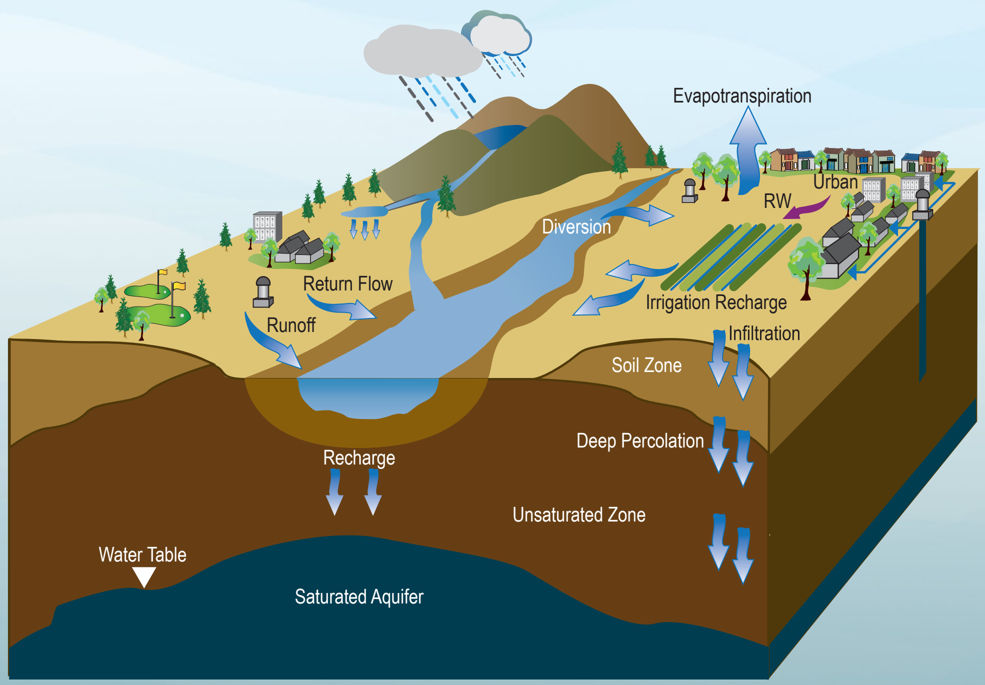
INTEGRATING STORAGE IN CALIFORNIA'S CHANGING WATER SYSTEM



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Summary

Surface water reservoirs provide water supply and flood management benefits by capturing water when available and storing it for use when needed. Surface reservoirs are commonly operated more for seasonal or short-term inter-annual needs. Groundwater aquifers generally provide longer-term storage and a source of water and seasonal storage in areas where surface water is limited. This paper reviews the benefits and challenges of water storage in California's evolving water system, and provides some quantitative insights from an integrated analysis of this system.

Water storage should not be viewed as isolated projects. For today's water management objectives and conditions, surface water and groundwater storage should be considered and analyzed as parts of larger systems or portfolios of actions that include a wide variety of water sources, types and locations of storage, conveyance alternatives, and managing all forms of water demands. Such an integrated, multi-benefit perspective and analysis is a fundamental departure from most ongoing policy discussions and project analyses.

The pilot study described in this paper focused on water storage and concludes that ability to utilize additional water storage in California varies greatly with its location, the availability of water conveyance capacity, and operation of the system to integrate surface, groundwater, and conveyance facilities.

At most, California's large-scale water system could utilize up to 5-6 million acre-feet of additional surface and groundwater storage capacity, and probably no more, which would likely provide 50-150 taf/year of additional water delivery for each million acre foot of additional storage capacity alone. The water supply and environmental performance of additional storage capacity is greatest when surface and groundwater storage are operated together. The benefits, and likely cost-effectiveness, of coordinating surface and groundwater storage and conveyance operations greatly surpass the benefits of expanding storage capacity alone, greatly expanding water delivery increases to as much as 200 taf/maf of additional storage capacity.

Because we did not quantify and compare the economic value and costs of water supply and other benefits of expanding storage capacity, we cannot yet say if particular expansions would be economically justified. Similarly, because we did not comprehensively analyze the environmental impacts of expanding storage capacity or specific storage projects, we cannot yet say if particular expansions would be environmentally justified. Further, this study does not consider reoperation of existing facilities, water demand management, changes in prioritization of water uses or rights, or other policy or regulatory actions that might change the ability to supply water demands using existing water storage capabilities.

