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Adapting California's Water Management to Climate Change

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Summary

California faces the prospect of significant water management challenges from climate change. The most certain changes are accelerated sea level rise and increased temperatures, which will reduce the Sierra Nevada snowpack and shift more runoff to winter months. These changes will likely cause major problems for flood control, for water supply reservoir operations, and for the maintenance of the present system of water exports through the fragile levee system of the Sacramento-San Joaquin Delta. Rising water temperatures also are likely to compromise habitat for some native aquatic species and pose challenges for reservoir operations, which must release cool water to support fish downstream. Although there is as yet little scientific consensus on the effects of climate change on overall precipitation levels, many expect precipitation variability to increase, with more extreme drought and flood events posing additional challenges to water managers.

Fortunately, California also possesses numerous assets – including adaptation tools and institutional capabilities – which can limit vulnerability of the state's residents to changing conditions. Water supply managers have already begun using underground storage, water transfers, conservation, recycling, and desalination to expand their capacity to meet changing demands, and these same tools present cost-effective options for responding to a wide range of climate change scenarios. Many staples of flood management – including reservoir operations, levees, bypasses, insurance, and land-use regulation – are appropriate for the challenges posed by increasing flood flows.

Yet actions are also needed to improve response capacity in some areas. For water supply, a central issue is the management of the Delta, where new conveyance and habitat investments and new regulations are needed to sustain water supply reliability and ecosystem conditions. For flood management, studies to anticipate required changes have only begun, and institutional constraints limit the ability to change reservoir operations, raise funds for flood works, prevent development in flood-prone areas, and encourage use of flood insurance. Needed reforms include forward-looking reservoir operation planning and floodplain mapping, less restrictive rules for raising local flood assessments, and improved public information on flood risks. For water quality, an urgent priority is better science. Climate change is likely to have far-reaching implications for water regulations and management, but we remain at an embryonic state of knowledge about these future changes. We will have to make policy, planning, and operational decisions without perfect knowledge of how much the climate is changing.

Although local agencies are central players in all aspects of water management, adaptation will require strong-willed state leadership to shape institutions, incentives, and regulations capable of responding to change. Cooperation of federal agencies will be essential, given the important roles they play in flood management, environmental regulation, and water supply, particularly in the Delta.

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Introduction

Californians have a history of adapting to different climates in the context of dynamic economic and population changes. The first settlers from the eastern United States arrived 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 experience 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 to 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 agencies and 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 programs. Over the past decade, city and county governments have become responsible for managing the quality of stormwater runoff. These local governments also oversee land development, which has 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 poses challenges to effective coordination (Bish 1982). California's water system often suffers from governmental fragmentation and an absence 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 shape the potential for adaptation to climate change over the decades to come.

Rising temperatures, sea level rise, and the anticipated increase in extreme drought and storm events associated with climate change are likely to have profound effects on the full range of water management activities, requiring adaptive responses. As described below, there is considerable variation in our current knowledge about climate impacts on water and water use, and different stages of thinking about adaptation strategies. Water supply planners already have begun discussions about how best to adapt to changing supply conditions, as evidence mounts for a diminishing role of the Sierra snowpack for water storage. In other areas, such as flood control and water quality, managers have been slower to react, either because information on climate impacts remains too speculative (the case with water quality), or because institutional obstacles have hindered the development of effective responses (the case with flood management). Effective response to climate change will require an integrated response, since 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 will require state leadership to re-align local, regional, and (where possible) federal interests, finance, and expertise to better address problems in a changed environment1. Climate change will add further uncertainty to water policy, planning, and management, on top of already formidable uncertainty in California's hydrology, institutions, and water demands.

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

1. **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, arising from observations of the distant past, recent observations, and climate model projections for the future. These concerns include:

- 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 temperatures and CO_2 concentrations
- Increased flood flows and flood frequencies

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, 2008). Many of California's water managers are now working with projections of a one foot rise by mid-century and a three to four foot rise by 2100, slightly above the levels projected in the higher emissions scenarios of the Intergovernmental Panel on Climate Change (IPCC).[2]

Rising sea level has implications not only for coastal areas (Hanak and Moreno, 2008) but also for the management of the Sacramento-San Joaquin Delta. The Delta region, at the eastern edge of the San Francisco Estuary, is a critical component of California's current water supply system, enabling passage of northern California water to the Bay Area and the southern half of the state (Lund, et al. 2007, 2008). Sea level rise will raise the elevation of salt water at the Delta's western end and initially increase water depths throughout the Delta, potentially changing the amplitude of tides and storm surges in this region. The consequences are increasing risk of levee failures and seawater intrusion into the Delta, which would disrupt the water supply system for several months to several years. Water supply effects of sea level rise also are likely in some coastal aquifers. In particular, additional sea water intrusion will affect agricultural production in the Salinas Valley and urban water supplies in Southern California. Rising sea level also will increase costs and difficulties for coastal drainage and wastewater systems.

