the structure of the economy, technological advances, and evolving societal goals. Such factors will affect not only the extent of climate impacts but also the ability to effectively adapt.

[5] See also www.safca.org/floodRisk/index.html, for a discussion of this issue in the Sacramento area.

California's need to compensate for climate-induced changes in water supply will depend largely on the evolution of water demands, driven by population growth and other factors (California Department of Water Resources 2005a). Although distant population projections are not very reliable, current expectations are for continued robust growth, with an additional 22 million people by 2050, to reach nearly 60 million (more than 60% above current levels) (California Department of Finance 2007). At today's average per capita water use levels (about 200 gallons per capita per day), this translates to an additional 5.5 million acre-feet (maf) (6800 million m^3) in annual urban water demand (compared with recent annual total human uses of around 40 maf (49,340 million m^3).[6] Most new residents are expected to locate in hotter inland parts of the state, where per capita water use is considerably higher than along the coast, largely because of greater lot sizes and outdoor water use. Recent trends suggest a decline in lot sizes in the inland areas, which could reduce growth in outdoor water demand (Hanak and Davis 2006).

Demand pressures also can be reduced through urban conservation and reallocating some water from agriculture. Even though climate change may affect agricultural productivity, agricultural land area will likely be somewhat smaller than today (California Department of Water Resources 2005a, 2005b). Markets and technology are likely to change the mix of crops and increase crop yields and water use efficiency. Water transfer opportunities will be available where agricultural water is devoted to low-value crops and where farmland comes out of production because of high salinity or urban development.

Although market incentives will aid this transformation toward reallocation and greater water use efficiency, the extent of such changes also will depend on the evolution of social norms and goals: homeowners' willingness to abandon the traditional green lawn in favor of drought-tolerant plants, acceptability of land-use mixes with less irrigated landscaping, and political acceptability of transferring water from farming if the local communities resist such changes.

Population growth also is likely to increase flood risk exposure. Currently, one of California's fastest growing areas is the Central Valley, much of which lies in a floodplain. A range of strategies exists for dealing with the greater flood risk from earlier winter and spring runoff, greater storm flow volumes, and more violent rain storms. However, land use policies over the coming years can create long-lasting flood vulnerabilities and costs of adaptation.

Finally, technological advances and societal objectives may alter environmental water quality goals. Recent decades have seen more stringent water quality standards for both human and ecosystem uses. As detection and treatment technologies improve, this trend might be expected to continue, even if compliance costs increase. Climate change may further increase the costs of meeting water quality goals.

4 Adaptations to climate change: options and costs

In contrast with California's early settlers, Californians today have many options for adapting to a changing climate. Today's predominantly urban economy also is less sensitive to climate-related shifts in water conditions than the agricultural economy of the settler era.

[6] Recent water use estimates exclude conveyance losses. See California Department of Water Resources, 2009. With the recent passage of SBX7-7 (2009), California's urban water utilities are expected to reduce per capita use by 20% below 2005 levels by 2020.

Some studies have estimated what promising adaptations might look like and how much they would cost.

4.1 Available adaptation options

California's water management systems are unusually complex, extensive, and interconnected. While this complexity often creates a political cacophony regarding water problems, it allows for a wide range of physical and economic adaptations to changes in climate, land use, economics, and societal expectations.

California's water supply system already has a relatively good record of adapting to major changes. Major droughts in 1976–77 and 1988–92, along with steady population growth and increased emphasis on protecting native ecosystems, have brought major innovations, with greater emphasis on non-traditional water management techniques. There is also considerable potential for adaptation in flood management, although a variety of technical and institutional constraints have hindered progress in this area.

Although water supply and flood management share much of the same infrastructure, for expositional purposes we discuss the adaptation options for each separately, before highlighting linkages between them.

4.1.1 Water supply: portfolio approaches

Contemporary managers of major water utilities and supply systems in California employ a portfolio approach that coordinates a range of options, varying with local cost, demand, and water rights (Table 1). Such portfolios can be explored and evaluated using integrated system models, such as CALVIN (Tanaka et al. 2006; Medellin-Azuara et al. 2008), CALSIM (California Department of Water Resources 2006), WEAP (www.weap21.org), and IRPSIM (Chesnutt et al. 1996).

The major categories of options are those which manage demand and those which manage supplies. Water demand and allocation options include a host of common demand management or water conservation techniques as well as actions that better allocate scarce water from the perspective of overall economic and social values. Pricing, water markets and transfers, insurance, and regulations are available to provide incentives for more cost-effective allocations or reallocations of water. Demand management options can be applied to urban, agricultural, environmental, or other water use sectors. Common examples include changes in plumbing codes, landscape ordinances, incentives to improve appliance water use efficiency, and reductions in agricultural consumptive use. Water scarcity is another generally less desirable form of demand management, whereby water users receive less water than desired. Water rationing and higher prices are the most common responses to water scarcity. Persistent scarcity can induce increased water conservation, and in extreme and unusual cases can cause relocation of water-intensive enterprises such as agriculture and some industries.

Water supply options include a variety of operational and expansion activities. In California, major improvements in water deliveries have occurred from coordinating operations of various dams and conjunctive use of surface and ground waters, storing water underground in wetter periods for use in drier periods. Additional water supplies can be made available through treatment of lower quality waters, including seawater and brackish groundwater (desalination) and wastewater reuse.