Introduction

California is a semi-arid state with tremendous variability in water conditions and demands. Water is relatively abundant in the northern and mountain regions in the wet winter and very scarce in the major agricultural and urban areas during the dry spring, summer, and fall. California's current drought is not unique. Over the last century, California has seen droughts up to six years long, as well as occasional severe floods. In the more distant past, more severe droughts have occurred, some lasting many decades, as well as numerous intense and large-scale floods (Kleppe et al. 2011). California's current drought is in its third year, and could last several more years. Surface water and groundwater storage are being discussed prominently in the context of this drought. Water storage in California is fundamental to managing variability in water supply for human purposes, but has fundamentally harmed many of the state's native habitats and species, which evolved in a naturally variable environment. Californians often hold conflicting views on water storage capacity and its expansion, a debate that will be prominent as the California Water Commission makes decisions on investments for public benefits associated with storage projects, as approved by California voters on the November 2014 ballot and as other storage opportunities and issues arise.

This paper begins with some background on California water storage development and challenges, followed by a discussion of how water storage works to address these challenges and the limitations of current storage capabilities. The paper then describes the advantages of a new approach to water storage investigation, an approach that considers storage and other actions in the context of a more integrated system. Lastly, the proposed new approach for evaluating the role of water storage in California is explored through a pilot study. The results from this study suggest some important directions for evaluations of water storage expansion in California and provide some technical and policy insights for moving forward.

Background

California water development has always been an evolving process of re-aligning infrastructure and operations to changing water demands and conditions (Hanak et al. 2011). This section reviews California water management from the perspective of the evolving purposes for which water is managed, and how this has affected the development and use of water stored in surface reservoirs and groundwater. The section concludes with a discussion of today's major storage questions and issues. Addressing today's issues will require new thinking and analytical approaches that treat storage as one integral component of California's complex water management infrastructure.

Table 1 summarizes the major purposes of California's water management system and the roles of surface reservoir and groundwater storage in serving these purposes.

Table 1. Surface and Groundwater Storage Serves Many Purposes in California

Purpose	Roles of Storage	Performance Indicators
Water supply delivery	Seasonal and short-term storage in surface reservoirs and groundwater; Annual and long-term storage mostly in groundwater	Local and regional water deliveries, South of Delta and Bay Area deliveries (for major Central Valley reservoirs), Economic production from deliveries (or economic losses from un-met deliveries)
Flood Management	Storage of flood peaks in surface reservoirs	Average annual flood damage (or avoided damage), Flood stage reduction
Energy production	Seasonal and peaking energy storage; Energy production from streamflow	Hydropower revenues; Kilowatt-hours generated
Water Quality	Reservoir flow regulation of temperature, contaminants, and Delta salinity; aquifer disposal of contaminants	Temperature, salinity, and other water quality metrics
Ecosystem support	Dams interrupt habitat and alter flow patterns; Reservoirs provide cold water downstream and regulate environmental flows; Groundwater supports overlying wetlands and riparian corridors	Temperature targets; Area of habitat type provided; Meeting prescribed salinity, temperature, depth, flooding pattern requirements; Delta flow patterns; San Joaquin river flow patterns; Fish production/populations
Recreation	Lakes and regulated streamflow for boating, fishing, and aesthetics	Recreation days, Recreation revenues, Quality of life indicators