[2] This range was recently recommended for use for planning purposes by the Independent Science Board for the CALFED Bay-Delta program(Mount 2007).

Additional environmental effects from sea level rise could be a further reduction in salt and brackish wetlands in California, particularly if marsh sedimentation cannot keep up with the rise in sea level and if currently upland urban or agricultural land uses are prevented from converting to wetlands (Caldwell and Segal, 2007).

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, Dettinger, and Cayan 2006). 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 has already been occurring earlier in the water year (Aguado et al. 1992; Dettinger and Cayan 1995). For reservoirs that lie downstream of significant mountain snowpacks, the resulting shift in reservoir inflows could pose major risks for flood control and water supply, particularly if reservoir operations are not modified to accommodate the new conditions (Department of Water Resources 2006; Medellin et al., 2008; Fissekis 2008).

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 shifts in inflows for most years. However, any reduction of annual runoff volumes due to declines in precipitation or increases in evapotranspiration in reservoirs or the broader watersheds would directly reduce water supplies.[3] In modeling studies, the effects of reduced runoff due to decreased precipitation levels appear to be much more important than the seasonal shifts, particularly for water supply purposes (Tanaka et al. 2006; Medellin et al. 2008). However, the net effects of climate warming on total runoff volumes are still unclear and highly uncertain (Dettinger 2005). It is likely to be decades before we know if and by how much precipitation and runoff volumes are changing (Klemes 2000a, b).

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 percent 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.

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[3] Evapotranspiration is the rate at which plants lose water through evaporation from soil and plant surfaces and transpiration through plant canopies. In surface reservoirs, it is the rate of evaporation.

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 significantly 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, one would expect salmon spawning and rearing to be restricted to higher elevations as water warms at lower elevations. On many streams we now provide cold water habitat at unnaturally low elevations for some salmon runs by releasing cold water stored in reservoirs from winter and early spring flows. 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 in the future. The smelt are thought to require temperatures below 20 °C to spawn (Bennett, 2005). Rising temperatures are likely to reduce the spawning season for this fish, and perhaps eliminate spawning entirely.

To date, there has been little research on other impacts of water temperature increases, although such changes are likely to significantly affect drinking water quality and habitats for native species. Higher temperatures are likely to increase the rates of chemical reactions in water generally, increasing rates of algal growth and decay, perhaps adding problems and instability to the water quality throughout the state. For human uses, several water treatment processes are affected by water temperature.

Increased Water Demands

Higher temperatures and increases in CO_2 are likely to also change water demands. These effects will vary considerably depending on other changes in the regional and global economy, population, and land use. However, several general tendencies and water demand effects can be noted. 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 (currently about 80 percent 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.

Urban water demands may also be affected by climate warming. Indoor water demand could rise if greater use is made of evaporative cooling of buildings and residences, as is common in some hot, dry areas in the southwestern United States. Increases in evapotranspiration and growing season are likely to increase outdoor consumptive water use for landscaping, which accounts for half or more of residential water use in the hot, inland areas (Hanak and Davis, 2006).[4] However, as discussed below, population growth and land use patterns are likely to be more significant drivers of outdoor water use than climate warming.

Hydropower demands are economic in nature, reflected in the price of power at different times of day and seasons of the year. 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. Energy demands are likely to increase from higher temperatures, since much power demand, particularly for peaking power, is for air conditioning (Vine, 2008). If the daily peak demand for power increases and broadens from additional air conditioning, this will raise the value of hydropower. Higher temperatures are also likely to lengthen the air conditioning season, increasing hydropower demands earlier in the spring and later in the fall. Warming would also reduce energy and hydropower demands for heating during winter.

Increased Flood Flows and Flood Frequencies

Most major floods in the last century have 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 for floods are not modified to accommodate the new conditions (Fissekis 2008).

Increased intensity and frequency of major storms, another anticipated effect of climate change, would further augment 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 stresses.

The Difficulty of Predicting Impacts

Overall, 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, and persistence of droughts. Most of these changes (including sea level rise) will occur against a noisy backdrop of natural variability. Although rising temperatures and sea level rise are relatively well identified, accurately characterizing the magnitude and variety of climate change is likely to take many decades. Most large climate models predict

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[4] In Phoenix, almost half of homes use evaporative cooling, which accounts for almost 15 percent of summer water use (Phoenix 2007).
[5] See also www.safca.org/floodRisk/index.html, for a discussion of this issue in the Sacramento area.

major changes in 50 to100 years. Probably, we will be able to detect and quantify most climate changes only long after these changes have occurred (Klemes 2000a, b). Moreover, these changes will not occur in isolation. California will have to adapt to a changing climate in concert with a host of other major changes and challenges.

2. Coincident Changes in California

Other changes in California over the coming decades will include population growth, changes in the structure of the economy, technological advances, and evolving societal goals. Many of these factors will affect not only the extent of climate impacts but also the ability to implement effective adaptation strategies.