Each of these actions improves water services under some circumstances, works better or worse with other options, and comes at a cost. The allocation of these costs to water

Table 1 Water supply system management options

Demand and Allocation Options
General Policy Tools
Pricing*
Subsidies, Taxes
Regulations (water management, water quality, contract authority, rationing, etc.)
Water markets, transfers, and exchanges (within and/or between regions/sectors)*
Insurance (drought insurance)
Demand Sector Options
Urban water use efficiency (water conservation)*
Urban water scarcity (water use below desired quantities)*
Agricultural water use efficiency*
Agricultural water scarcity*
Ecosystem restoration/improvements (dedicated flow and non-flow options)
Ecosystem water use effectiveness (e.g. flows at certain times or with certain temperatures)
Environmental water scarcity
Recreation water use efficiency
Recreation improvements
Recreation scarcity
Supply Management Options
Operations Options (Water Quantity and/or Quality)
Surface water storage facilities (new or expanded)*
Conveyance facilities (new or expanded)*
Conveyance and distribution facility operations*
Cooperative operation of surface facilities*
Conjunctive use of surface and ground waters*
Groundwater storage, recharge, and pumping facilities*
Supply Expansion Options (Water Quantity or Quality)
Supply expansions through Operations Options (reduced losses and spills)
Agricultural drainage management
Urban water reuse (treated)*
Water treatment (surface water, groundwater, seawater, brackish water, contaminated waters)*
Desalination (brackish and sea water)*
Urban runoff/Stormwater collection and reuse (in some areas)

1. Options represented in the CALVIN model (see text) are denoted by an asterisk (*)

users, local and regional water utilities, or state agencies or taxpayers is a major opportunity for establishing incentives for more efficient system management. Because this process often requires considerable negotiation, implementation of these options usually requires more institutional time than construction time.

4.1.2 Flood management

Adaptation options for flood management are summarized in Table 2. All are currently employed in California. As with water supply, local, regional, statewide, and federal

Table 2 Flood management toolbox

Structural Options
Levees (peak accommodation)
Flood walls and doors (peak accommodation)
Closed conduits (peak accommodation)
Channel improvements (peak accommodation)
Reservoirs (peak and duration reduction)
Channel bypasses (peak accommodation, spreading, and infiltration)
Non-Structural Options
Flood warning/evacuation
Floodplain zoning and building codes
Floodproofing: structure raising, sacrificial first storey, watertight doors
Flood insurance and reinsurance
Flood education
Real-time Flood Operations
Levee and flood wall monitoring (structures and seepage)
Sandbagging of levees and flood walls
Flood door closure
Reservoir operation
Warning and evacuation decisions and emergency mobilization

authorities all make decisions regarding flood management, although water supply and flood management are often handled by different agencies or sections at each governmental level. Many flood management options require the cooperation of several authorities.

Flood management options are commonly divided into structural and non-structural categories. Structural options include major constructed facilities such as levees, dams, bypasses, and improvements in flood channel capacities. Non-structural options include a host of actions for reducing damages from flooding, such as flood warning and evacuation, zoning to reduce damage-prone land uses in floodplains, "flood-proofing" of structures, and flood insurance to reduce flood damage potential. Various real-time flood operation activities support both structural and non-structural flood control activities.

Whereas water supply problems usually arise over a period of years, large floods develop over a period of days or weeks (as storm systems develop and encounter watersheds) and inflict damage over the course of hours or days. This timing affords little opportunity for institutional response or implementation of new options in the course of the event. As a consequence, flood management is overwhelmingly about preparation.

Flood management adaptation is problematic with a changing climate, which diminishes our understanding of the types and frequency of flood events to prepare for. When faced with expensive preparatory actions and rare occurrences, institutions often delay major actions until the situation becomes clearer. The time required to understand how changes in climate will affect flooding and flood frequencies is likely to be decades or more (Klemes 2000a, b). Delays in preparation may result in terrible flood losses, but over-preparation is also costly.

4.1.3 Linkages

Water supply and flood management are only loosely linked at present, managed by largely separate organizations but jointly reliant on many common reservoirs and channels. Yet they are part of an integrated system. Traditionally, winter flood and spring snowmelt waters are captured for water supply, and the amount of drought (or cross-year) and seasonal water supply storage in reservoirs is limited to keep space in reservoirs for regulating floods. Both purposes also are driven by human land uses, which seek water supplies and protection from flooding. As the population and land use intensity increase and the climate changes, the linkages between these two purposes will become tighter and more important. Seasonal shifts in spring runoff to winter will worsen the conflict between filling reservoirs for water supply and keeping them empty for winter floods.

4.2 Physical and economic potential for adaptation

Dozens of studies have explored the potential magnitudes and impacts of climate change on California (examples include Lettenmaier and Gan 1990; Wilkinson 2002; California Department of Water Resources 2006; Vicuna 2007). Most of these studies assume current levels and types of water demands and land use, water allocations, and water management policies.[7] The likely effects of climate change are great indeed when one assumes little or no adaptation. A more realistic approach is to model how California's water management system might adapt to simultaneous changes in climate, land use, population, and water demands over the coming 50 to 150 years. This section summarizes some early analyses along these lines. Alas, at this early stage these analyses are neither comprehensive nor integrated and generally treat water supply, hydropower, and floods separately.

4.2.1 Water supply

The most comprehensive adaptation studies done for water supply in California have employed the CALVIN economic-engineering model of California's water supplies and demands.[8] The CALVIN model employs optimization to examine how many thousands of options for California's system could be coordinated to adapt to changes in policies or water supply conditions within a planning time frame (Draper et al. 2003). The options included are indicated in Table 1 and include operation of reservoirs, aquifers, pumps, treatment plants, water reuse, water conservation, water markets, and desalination. CALVIN, like any model, has assumptions and limitations (Lund et al. 2003; Tanaka et al. 2006), but its results offer unique insights into cost-effective adaptations to climate change under likely future conditions.

Several CALVIN studies that explore a variety of wet and dry climate warming scenarios indicate that California's water supply sector has a fair ability to adapt to climate warming (Lund et al. 2003; Tanaka et al. 2006; Medellin-Azuara et al. 2008; Connell 2009). Even with significant population growth and urbanization, it appears to be physically possible to

[7] Some simulation and optimization studies have made modest attempts to adapt system operating rules to a changed climate (Yao and Georgakakos 2001; VanRheenen et al. 2004; Vicuna 2007; Medellin-Azuara et al. 2008).