Surface Storage Development

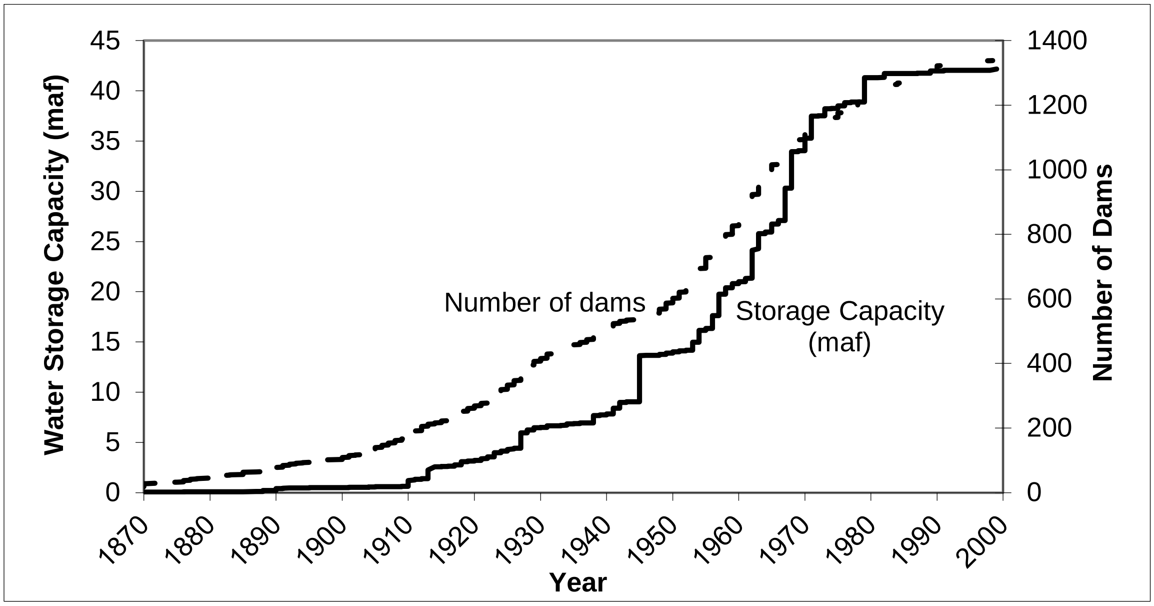
Figure 1 shows the growth in the number and total storage capacity of dams in California since the late 1800s. The earliest dams in California, built in the late 1800s and very early 1900s, only diverted water for hydropower, local irrigation, and drinking water supplies and usually had little storage capacity. Nevertheless, these dams disrupted fish migrations and reduced downstream flows. Between 1900 and 1920, increasing diversions for local irrigation greatly depleted Sacramento River and San Joaquin River inflows to the Sacramento-San Joaquin Delta (Delta) during the irrigation season, causing the City of Antioch to move its intake eastward and considerable salinity intrusion into the Delta in dry months of dry years (Pisani 1986; Lund et al. 2010; Division of Water Resources, 1930; Hanak et al. 2011).

The first major surface water reservoirs for storage were developed further upstream, in the Owens Valley (1913) and Hetch Hetchy Valley of the Tuolumne River (1923) where larger dams were built in valleys to store significant volumes and allow diversion of the stored water from these watersheds to the distant cities of Los Angeles and San Francisco (Kahrl 1986; Hundley 2001).

The Central Valley Project (CVP) was conceived to protect the Central Valley from crippling water shortages and devastating floods. Financed by the federal government, construction of the CVP began in 1937 and now includes 20 dams, over 400 miles of conveyance facilities, and 9 million acre-feet (maf) of storage capacity. The State Water Project (SWP) was authorized by the California legislature in 1951 as a water storage and supply system to capture and store rainfall and snowmelt runoff in Northern California for delivery to areas of need throughout the

State. The SWP includes 33 reservoirs, 29 pumping or generating plants, approximately 700 miles of aqueducts and 5.8 maf of storage capacity. Including local projects, California now has approximately 1,400 regulated reservoirs, with a total storage capacity of about 42 maf. The largest 10% of these reservoirs have 95% of this capacity and the 14 largest 1% of these reservoirs have 60% of all surface storage capacity.

Figure 1. Historical Development of Surface Storage in California



Source: California Division of Safety of Dams data

Roughly 35 maf of California's surface water storage also stores energy (as well as water) and supports hydropower production with 13 gigawatts of combined turbine capacity at 343 hydropower plants, providing 5% to 15% of the state's electricity, depending on drought conditions.[1] Most hydropower plants were built between the early 1900s and 1980. Most major water supply storage reservoirs also have considerable generation capacity, albeit at lower elevations, and their hydropower operations are usually secondary to water supply and flood management.

Reservoirs also can be operated for ecosystem management. Dams have severely disrupted fish migration corridors, altered water and sediment flows, and cut off access to habitat for many native species, and overall have been a key factor in the decline of California's once abundant runs of wild salmon and steelhead, many of which are now listed as threatened or endangered under state and federal law (Moyle et al 2013). However, within this highly altered environment, dams are increasingly operated to support native species, sometimes in novel ways. For example, the endangered winter run of Chinook salmon naturally spawned and reared on the Pit and McCloud rivers, which are now inaccessible due to construction of Shasta Dam in the 1940s. Today, the winter run salmon rely on the operation of Shasta Dam to maintain water temperatures suitable for spawning and rearing downstream of that dam for their survival, at an unnatural location and elevation for winter-run salmon. Temperature control using dams is sometimes discussed as a strategy for supporting salmon populations in the face of climate

[1] http://www.energyalmanac.ca.gov/renewables/hydro/

warming. Also, dam releases now often supply water to wetlands which were more extensively supplied by seasonal flooding and groundwater prior to the extensive development of our water system. So far, most ecosystem-focused operations have been conducted and financed by dam owners under obligations to help meet state and federal endangered species and water quality requirements.