California's need to compensate for climate-induced changes in water supply will depend largely on the evolution of water demands, a key driver of which is population growth (Dept. of Water Resources 2005). 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) (Dept of Finance 2007). At today's average per capita water use levels, this translates to an additional 5.5 million acre-feet in annual urban water demand (compared with recent levels of total human uses of around 40 million acre-feet per year).[6] At least half of the new residents are expected to locate in the hotter inland regions of the state, where per capita water demands are considerably higher than along the coast, largely because of larger lot sizes and higher outdoor water use (Hanak and Davis 2006). Recent trends do suggest a decline in lot sizes in the inland areas, which could reduce the growth in outdoor water demand (*Ibid*.).

These demand pressures also can be reduced significantly through urban conservation and the reallocation of some water from agriculture, two important adaptation tools. Even though, as noted above, climate change may increase agricultural productivity in California, the agricultural sector of the future will likely be somewhat smaller than today (Dept. of Water Resources 2005). 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 pressures also are likely to increase flood risk exposure. At present, one of the state's fastest growing areas is the Central Valley, much of which lies in a floodplain. As we will see, a range of strategies exist 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 followed over the coming years create long-lasting flood vulnerabilities and costs of adaptation.

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[6] In 2000, a "normal" rainfall year, total agricultural and urban uses were estimated at 43.1 million acre-feet (maf). The amount was slightly lower (42.3 maf) in 2001, a dry year, and somewhat lower (35.1 maf) in 1998, a very wet year, when irrigation and landscaping demands were considerably reduced (Department of Water Resources, 2005).

Finally, both technological advances and societal objectives may alter environmental water quality goals. In recent years, the trend has been toward more stringent standards for water quality, 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.

3. Adaptations to Climate Change: Options and Costs

In contrast with the climate change experienced by California's early settlers, Californians today have many options for adapting to a changing climate. In addition, today's predominantly urban economy is less sensitive to climate-related shifts in water conditions than the agricultural economy of the settler era. Some studies have estimated what promising adaptations might look like and how much they would cost.

Available Adaptation Options

California's water management systems are unusually complex, extensive, and inter-connected. 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. Such adaptations are likely to be more timely and effective if local and regional water managers (who govern most water management decisions) have incentives to develop and implement integrated portfolios of adaptations.

Relative to water management systems in many parts of the world, California's water supply system 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 changes in water management, with greater emphasis on water conservation, environmental restoration, water markets, and other non-traditional water management techniques. While change is never as smooth, rapid, and efficient as would be ideal, water management in California has demonstrated capacity for widespread innovation. 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 the linkages between them.

Water Supply

In recent decades, water managers have developed a rich menu of options for improving water supply service at local and regional scales. These options are summarized in Table 1, and all have been used in California. Contemporary managers of major water utilities and supply systems in California employ a portfolio approach which includes a coordinated range of these options, varying with local cost, demand, water rights, and other circumstances as well as current and expected water availability conditions. Such portfolios can be explored and evaluated using integrated system models, such as CALVIN (Tanaka et al 2006; Medellin et al 2008), CALSIM (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 allocate scarce water better from the perspective of overall economic and other 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 where 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 some industries and agriculture.

Water supply options include a variety of operational and expansion activities. These must typically be closely coordinated to ensure the water delivery system functions properly to serve water demands. The delivery capability of many water systems can be improved through changes in system operating policies. 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 water, including 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 users, local and regional water utilities, or state agencies or taxpayers is a major opportunity for establishing incentives for more effective and efficient system management. Because this process often requires considerable negotiation, implementation of these options usually requires more institutional time than construction time.

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)

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

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 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, "floodproofing" 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.

In some ways, implementing adaptations for flood management is more problematic than for water supply. Water supply problems usually arise over a period of years from drought or growth in water demands, affording time for institutional response and implementation. By contrast, large floods are relatively rare, swift, and devastating if preparations are insufficient (as with Hurricane Katrina in New Orleans). 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.

Adaptation to flooding becomes very 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.

Table 2. Flood Management Tool-Box

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

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.

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; 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

[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 et al 2008).

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; they generally treat water supply, hydropower, and flood management separately.

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 (Lund et al 2003; Tanaka et al 2006; Medellin et al 2008; Harou et al, in preparation). 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. 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 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 have explored a variety of wet and dry climate warming scenarios and the return of a severe sustained drought, such as those occurring about a thousand years ago. These studies 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 et al 2008). Even with significant population growth and urbanization, it appears to be physically possible to accommodate major seasonal shifts in inflows to the winter months, albeit at some cost. 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, 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 (whose water levels would often be lower) 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 percent reduction in average streamflows would increase water supply costs by about $3 billion per year (2008 dollars) relative to a baseline scenario with no climate change[8]. 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.