[8] Some preliminary local studies also have been done for the Inland Empire Utilities Agency (Groves, et al. 2008), East Bay Municipal Utilities District (EBMUD), and Metropolitan Water District of Southern California using simulation models.

accommodate major seasonal shifts in inflows to the winter months. This accommodation is made possible by moving much of California's "drought" water storage from surface reservoirs to aquifers, which already provide most of this type of multi-year storage. This adaptation requires changes in reservoir operating policies, additional investments in groundwater recharge and pumping facilities, effective groundwater management, continued ability to change water operations and allocations using water markets and exchanges, and continued ability to move water across the Delta.

Adaptation would not be costless to the state's economy; it would decrease hydropower production and recreation at surface reservoirs (with lower summer water levels) and it would increase pumping costs for access to drought storage in aquifers. If climate warming is also drier, problems are greater. For the year 2100, with population levels estimated at 92 million and commensurately denser land use patterns, a 26% reduction in average streamflows (based on the PCM model, run B06.06) would increase water supply costs by about $3 billion per year (2008 dollars) relative to a baseline scenario with no climate change.[9] If climate warming comes with increased precipitation, water management and scarcity costs could actually decline, although flood problems would likely increase. From a water supply perspective, it is typically more costly to build new surface reservoirs to adapt to changes in runoff than it is to increase use of other tools, including more underground storage. Wetter forms of climate warming have much less potential for economic damage for water supply (Tanaka et al. 2006; Connell 2009)

If the predominant form of climate change is not warming, but a return to a severe sustained drought, adaptation strategies differ substantially, while retaining some common elements (Harou et al. 2010). Adaptations could include major market-based reallocations of water from agriculture to urban users (with 30–50% reductions in agricultural water deliveries in many areas), major increases in wastewater reuse and water conservation, some sea water desalination, major losses of hydropower, and increases in urban water scarcity. For a severe sustained drought, conjunctive use of ground and surface waters and the transfer of drought storage from surface reservoirs to aquifers are ineffective because most reservoirs never fill. This type of climate change is more costly than the scenarios examined above. Economic costs (relative to a baseline with no climate change) are already on the order of $3 billion per year by 2020, and they rise over the century with sustained population growth. For such an extreme sustained drought, additional reservoir capacity provides no water supply benefits; there is a shortage of water, not a shortage of storage capacity for water supply.

In sum, the economic costs to water users of climate change could exceed several billion dollars per year by some point in this century. Although this cost may seem high, it is manageable in the context of a growing statewide economy, now worth over $1.7 trillion per year and a current state budget on the order of $100 billion per year. However, some communities would be seriously affected by reductions in agricultural water supplies, enough to threaten their existence.

Some aspects of climate change for California's water supplies have yet to be investigated in any detail. These include the effects of climate warming on agricultural and urban water demands and how increased water temperatures affect maintenance of cold water habitat for salmon and other species. The loss of cold water within and downstream of reservoirs could become a major impediment to adapting the water supply system for

[9] Because these results are obtained using an optimization model, this figure probably represents the minimum cost for optimal water supply adaptation.

climate change. Without extensive preparation, the loss of the Delta due to levee failures from sea level rise and flooding would also impose major additional restrictions, controversies, and costs on the water system and its users, as might requirements to increase Delta outflows to manage salinity (Lund et al. 2010; Tanaka et al. 2011).

4.2.2 Hydropower

With adaptation, the large water supply reservoirs are able to mostly accommodate seasonal shifts in inflows for hydropower production, resulting in only small hydropower losses (Tanaka et al. 2006; Connell 2009). Because these large reservoirs can often store a large proportion of the average annual streamflow, they have the capacity to accommodate some seasonal shifts in inflows when drought storage is moved elsewhere. However, there is somewhat less flexibility at the smaller, higher-elevation reservoirs that produce much of California's hydropower. Vicuna et al. (2008) and Madani and Lund (2010) have examined the ability of high-elevation hydropower production to respond to climate warming. Both studies indicate that the seasonal storage capacity of these smaller reservoirs can blunt most of the effects of climate warming, although there is some loss of revenues and more years when reservoirs must "spill" some inflows because of limited turbine and storage capacities. For wetter years, the shift of runoff to winter increases this "spill" of energy inflows which can be neither stored in the reservoir nor passed through limited turbine capacity. Drier warming, with its reductions of overall streamflow, commensurately reduces energy production and hydropower revenues. These early studies do not yet include the effects of climate warming on energy prices and demands, which are likely to increase due to warming (Vine 2011).

4.2.3 Flood management

Studies of the implications of climate change for flood risk and flood management have only begun. Because flood management requires quick reaction times and advance preparation, and given the great uncertainty of how floods will change with climate warming, modeling studies of effects and adaptations are much more difficult than for water supply. California's flood management system is particularly complex, relying on a system of levees, flood bypasses, and reservoirs.

Early studies (Lettenmaier and Gan 1990) and more recent studies (Miller et al. 2003; Fissekis 2008; Das et al. submitted), suggest that climate warming alone could worsen flood frequencies, and that such effects could be much worse if climate warming is accompanied by increased precipitation. To date, few studies have examined the implications of such changes for flood management operations and investments. Fissekis (2008) found that even modest warming and increases in precipitation could create dangerous flood conditions at some Sacramento Valley reservoirs. Yao and Georgakakos (2001) found that incorporating improved flood forecasting into reservoir operation at Folsom Dam has good potential to improve flood and water supply operations.

Zhu et al. (2007) conducted a preliminary examination of how the levee system on the Lower American River, protecting parts of the Sacramento metropolitan area, should optimally adapt to several combinations of changes in climate and urbanization over the next 150 years. With urbanization alone (without climate change), it appears economically desirable to steadily increase levee heights to protect increasingly valuable land; this investment strategy would balance average annual flood damages against levee construction and maintenance costs. Worsening flood frequencies alone (in line with historical trends) or a wet form of climate warming also steadily increases optimal levee heights over the planning horizon. With combined urbanization and wet climate warming, it appears optimal to increase levee setbacks as well as levee heights in the future, despite immense costs. Climate warming, especially when combined with other changes, can have serious implications for flood investment and floodplain planning in California.