Recreation on lakes and rivers has major local economic and social benefits and moderately affects the operation of reservoirs, particularly for reservoirs that release water for river rafting. In fact, without surface reservoirs, lake and river recreation would be severely limited during California’s many dry months. Wetlands, supported by reservoir releases and by groundwater, also are important for fishing and other wildlife-focused recreation, such as bird-watching.

Groundwater Development

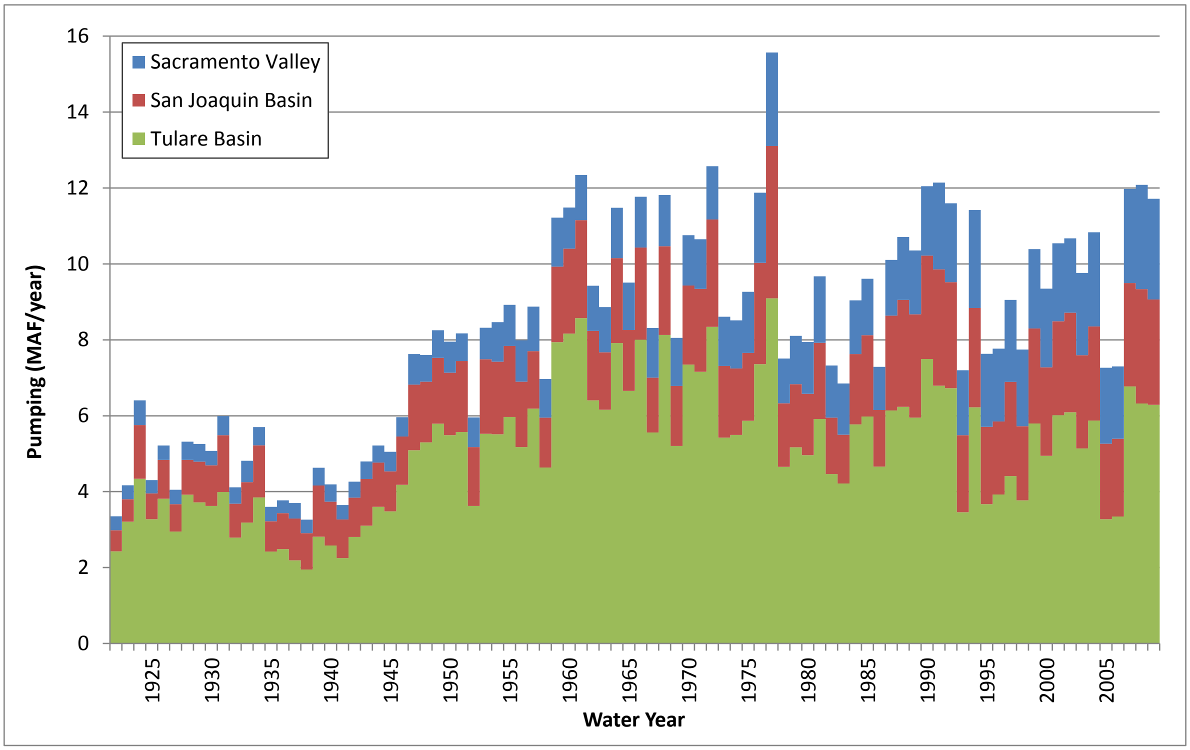
During the early period of surface storage development in California, little groundwater was used beyond shallow wells mostly for domestic supply. Later, following the development of drilling technology, aquifers were tapped in many parts of California for local irrigation. With the development of diesel and electric pumps in the 1910s to 1920s, groundwater pumping became widespread for areas lacking developed surface water supplies (Pisani 1986). By the 1930s and 1940s, groundwater was a major water supply for many areas with little or no access to surface water resources. Increasing agricultural and urban water demands caused significant reliance on groundwater resources. In average years, approximately 30-40 percent of statewide annual agricultural and urban water demand is met by groundwater, while in wet years, the groundwater usage is less, and in dry years, the groundwater can provide approximately 50% of total statewide water demand. These estimates vary greatly with local conditions and hydrology. In the Central Coast, groundwater provides more than 80% of the total average water use, while the San Francisco Bay area supplies only about 5% of total average year water use with groundwater (DWR, 2014).