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

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., in preparation). The geologic record shows several severe sustained droughts during the medieval period, lasting for more than a century, with streamflows as low as 40 percent of the historical average and without intermittent wet periods (Stine 1990). An examination of such a drought using the CALVIN model found that adaptations could include major market-based reallocations of water from agriculture to urban users (with 30 to 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 this severe sustained drought, conjunctive use of ground and surface waters and the transfer of drought storage from surface reservoirs to aquifers are ineffective; most reservoirs never fill for this form of climate change. This type of climate change is more costly than the scenarios examined above. For 2020 population and land use patterns, optimal water supply adaptation results in economic costs (relative to a baseline with no climate change) on the order of $3 billion per year. These costs would 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.

In sum, the economic costs to water users of climate change are likely to be as much as several billion dollars per year. Although this cost may seem high, it is a manageable number when seen in the context of a growing statewide economy, now worth over $1.5 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 prosperity or 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 water temperatures as they 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 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 (Lund et al. 2008).

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. Because these large reservoirs can often store a large proportion of the average annual streamflow, they also have the capacity to accommodate some seasonal shifts in inflows when drought storage is moved elsewhere. 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 (2007) 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 are unable to make use of all streamflow for hydropower production. For wetter years, the shift of runoff to winter increases the "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, results in commensurate reductions in 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 as a result of warming (See also Vine, 2008).

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 involves 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), 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 (Tanaka et al. 2006; Lund et al., 2003). To date, few studies have been done to examine the implications of such changes for flood management operations and investments. Yao and Georgakakos (2001) examined the potential of changes in Folsom Dam's operating rules to adapt to changes in flood forecasts. They found that incorporating improved flood forecasting into reservoir operation has good potential to improve flood and water supply operations. Fissekis (2008) found that even modest warming and increases in precipitation could create dangerous flood conditions at some Sacramento Valley reservoirs.

Zhu et al. (2007) conducted a preliminary examination of how the levee system on the Lower American River, protecting the Natomas area of the Sacramento metropolitan area, should optimally adapt to a combination of several climate change and urbanization scenarios over the next 150 years. With urbanization alone (without climate change), it appears economically desirable to steadily increase levee heights along the river 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 increase optimal levee heights over the planning horizon. And with combined urbanization and wet climate warming, it appears optimal to not only increase levee heights, but also to increase levee setbacks in the future, despite immense costs. This example illustrates that climate warming 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. At present, major policies and investments are being made related to flood management and land use in California's floodplains. These land use and investment decisions are largely irreversible and set long-term precedence. 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.

Water Quality

Last, but not least, adaptations will be needed in the area of water quality management. Although the effects of climate change on water quality management are potentially vast, we are at an embryonic stage of knowledge about these processes. 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. Salinity incursions further into the San Francisco Estuary from sea level rise will profoundly alter conditions in this unique and threatened ecosystem, permanently returning some land to open water habitat and reducing or eliminating the suitability of the Delta for major water exports (Lund et al 2008; Fleenor et al 2008). As discussed below, all of these changes have implications for regulatory policy regarding public health and species protection.

4. Institutional Capacities and Constraints to Adaptation

On the face of it, 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.[9] In 2006, the Department of Water Resources (DWR) released a widely publicized report detailing implications of climate change for water supplies and flood control (Department of Water Resources 2006), and a new report addresses adaptation strategies (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.[10] 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, 2008).

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 precipitation 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: (i) a highly integrated plumbing network, which allows water to be moved across most parts of the state; (ii) a decentralized management system, which fosters innovation; (iii) operational and planning experience dealing with wet and drought periods and related uncertainties as part of normal system management, and (iv) nearly two decades of experience in building portfolio-based strategies for water supply. In effect, many of the water management tools that will be needed for adaptation to climate change – conjunctive use of groundwater and surface water, water transfers, increased water use efficiency, recycling, and desalination – have already become important tools in planning for urban demand growth and coping with periodic droughts. The importance of these management tools increases with climate change.

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. However, several state actions

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[9] See http://www.energy.ca.gov/publications/searchReports.php?pier1=climate%20change
[10] 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), California Climate Change and Water Summit, Santa Barbara, 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.

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 five 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 to take better advantage of more flexible water management tools. 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 in water supply management: 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, a potential response to climate that is currently subject to considerable debate.

Strengthening Groundwater Basin Management

In California, the state has very little legal authority over groundwater, and groundwater management in many areas is still in its infancy, with few rules to limit overdraft and use. The impressive expansion of conjunctive use projects since the mid-1990s occurred largely in areas that already benefit from strong basin management, with a system of checks and balances to protect both water bankers and other users of the basin (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 the incentives for groundwater banking are pushing local agencies to develop programs, the state may want to consider targeting more support to this process, with additional technical support to develop knowledge about basin characteristics and continued incentives tied to the use of bond funds.