Further analysis is needed to explore the effects of different climate and precipitation scenarios and to examine how investments should change if the full range of policy levers were at work simultaneously, including levees, bypasses, and reservoir systems as well as land use decisions. Presently, major investments are being made in flood management and land use in California's floodplains. Given the long-term implications of today's decisions on future risk, the flood management-climate connection is one of the greatest gaps in thinking and analysis regarding water system adaptation to climate change.

4.2.4 Water quality

Finally, adaptations will be needed in the area of water quality management. Analysis is needed of the likely effects of changing temperatures and runoff patterns on aquatic habitat, sedimentation, and contaminant deposits and chemical and biological processes. Sea level rise will profoundly alter conditions in the San Francisco Estuary and Delta, increasing its salinity, permanently returning some land to open water habitat, and reducing or eliminating the suitability of the Delta for major water exports (Lund et al. 2010; Chen et al. 2010; Fleenor et al. 2008). As discussed below, these changes have implications for regulatory policy regarding public health and species protection.

5 Institutional capacities and constraints to adaptation

Overall, California's water managers seem well ahead of their counterparts in most other sectors regarding awareness of the impacts of climate change. The California Energy Commission PIER program has funded groundbreaking climate change research for about a decade.[10] In 2006, the California Department of Water Resources (CDWR) released a widely publicized report detailing implications of climate change for water supplies and flood control (California Department of Water Resources 2006), and a new report addresses adaptation strategies (California Department of Water Resources 2008). In 2007, at least four statewide conferences focused exclusively on water and climate change, as did sessions at virtually every major gathering of water managers.[11] In keeping with what we have described above, however, the institutional capacity to identify and implement adaptation strategies varies significantly across different parts of the water management system, as do the constraints to adaptation, with water supply management far ahead of flood or water quality management and regulation. Hydroelectric managers—particularly in the private sector—also seem well positioned to respond to a changing climate (Vine 2011).

[10] See http://www.energy.ca.gov/publications/searchReports.php?pier1=climate%20change

[11] Water Utility Climate Change Summit, San Francisco, Jan. 31–Feb. 1, 2007 (sponsored by the San Francisco Public Utilities Commission), Water Policy Through a Carbon Lens, Sacramento, Aug. 23, 2007 (sponsored by the State Water Resources Control Board and the Department of Water Resources), California Climate Change and Water Summit, Santa Monica, Oct. 3, 2007 (sponsored by the Dept. of Water Resources and the Water Education Foundation), and the California Water Policy Conference 17, Los Angeles, Nov 14–15, 2007.

5.1 Water supply management

Water supply managers are already relatively well poised to incorporate climate change impacts into their system plans, policies, and operations. In part, this advantage stems from the relative clarity of scientific predictions on how climate will affect supplies. Although there is still great uncertainty regarding changes in average annual runoff levels, there is already a broad scientific consensus on the predicted reduction in the snowpack, as well as the threats to Delta levees from sea level rise and changing runoff patterns. This body of knowledge, though imperfect, provides a concrete basis for developing response strategies.

Other advantages stem from several characteristics of the state's supply system: (a) an integrated plumbing network, which allows water to be moved across most parts of the state; (b) a decentralized management system, which fosters innovation; (c) operational and planning experience dealing with wet and drought periods and related uncertainties as part of normal system management, and (d) nearly two decades of experience in building portfolio-based strategies for water supply. In effect, many water management tools needed for adaptation to climate change—conjunctive use of groundwater and surface water, water transfers, increased water use efficiency, recycling, and desalination—are already important tools in planning for urban demand growth and coping with droughts.

Many of these management innovations were developed and funded at the local and regional level, rather than at the initiative of the state and federal agencies that built (and still own) large statewide facilities for water storage and conveyance (Lund 2006). However, several state actions have facilitated the transition to more flexible, portfolio-based water supply planning. Since the early 1980s, the state has fostered the development of water markets, first by introducing legislation to reduce the barriers to transfers, then by launching a water bank during the early 1990s drought, and later establishing the Environmental Water Account for some Delta operations (Hanak 2003).

The state also has combined regulations and financial incentives to encourage local agencies to strengthen planning systems and diversify water supply sources (Hanak 2005). Since the mid 1980s, urban water suppliers with at least 3,000 customers have been required by law to develop long-term (20 year) urban water management plans (UWMPs), updated every 5 years. A complete drought response plan has been a condition of eligibility for some forms of state financial assistance since the early 1990s. In the early 2000s, when billions of dollars of bond funds became available to support water resource development, a complete UWMP became a condition of eligibility for local grants. Bond funds also have been used to encourage local groundwater management programs and integrated regional approaches to water management—two areas where institutional strengthening is needed. Federal support to this process has been more limited, confined largely to improving the conditions for marketing water from federal projects, with some financial support for local infrastructure investments.

Progress notwithstanding, several institutional challenges must be tackled to facilitate effective adaptation: improved groundwater basin management, more flexible water transfer arrangements, changes in operating rules for surface reservoirs, and new policies for the Sacramento-San-Joaquin Delta. Questions also arise for new state-sponsored investments in surface storage, for example, a potential response to climate that is currently subject to considerable debate.

5.1.1 Strengthening groundwater basin management

In California, the state has exercised little legal authority over groundwater, and groundwater management in most areas remains in its infancy, with few rules to limit overdraft and use. Local users and governments often fear making their groundwater available for statewide supplies (Hanak and Dyckman 2003). The impressive expansion of conjunctive use projects since the mid-1990s occurred largely in areas that benefit from stronger basin management, with a system of checks and balances to protect both water bankers and other groundwater users (Thomas 2001; Hanak 2003). Improved management is a prerequisite for expanding underground storage in much of the Central Valley, an area with considerable untapped potential. Although incentives for groundwater banking are pushing local agencies to develop programs, additional technical support would be helpful to develop knowledge of basin characteristics and continued incentives tied to the use of bond funds.

5.1.2 Developing more sophisticated water transfer mechanisms

New types of water transfers, such as multi-year options, will be valuable for coping with greater uncertainties in water availability. Option trades allow buyers and sellers to agree to a transfer before they know how much water will be available for the coming year, and incremental payments are made to the seller until the buyer's decision deadline (Hollinshead and Lund 2006). The state ran a small options bank in 1995, and the Metropolitan Water District of Southern California successfully implemented single-year options with Northern Sacramento Valley rice farmers in 2003 (Howitt and Hanak 2005). Going forward, urban agencies and farmers are both likely to find multi-year options attractive for improving supply reliability. Here again, economic incentives and opportunities will push local agencies to develop such mechanisms. However, the state can facilitate this innovation by making it easier to pass regulatory hurdles involved in multi-year deals. More complex multi-party deals also may be desirable, where the water can be committed in advance to different sellers depending on the nature of the water year. Pre-approval of such arrangements is difficult under current water transfer law.

5.1.3 Changing reservoir operation policy

Surface reservoirs are a key element of California's water supply and flood management systems. The two systems operate distinct portions of the reservoir: "conservation space" for water supply and "flood space" for flood management. Even with historical patterns of runoff, the storage capacity of the state's water system could be increased significantly by operating the water held in conservation space to make greater use of underground storage potential (Jenkins et al. 2004; Pulido-Velasquez et al. 2004; Purkey et al. 1998; Connell 2009). The process involves drawing down reservoirs in the summer and fall to recharge groundwater basins, making more room available to store the next winter and spring rains. The value of such a strategy increases as warming shifts more precipitation from snow to rainfall. These shifts will also have significant consequences for the optimal use of reservoirs for flood protection, because it will probably be necessary to alter flood storage allocations as runoff patterns change (Fissekis 2008).

Greater overall gains can arise from reassessing water supply and flood operating rules in an integrated manner. Achieving such changes will require state and federal leadership and cooperation. The Army Corps of Engineers is responsible for managing the flood operations for most reservoirs in California, and state and federal water projects and various local agencies and power companies own the rights to the conservation space. Releasing water stored in conservation space to underground reservoirs will require amendments to current water rights agreements, to protect those with storage rights in case the following year's rains are less abundant than forecasted. Altering flood operating rules can require an Act of Congress, as some operating rules are established in federal law. In all cases, significant analysis will be needed to identify better alternatives for re-operation, including environmental impact reviews.

5.1.4 New policies for the Sacramento-San Joaquin Delta

Climate change simultaneously makes an already-fragile Sacramento-San Joaquin Delta more fragile and more important for adapting to the most likely forms of climate change. The scale of potential water supply losses from a catastrophic failure of Delta levees—on the order of 6 maf per year (roughly 7400 million m^3, or 15% of developed supplies)—makes finding new solutions to Delta management a top climate adaptation priority. Delta issues are complex, involving ecosystem, water supply, and flood threats and numerous stakeholders, including water agencies relying on Delta exports, local water rights holders and governments in the Delta, state and federal wildlife protection agencies and numerous environmental and landowner advocacy groups. As a result, state leadership, with strong federal participation, is needed urgently to craft new policies and coordinate new investments (Lund et al. 2007, 2010).

The beginnings of a process to seek solutions are now well underway, with significant administration and legislative attention to Delta problems since 2006. Several efforts, including the governor's "Delta Vision" effort (Isenberg et al. 2008) and the California Natural Resource Agency-led Bay Delta Conservation Plan process,[12] seek to develop new long-term strategies for the Delta. These efforts need to be followed by significant investments in scientific and technical work to flesh out the details of a new Delta strategy, which might involve conveying water around the Delta as well as major changes in the management of the Delta for ecosystem purposes. New governance and financing arrangements will also be essential. However, despite the best efforts of many parties, there is a significant likelihood that major land use, environmental, regulatory, and water export aspects of the Delta will collapse before an adaptation strategy can be agreed upon and implemented.

5.1.5 New surface storage investments

One of the most vocal debates about California water supply concerns the state's role in building new surface storage. Although some agricultural water interests have long promoted new state-sponsored storage as a response to population growth and increased environmental water use, the reduction in snowpack from climate change has provided an additional rationale for such investments. Yet, as noted above, modeling of the California water supply system demonstrates that new surface storage is unlikely to be broadly cost-effective for dealing with the water supply implications of climate change, with either wetter or drier climate changes. Technical analyses show reservoir re-operation to stretch the existing surface storage capacity is more promising and less costly.

Nevertheless, new surface storage investments might be employed to improve flood management and improve flexibility to environmental water managers. But, this too should be assessed in the context of a portfolio of management options to achieve these goals. Should surface storage expansion go forward, several institutional hurdles will need to be

[12] http://resources.ca.gov/bdcp/

overcome, most notably in the allocation of new water rights on river systems which already experience excess demands.

5.2 Flood management

In contrast to water supply management, the current institutional framework for flood management significantly hampers the ability to implement adaptation strategies. Although local governments are responsible for most levee maintenance, state and federal agencies play major roles in the management and finance of the overall system, and climate change was only recently recognized at the federal level. The Army Corps of Engineers has only recently begun to analyze the implications of changing runoff patterns for reservoir management, and revisions to current reservoir operation rules are likely to be cumbersome.

The other major federal player is the Federal Emergency Management Agency (FEMA), which manages the National Flood Insurance Program. FEMA issues flood insurance rate maps, the major regulatory tool for land use decisions. Even without climate change, these maps create incentives to locate in areas of high risk, because flood insurance is only required within areas with more than a 1% chance of serious flooding in any given year.[13] Everything outside this "100-year floodplain" is considered to be low risk from the regulatory perspective—no building restrictions are applied in these areas, and homeowners are not required to hold flood insurance. In the past, generous federal funding enabled many communities to take lands "out of the floodplain" by building levees and other flood protection infrastructure (for which the federal cost share has been up to 65%). In recent years, it has become apparent that many of these levees are in poor condition, and that many communities in the fast-growing Central Valley face considerable flood risk. Although major flood map improvements are underway, there are no plans to update the maps for the effects of several decades of new development or climate-induced changes in runoff.[14]

In contrast to the federal agencies, the state of California has been sounding the alarm about increased flood risks from climate change (California Department of Water Resources 2006). The state is particularly concerned about flood risk because of its legal liability for flood damages on any lands within the federal flood management system, including much of the Central Valley, following a 2003 California Supreme Court ruling (California Department of Water Resources 2005b).