Developing More Sophisticated Water Transfer Mechanisms

It is likely that new types of transfers, such as multi-year options, will be valuable for coping with greater uncertainties in future water availability. With option trades, buyers and sellers 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 final decision deadline (Hollinshead and Lund 2007). 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 these mechanisms. However, the state (particularly the State Water Resources Control Board (SWRCB)) 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 would be difficult under current water transfer law.

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 et al 2004; Purkey et al 1998). 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. As noted above, the value of such a strategy will increase 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 space requirements as the pattern of runoff changes (Fissekis 2008).

Although it is possible to improve the water supply system by changing the operating rules for water supply storage alone, greater overall gains can arise from reassessing operating rules in an integrated manner. Achieving these changes will require state and federal leadership and cooperation, because state and federal agencies own, operate, or regulate various reservoirs. 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 water supply storage ("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 the operating rules for flood space can require an Act of Congress, because some operating rules are established in federal law. In all cases, significant analysis will be needed to identify better alternatives for re-operation, followed by environmental impact reviews.

New Policies for the Sacramento-San Joaquin Delta

The scale of potential water supply losses from a catastrophic failure of Delta levees – on the order of 6 million acre-feet per year – makes finding new solutions to Delta management a top climate-change related priority. The issues are complex - involving ecosystem, water supply, and flood threats – and numerous players are involved: water exporting agencies, water rights holders and local governments within the Delta itself, 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, 2008).

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 and the Resource Agency-led Bay Delta Conservation Plan process, seek to develop new long-term visions for the Delta by the end of 2008. To be successful, these efforts will need to be followed by a significant investment in scientific and technical work to flesh out the details of a new Delta strategy, which might involve new investments to convey water around the Delta as well as important 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.

New Surface Storage Investments

Presently, 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 needs, the reduction in snowpack associated with climate change has provided an additional rationale for such investments. However, 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, under either wet or dry precipitation scenarios. Technical analyses show reservoir re-operation to stretch the existing surface storage capacity is more promising and less costly.

Nevertheless, new surface storage investments could be employed to improve flood management and improve flexibility to environmental water managers. But, this too should be assessed in the context of the portfolio of management options available to achieve these goals. Should surface storage expansion investments go forward, several institutional hurdles will need to be overcome, most notably in the allocation of new water rights on river systems which are already experiencing excess demands.

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 is barely 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 at least a 1 percent chance of serious flooding in any given year.[11] 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

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[11] 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."

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 percent). In recent years, it has become apparent that many of these levees are in poor repair, and that many communities in the fast-growing Central Valley face considerable flood risk. Although major map improvements are underway, there are no plans to update the data to account for the effects of several decades of new development, nor to incorporate climate-induced changes in patterns of runoff in floodplains.[12]

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

The combination of lax federal insurance zone mapping rules and a 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 than currently required by the federal system – 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 incorporate flood protection into 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 that new development does not diminish the integrity of the region's flood protection system.

Although this package of reforms represents significant progress (somewhat stricter bills failed to pass in 2006, due to opposition from the building industry and local governments), important questions remain on the implementation of a more robust protection strategy against riverine flooding. The key reforms rely on the completion of a new flood protection plan by DWR, 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 many years into the future. Although DWR has widely acknowledged the changing nature of flood risks, it has limited capability to analyze the implications for the flood management system, including reservoir re-operation and other improvements such as flood bypasses. 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.[13] There is also an issue of cost.

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[12] 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.

[13] 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,

Structural flood control infrastructure, such as dams, levees, and bypasses, is extraordinarily difficult and expensive to expand and relocate in a landscape which is 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 precipitation events, even areas outside major riverine or coastal flood zones are likely to face greater periodic flood risks from stormwater runoff. In addition to the traditional response of expanding storm drain system capacity, attention has increasingly turned to low impact development, which aims to combine on-site catchment and filtration technologies to limit runoff from new construction.[14] 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.

Water Quality Management

Changes in water quality as a direct result of temperature increases and salinity incursion, as well as chemical interactions 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 supply management tools (reservoir management and water diversions) in addition to the two primary programs for managing water quality under the Clean Water Act: discharge permits for wastewater and urban runoff and total maximum daily loads (TMDLs).[15]

The SWRCB, which oversees the implementation of the Clean Water Act as well as aspects of the Endangered Species Acts within California, has identified climate change as a priority issue for its basin management plan updates, scheduled to take place over the next five years. But the task is vast, and the process raises the potential for significant conflicts with stakeholders over changing norms and standards. These conflicts may become all the more difficult when they arise over species protection, given the great uncertainties regarding how species are likely to adjust to changing climate and habitat conditions (see Barbour and Kueppers, 2008).

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. The primary source of funds is 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 – a key adaptation tool (Hanak and Barbour 2005).

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incorporating synthetic measures of hydrologic distributions, may need to be developed to give a better sense of changing risk under a changing climate.

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

[15] TMDLs are a mechanism for setting quantitative limits on pollutants ranging from chemicals, to temperature, to trash, to sediment.