The combination of lax federal insurance zone mapping rules and a state liability system that essentially absolves local governments of responsibility has meant that local cities and counties have had few incentives to avoid building in high risk areas. A recent legislative package on flood management reform, signed into law by the governor in October 2007, attempts to address some of these issues. The legislation aims to raise the standard for flood protection for new development to a higher level—banning new development in areas with more than a 1 in 200-year flood risk by 2014—once state officials develop a new flood protection plan for the Central Valley, due in 2012. Existing neighborhoods will have until 2025 to reach 200-year protection levels. Cities and counties also will be required to

[13] Technically, properties in this category are susceptible to being flooded by a flood event large enough that it is only likely to occur once in a century, often called a "100-year flood."

[14] The map updating exercise is focusing on digitizing existing flood insurance maps, many of which are twenty years old. In some targeted areas, FEMA is also working to develop more detailed flood hazard maps, but it does not have funds to do this on a broader scale.

incorporate flood protection in their general planning documents, and will become financially liable for developments they approve "unreasonably." The package also overhauls the state Reclamation Board (renamed the Central Valley Flood Protection Board), which has responsibilities for ensuring new development does not diminish the integrity of the region's flood protection system.

Although this package of reforms represents significant progress, important questions remain on the implementation of a more robust protection strategy against riverine flooding. The key reforms rely on completing a new flood protection plan by CDWR, which is already overwhelmed with catching up on years of deferred maintenance for the existing system. To be effective, this new plan should incorporate the implications of climate change, because the plan will influence building decisions for decades into the future. CDWR has limited capability to analyze these implications. Attempts to override the lower federal standard of 100-year protection may also pose technical difficulties, at least using current statistical methods for analysis of extreme events.[15] Cost is also an issue. Flood control infrastructure, such as dams, levees, and bypasses, is extraordinarily difficult and expensive to expand and relocate in a landscape already substantially developed. Finally, there are questions about how to increase use of flood insurance within floodplains, where there will always be a residual risk of flooding

If climate change leads to more extreme storms, even areas outside major riverine or coastal flood zones are likely to face greater periodic flood risks from local stormwater runoff. In addition to the traditional response of expanding storm drain system capacity, attention has turned to low impact development, which aims to combine on-site catchment and filtration to limit runoff from new construction.[16] Because this strategy may involve changes in building codes, implementation will require increased coordination between local flood managers and city and county planning departments, as well as outreach to the development community.

5.3 Water quality management

Changes in water quality as a direct result of temperature increases and salinity incursion, as well as chemical reactions resulting from these processes, are likely to have significant implications for regulatory programs under state and federal authority, including the Clean Water Act and Endangered Species Act. The effects will likely extend to classic water management (reservoir management and water diversions) in addition to the primary programs for managing water quality under the Clean Water Act, discharge permits for wastewater and urban runoff and total maximum daily loads (TMDLs).[17]

California's State Water Resources Control Board (SWRCB), which oversees implementation of the Clean Water Act (including aspects related to endangered species) within California, has identified climate change as a priority issue for its basin management plan updates, scheduled over the next 5 years. But the task is vast, and the process has potential for significant conflicts with stakeholders over changing norms and standards. These

[15] Current methods rely heavily on the historical record, which makes it difficult to assess the distribution of low probability of events, particularly if the patterns are changing over time. Alternative methods, incorporating synthetic measures of hydrologic distributions, may need to be developed to give a better sense of changing risk with a changing climate.

[16] See Debo and Reese (2003) for examples of best management practices.

[17] TMDLs are a mechanism for setting quantitative limits on pollutants including chemicals, temperature, trash, and sediment.

conflicts may become more difficult when they arise over species protection, given uncertainties regarding how species are likely to adjust to changing climate and habitat conditions (Barbour and Kueppers 2011).

5.4 Funding adaptation

It is perhaps no coincidence that the part of the water management system best poised to identify and implement adaptation strategies also faces the fewest financial constraints. Local agencies responsible for water supply generally have solid mechanisms for planning and finance. Most funds are from user fees, through monthly water bills and one-time fees on new development. Water rates are generally still quite low as a share of household income, and there is considerable scope for improving rate structures to increase incentives for water conservation (Hanak and Barbour 2005).

Financing flood management is more problematic. The Army Corps of Engineers has little funding for changes in reservoir operation rules, processes costing several million dollars each. Similarly, although FEMA has funding to update flood risk maps, it does not have the resources to update their accuracy (see footnote 13). The Army Corps is also limited in its financial capacity to invest in flood management in California, even though the federal government is nominally responsible for covering up to 65% of the costs of many projects. This federal funding deficit—with a serious investment backlog—was one of Governor Schwarzenegger's principal motivations for promoting a $5 billion dollar state flood bond package in November 2006. Although California now significantly outspends the federal government on flood works, the available resources fall far below the long-term need.

Meanwhile, local agencies are highly constrained on raising funds for flood works in following Proposition 218, a constitutional amendment passed by voters in November 1996. Since this reform, funds for flood management must meet high thresholds of voter approval—either two-thirds of all voters or half of all property owners. In contrast, water utilities generally can raise rates through actions of their elected or appointed boards. Recently, some communities in the Sacramento area (with leadership from the Sacramento Area Flood Control Agency (SAFCA)) were able to muster more than the two-thirds threshold for local flood assessments. However, on the November 2006 ballot, flood and stormwater control bonds in the San Francisco Bay Area Cities of Burlingame and Orinda were rejected despite over 60% voter support.