For flood management, the situation is more problematic. The Army Corps of Engineers does not have a budget to fund changes in reservoir operation rules, which can cost several million dollars each. As a result, beneficiaries need mechanisms to raise these funds on their own. Similarly, although FEMA has funding to update flood risk maps, it does not have the resources to update their accuracy (see footnote 12). The Army Corps is also limited in its financial capacity to invest in flood management activities in California, even though the federal government is nominally responsible for covering up to 65 percent of the costs of many projects. This federal funding deficit – in the face of a serious investment backlog – was one of Governor Schwarzenegger's principal motivations for promoting a multi-billion dollar state flood bond package in November 2006. Although the state is currently awash in bond funds for flood control investments (with nearly $5 billion passed by voters), these funds fall far below the long-term need.

Meanwhile, local agencies are highly constrained on raising funds for flood works in the wake of 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.[16] Although recent court rulings have tightened conditions for water utilities, their constraints are less limiting. Recently, some communities in the Sacramento area (under the leadership of the Sacramento Area Flood Control Agency (SAFCA)) managed to pass the two-thirds threshold for local flood assessments. But these successes do not diminish the fundamental flaws of this system for financing flood management.

Water quality management has a mixed bag of funding situations. As in the case of water utilities, local wastewater systems have solid local funding mechanisms based on user fees, which can be raised when 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 been highly supportive of runoff control programs, which directly affect local tourism and recreational opportunities, while inland communities have been more resistant).

[16] Agencies generally can raise rates when necessary through actions of their elected or appointed boards. Since the *Bighorn-Desert View Water Agency v. Verjil* ruling in 2006, however, rate increases cannot take effect if a majority of property owners protests in writing.

5. Links between Adaptation and Mitigation Actions

Not only does the water sector face important consequences of climate change; it has also been highlighted as a major source of the greenhouse gas emissions which contribute to the problem. Water-related energy use consumes nearly one-fifth of California's electricity, 30 percent of its natural gas, and large quantities of diesel fuel, mostly for end uses of water such as 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 a complex one for water management. As Figure 1 shows, some water management actions that will be important for adaptation are compatible with mitigation. Examples of measures that reduce both water and energy use include 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 actions that could become more important as part of a portfolio of water adaptation tools 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 do so at a cost of increasing energy use. Similarly, many actions which could reduce greenhouse gas emissions would simultaneously increase water use, thereby reducing the adaptability of the water system to climate change. Examples include biofuels production, evaporative cooling (which lowers the energy costs of air conditioning), reforestation, and the planting of shade trees. The interaction of climate change adaptation and mitigation will also change over time with regulations and technology. For example, increasing wastewater treatment and disposal standards might lower the additional costs for wastewater reuse.

As policies develop in the area of mitigation, it will be important to consider these relationships, and to maintain as much flexibility as possible on the adaptation side of the equation. Policies which allow flexibility include cap and trade methods for controlling emissions (which would allow water utilities to purchase emissions credits if they needed 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).