Water quality management faces a mixed bag of funding situations. As with water utilities, local wastewater systems have solid local funding mechanisms based on user fees, which can be raised as needed by utility boards (albeit subject to potential property owner protest). In contrast, managers of local runoff programs face the same constitutional constraints as local flood control agencies, with perhaps less public support, particularly when communities are responsible for controlling polluted runoff that protects water bodies at some geographic distance. (This has been a source of contention in Southern California, for instance, where coastal communities have generally supported runoff control programs, which directly affect local tourism and recreation, while inland communities have been more resistant).

6 Links between adaptation and mitigation actions

The water sector has been highlighted as a major source of the greenhouse gas emissions contributing to climate change. Water-related energy use consumes nearly one-fifth of California's electricity, 30% of its non-power plant natural gas, and large quantities of diesel fuel, mostly for residential and commercial water heating (California Energy Commission 2005). As a consequence, the water sector has come under pressure to find ways to reduce emissions. The potential leverage points include direct energy use for delivering and treating water, as well as far larger energy costs incurred by homes and businesses when they use water (e.g. water heaters and other appliances).

Although it is sometimes assumed that actions to reduce (or "mitigate") greenhouse gas emissions are compatible with measures to adapt to climate change, this question is actually more complex for water management. As Fig. 1 shows, some water management actions important for adaptation are compatible with mitigation, including water conservation (especially hot water conservation) and crop yield improvement. Some energy mitigation actions also would reduce water use, such as the development of solar power sites on land currently occupied by irrigated agriculture.

However, many water adaptation actions have decidedly less favorable energy implications. Wastewater reuse, conjunctive use of surface and ground waters, seawater desalination, and fish screens improve the adaptability of water management for climate change, but at a cost of increased energy use. Similarly, many actions that could reduce greenhouse gas emissions would increase water use, thereby reducing the adaptability of the water system to climate change. Examples include biofuels production, evaporative cooling (which lowers energy use for air conditioning), reforestation, and the planting of shade trees.

When developing mitigation policies, it will be important to consider these relationships, and maintain adaptation flexibility. For instance, cap and trade methods for controlling emissions would allow water utilities to purchase emissions credits to increase energy-intensive activities that relied on fossil fuels. Another flexible tool is a carbon tax, which sends a price signal about the full energy costs of different policy options (including their effects on the environment).

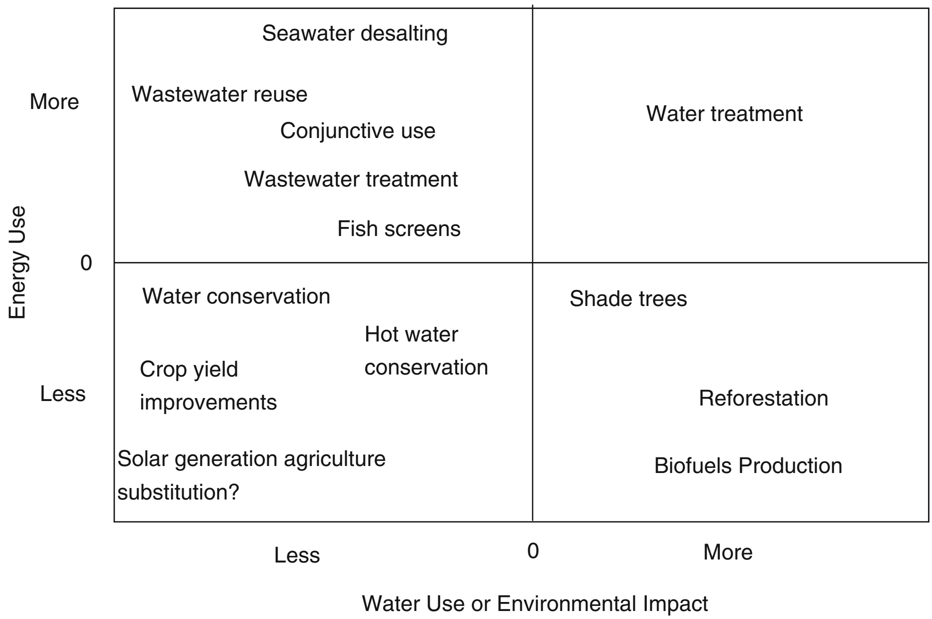

Fig. 1 Energy and water use changes for different water management actions

7 Improving adaptation capacity

What is the scope for improving climate change adaptation capacity in this sector, and where can policy responses facilitate this process? In addressing these questions, we focus on useful actions for the near term, to improve information on adaptation needs and options or to increase the system's flexibility to adapt in the future.

7.1 Improving scientific understanding

Better scientific knowledge should help in developing better management policies. Even without better knowledge of how average precipitation may change, it will be useful to explore the implications of changes that are more certain: shifts in the seasonal runoff patterns, higher stream temperatures, and increasing sea and salinity levels in the San Francisco Estuary. To make this problem manageable for water quality, it may make sense to focus initially on particularly important or representative ecosystems, such as the Klamath (where temperature has already become a central issue for salmon)[18] and the San Francisco Estuary (important for various endangered fishes affected by changes in temperature and salinity). For flood management, studies of the effects of higher temperatures and smaller snowpacks on flood flows is a high priority, as is updating flood risk analysis procedures to incorporate future climate and land use conditions. An early step in this direction has been taken by the Sacramento District of the Corps of Engineers, which has begun studying how climate warming would affect flood hydrology and reservoir operations (Fissekis 2008).