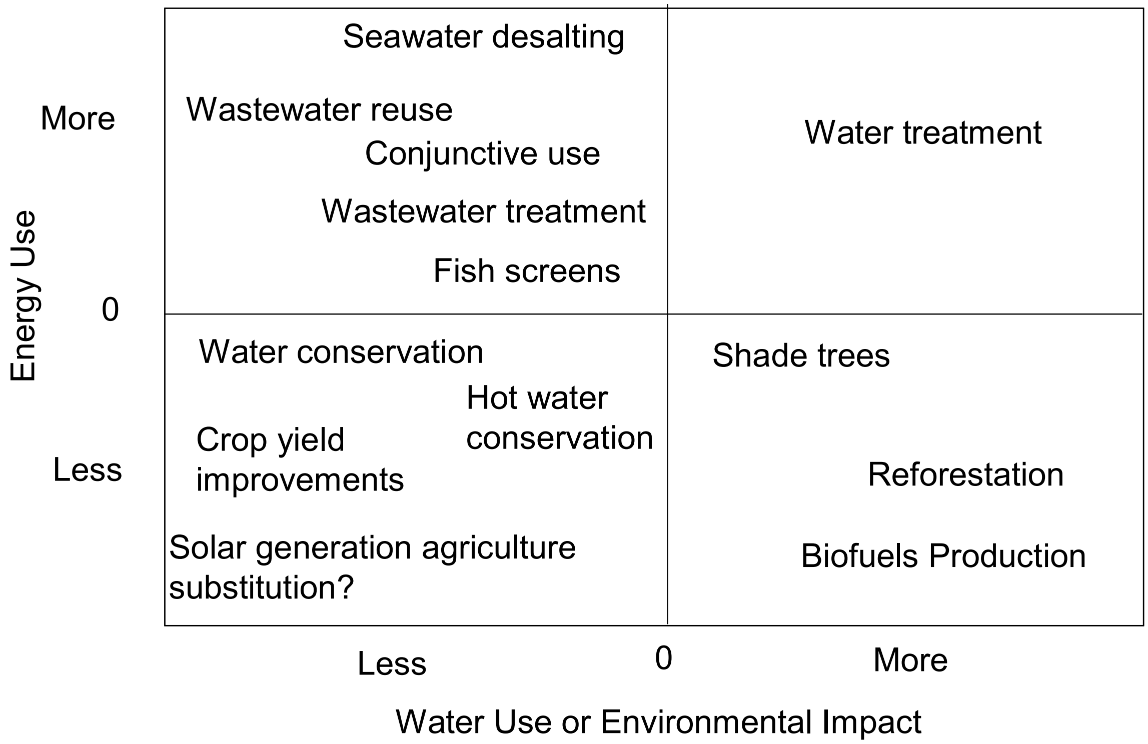

Figure 1. Energy and water use changes for different water management actions

6. Improving Adaptation Capacity

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 the water supply from shifts in precipitation and reduced snowpack is high, and many of the tools agencies will need to compensate for these effects are already being developed as part of local and regional strategies to meet future water needs and to cope with variable rainfall. Although the same scientific information has implications for flood risk, there is as yet little analysis of how flood management should respond to changing patterns of winter and spring runoff. In addition, the institutional rigidities of the flood management system, in which federal agencies play a central role, may limit or hinder adaptation. In the area of water quality, a better understanding of the likely effects of temperature increases and sea level rise is a precondition for developing effective response strategies, which could impose new constraints and costs on a wide range of water and land use agencies.

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

Improving Scientific Understanding

A top priority is better information on potential climate impacts, particularly for flood risk and water quality. Even without better knowledge of how average precipitation levels may change, it will be useful to explore the implications of changes that are relatively certain: shifts in the seasonal patterns of runoff and higher stream temperatures from increased water 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 some particularly important or representative ecosystems, such as the Klamath (where temperature has already become a central issue for salmon) and the San Francisco Estuary (an important area for various endangered fishes, affected by changes in both 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).

Understanding the Regulatory Implications

Getting a better handle on the science is the entry point into developing better management policies. Most resulting changes in water management will require alterations in regulatory practice. For water supply, many changes have already occurred to accommodate modern portfolio approaches to water management – such as reforms of water marketing law. In other areas, a better understanding of the precise regulatory implications of the new management strategies is required to see what changes may be needed. Under current regulations for water quality in the Delta, it would not be legally possible to implement major changes in Delta operations that could make the system more resilient to sea level rise and increasing flood threats. 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 in the face of 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 acquisitions of areas to expand or maintain wetland habitat. Given the lead times to implement such regulatory changes, developing a clearer picture of the likely needs is a priority. Since climate change will affect the efficacy of a host of environmental laws and regulations, a systematic review of state and federal regulatory frameworks in the context of a changing climate should be undertaken.17

Legislating Awareness

Although some local and regional agencies have considerable analytical capabilities, state leadership will be essential to develop information on sector-specific climate impacts and the regulatory implications of adaptation strategies. One recent legislative proposal (Assembly Bill 224) took a step in this direction, explicitly requiring some of this work of state agencies. The proposal would have also required local water suppliers to incorporate climate change in their water planning efforts. Some state guidance will be useful for such local and regional activities.

Implementing "No Regrets" Policies for New Investments

Even when there is still considerable uncertainty about climate impacts, it will often make sense to build new infrastructure – which typically has a lifespan of many decades – in ways that increases the resiliency of the system. For instance, given scale economies, oversizing new stormwater and wastewater systems to account for potential future problems of peak runoff is likely to 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; this approach 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 an important goal under today's hydrology – becomes more valuable to reduce risk in the face of larger runoff events from climate changes.

Improving Information on Flood Risk

Laws that restrict new housing developments in the floodplain – such as those recently passed in California – are one means 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 instance, if they are 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 increasingly complement building restrictions in flood management portfolios. An independent review panel on Central Valley

[17] For a discussion of these issues in the Sacramento-San Joaquin Delta, see Lund et al 2008.

flood risk recently recommended broadening this type of information campaign and extending the zones where flood insurance is mandatory (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 of those living in at-risk areas and limiting the expansion of population and assets exposed to risk.

Improving Funding Mechanisms

The Sacramento example of SAFCA shows how a local agency has been able to innovate to overcome the constitutional restrictions on funding that face local flood and runoff management agencies. But another illustration serves to highlight the problems in the current system: on the November 2006 ballot, flood and stormwater control bonds in the Bay Area Cities of Burlingame and Orinda were rejected despite over 60 percent voter support. Recent years have seen several unsuccessful legislative attempts to amend the constitution, putting flood control and stormwater agencies on the same footing as water and wastewater utilities, which have not needed to go to voters to raise fees. Instead, court interpretations of Proposition 218 have tightened the restrictions on water and wastewater utilities, requiring them to offer property owners the possibility of rejecting rate increases (see footnote 16). A constitutional reform to restore the rights of agency boards to raise fees for these services 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.