7.2 Regulatory implications

Some water management adaptations will require alterations in regulatory practice. For water supply, many legal changes already have occurred to accommodate modern portfolio approaches to water management—such as reforms of water marketing law. In other areas, a better understanding of the regulatory implications of the new management strategies is required to explore policy changes. Current water quality regulations for the Delta would prohibit many changes in Delta operations that could make the system more resilient to sea level rise and increased flooding (Lund et al. 2010). Modifying reservoir operations to improve flood management will require new, reservoir-specific operation plans approved by Congress or the Corps. Helping aquatic species maintain viable habitat conditions with temperature increases, sea level rise, and salinity incursions will likely require changes to reservoir operations, water diversions, water right permits, and discharge permits—as well as land acquisitions to expand or maintain wetland habitat. Given the lead times to implement such regulatory changes, developing a clearer picture of likely regulatory needs should be a priority.

7.3 Integrating local and state efforts

Most water management and infrastructure decisions are local, and for quite some time, state and federal governments are likely to have less funding for climate adaptation than local governments and water users. Although some local and regional agencies have considerable analytical capabilities, state leadership will be essential to develop information

[18] See National Research Council (2007).

on sector-specific climate impacts and the regulatory implications of adaptation strategies. Some such efforts are already underway. However, there remains little state or federal guidance for local planning or regional coordination efforts. Additional state guidance will be useful for such local and regional activities.

7.4 Implementing "No regrets" policies for new investments

Despite unavoidable uncertainty about climate impacts, it will often make sense to change water management or build new infrastructure—with a lifespan of many decades—in ways that increase the resiliency of the system to changes in climate and other conditions. Many changes in management that are useful adaptations for changes in climate also can be justified without climate change, for adaptation to other conditions, such as increasing water quality concerns. These are called "no regrets" actions. Increased use of water markets, conjunctive use of ground and surface waters, urban water conservation, and major improvements in habitats for native species are likely examples of "no regrets" actions.

Given scale economies, immense costs for retrofitting, and the likelihood of higher regulatory standards for discharges, oversizing new stormwater and wastewater systems to account for potential future problems of peak runoff could be a good insurance policy. The prospect of increased flood risk also raises the benefits of making private investments more resilient. Low impact development is already beginning to improve management of today's stormwater problems, and becomes more valuable if added protection against more intense storm events is included. By the same logic, discouraging new construction in flood-prone areas—already important with today's hydrology—becomes more valuable to reduce risk from larger runoff events with climate changes.

7.5 Improving information on flood risk

Stricter laws on new developments in floodplains—such as those recently passed in California—are one way to reduce future flood risk despite more lenient federal policies. Given that many people already live and work in high-risk areas, other approaches may build in resiliency, by improving risk information. Under the current system, property owners outside of the regulatory 100-year floodplain are generally not given information about their flood risk, even though inundation depths might be quite high (for those living behind a levee). In the Sacramento area, flood management officials have developed more differentiated risk information, indicating the depth of flooding with a levee failure. This information was used to develop risk-adjusted property assessments for local flood works, and has also been valuable in a public information campaign to encourage flood insurance in areas where it is not legally required. Such an approach may complement building restrictions in flood management portfolios. An independent review on Central Valley flood risk recently recommended broadening such information campaigns and extending zones where flood insurance is required (Galloway et al. 2007). Although such measures do not diminish the prospect of worsening floods from climate change, they can reduce vulnerability by improving insurance coverage for those living in at-risk areas and limiting the expansion of population and assets exposed to risk.

7.6 Improving funding mechanisms

Local and water user funding will be the mainstay of climate change adaptation. A constitutional reform to restore the rights of local agency boards to raise fees for flood and stormwater management would go a long way towards increasing the capacity of local agencies to respond to flood and water quality threats, including local support for funding Army Corps of Engineers reservoir re-operation plans. Such a reform may also be needed to solidify the ability of water and wastewater utilities to raise rates to meet increasing water quality costs and water quality standards.

7.7 Fostering coordination

Although decentralization creates opportunities for innovation, it also runs the risk of missed opportunities when a larger regional scale is more appropriate. Examples abound of opportunity and necessity spurring regional cooperation and coordination—in groundwater basin management, water supply, flood management, and most recently regional approaches to integrated water management. Because of start-up costs to coordination, state and federal financial and regulatory incentives are often useful. Much recent progress in regional collaboration has been supported by state bonds.

8 Conclusions

On balance, water management in California gets mixed reviews on its capacity to develop and implement strategies to adapt to the effects of climate change. Awareness of potential impacts to water supply from shifts in precipitation and reduced snowpack is high, and many tools needed by agencies are already being developed as part of local and regional strategies to meet future water needs and cope with variable rainfall. Although the same scientific information has implications for flood risk, little analysis exists of how flood management should respond to changing winter and spring runoff. In addition, the institutional rigidities of the flood management system, where federal agencies play a central role, hinder adaptation. Regarding water quality, a better understanding of the likely effects of temperature increases and sea level rise is a precondition for developing effective responses, which could impose new constraints and costs on many water and land use agencies.

Several actions would be useful now and/or provide information to improve future capability to adapt to climate warming and other changes:

- Implement a long-term strategy that makes the Delta ecosystem and water supplies less vulnerable to a changing climate.
- Discourage development in flood-prone areas. Assess how to go beyond the package of new state laws—for instance by developing better information on risk, as recently done in the Sacramento area.
- Commission studies to understand the implications of climate change for flood management and water quality management.
- Commission a broad examination of how environmental regulations and laws will be affected by climate change, particularly sea level rise and temperature increases.
- Encourage “no regrets” decisions on current infrastructure investments for stormwater and wastewater to account for potential future problems of peak runoff.
- Encourage low impact development (also useful for existing stormwater permits).
- Expand use of state incentives and requirements for state and local agencies to consider climate in water planning and integrate local and state assessments of climate change.
- Implement constitutional reform to improve local agency capabilities to raise funds to meet their regulatory responsibilities.

Floods, the Delta, and maintaining native species are the greatest water-related climate change challenges for California, compounding ongoing challenges in these areas. In all cases, adaptation will require strong-willed state leadership to shape institutions, incentives, and regulations capable of responding to change. Federal participation will be helpful in all cases, and altogether necessary in the areas of flood control and endangered species management, where federal agencies and regulations dominate the policy environment.

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