Fostering Coordination

The Sacramento example highlights a feature of California water management that will become increasingly important under changing climatic conditions: regional coordination. Several local governments came together to form SAFCA after it became clear that the region faced a higher flood risk than had previously been thought. Examples abound across the state of opportunity and necessity spurring regional cooperation and coordination – in groundwater basin management, water supply, flood management, and most recently regional approaches that aim to tackle a host of water management issues in an integrated fashion. Because there are often start-up costs to coordination, this is an area where the state can provide financial and regulatory incentives. The state has actively pursued this policy in distributing bond funds in recent years (e.g., Proposition 50 bond funds for integrated regional water management). It should continue to do so, targeting areas where progress is needed.

Conclusions

California faces the prospect of significant water management challenges from climate change. The most certain changes are accelerated sea level rise and increased temperatures, which will reduce the Sierra Nevada snowpack and shift more runoff to winter months. These changes will likely cause major problems for flood control, for water supply reservoir operations, and for the maintenance of the present system of water exports through the fragile levee system of the Sacramento-San Joaquin Delta, Rising water temperatures also are likely to compromise habitat for some native aquatic species and pose challenges for reservoir operations, which must release cool water to support fish habitat. Although there is as yet little scientific consensus on the effects of climate change on overall precipitation levels, many expect precipitation variability to increase, with more extreme drought and rainfall events posing additional challenges to water supply and flood managers.

The good news is that California has a rich variety of options for adapting water supply and flood management systems to these changing conditions, even for extreme scenarios. For water supply, a central cost-effective strategy is to expand conjunctive use, shifting drought storage from surface reservoirs to groundwater basins. Other key adaptations involve reallocation and more efficient use, through transfers, conservation, and in some cases recycling. To avoid the loss of up to 6 million acre-feet of water exports through the Delta, investments in an alternative conveyance system will be needed.

For flood management, changing reservoir operations also will be important to adjust to increased winter flows. Costly investments in levee upgrades and flood bypasses also are likely to be needed to protect urbanized areas. Other adaptation tools include expanding insurance coverage and limiting new development in flood-prone areas. Larger storm drain systems and low impact development are two approaches to limit the costs of localized urban flooding from more extreme precipitation events.

California's economy has the ability to cover the costs of these various investments and management changes, even though they are likely to be substantial – on the order of several billion dollars per year. However, institutional limitations could hamper effective implementation, even for water supply management, which is ahead of other areas.

California's water supply managers – including the hundreds of local and regional agencies that are responsible for water delivery - are largely aware of the challenges resulting from a reduction in the snowpack. They have already begun to use many of the adaptation tools that will be important for climate change to manage rainfall variability and accommodate changing demands. The state has facilitated adaptation by reducing barriers to water transfers and providing incentives to strengthen local and regional planning systems and diversify water supply sources. Nevertheless, several steps are needed to further adaptation potential: (i) strengthening groundwater basin management, (ii) developing more sophisticated water transfer mechanisms, such as multi-year options, (iii) creating new rules for operating reservoirs, and (iv) creating new regulations and undertaking new investments for managing water now moving through the Delta. These actions will require significant participation by state and federal agencies.

For flood management, the current institutional framework significantly hampers the ability to develop and implement adaptation strategies. Federal agencies play a major role, but barely recognize climate change. The Army Corps of Engineers, responsible for managing the flood space in most California reservoirs, 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 (requiring both environmental review and congressional approval). FEMA’s floodplain maps, the major regulatory tool for land use decisions, create incentives to locate in high risk areas, because they neglect the effects of build-out and climatic changes. Because the state is liable for most flood damage within the Central Valley, local cities and counties have few incentives to avoid building in at-risk areas. Continued urbanization in floodplains imposes an essentially permanent and growing flood risk on future residents and the state. Funding mechanisms are also particularly problematic for flood control. The Army Corps of Engineers has no budget to fund changes in reservoir operation rules, and local agencies are highly constrained on raising funds for flood works because of Proposition 218 requirements.

Changes in water quality are likely to have significant implications for regulatory programs under state and federal authority, including the Clean Water Act and Endangered Species Act, with effects on reservoir management, water diversions, discharge permits, and TMDLs. However, we are at an embryonic stage of knowledge about these processes. The SWRCB has identified assessment of climate change impacts as a priority for basin management plan updates, but the task is vast, and the process raises the potential for significant conflicts with stakeholders over changing norms and standards.

Several short-term actions would be useful now and/or provide us with options and information needed to improve future capability to adapt to climate warming and other changes:

- 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.
- 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 has recently been done in the Sacramento area.
- Implement a long-term strategy which makes the Delta ecosystem and water supplies less vulnerable to a changing climate.
- 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).
- Consider the use of state incentives and requirements (e.g. such as AB1066) for state and local agencies to take into account climate in water planning.

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.

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