Figure 2 shows the history of groundwater pumping in the Central Valley. Similar trends have occurred in other developed areas of California (DWR, 2003). Aggressive groundwater development earlier in the 20th Century led to significant overdraft, especially in the San Joaquin Valley and in the Central and South Coast areas. The widespread lowering of groundwater levels substantially dewatered many wetlands and streams (Howard and Merrifield 2010). Groundwater overdraft in the San Joaquin and Tulare basins also caused significant land subsidence from 1945 to 1970. While the rate of land subsidence slowed in 1970s, after the State Water Project imported water to the west side of San Joaquin Valley, increased groundwater pumping, especially in the lower aquifer systems during the recent dry years (after 2005) has increased current land subsidence to over one foot per year in some areas (Sneed et al. 2013). With the current drought of 2014, reduced surface water deliveries and increasing reliance on groundwater for agricultural and municipal water uses in the Central Valley, could cause additional subsidence.

Throughout California, groundwater pumping has significantly reduced flows in rivers and streams. For example, many Sacramento Valley rivers that previously gained considerable summer flows from groundwater in the early 20th century now lose flows to groundwater, primarily from lower groundwater levels due to increased groundwater pumping (TNC, 2014).

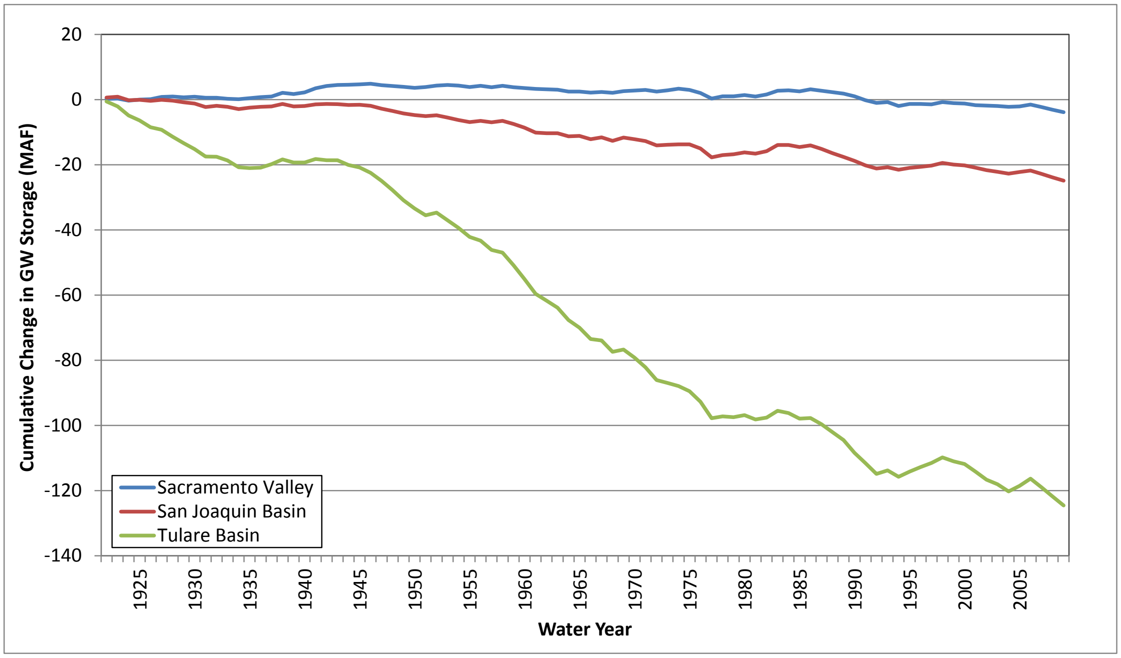
Total overdraft in Central Valley over the 20th Century is estimated to be 155 million acre feet (maf), averaging 1.9 maf per year of overdraft (TNC, 2014). Figure 3 shows the cumulative reduction in groundwater storage in the Central Valley.

Figure 2. Historical Central Valley Groundwater Pumping



Source: C2VSIM simulations 2013 (TNC, 2014)

Figure 3. Cumulative Change in Groundwater Storage in the Central Valley



Source: C2VSIM simulations (TNC, 2014)

Since 2005, limited surface water availability and the high profitability of expanded agricultural acreage have increased groundwater pumping. From 2005 to 2009, this increased groundwater use has increased depletion of groundwater storage by approximately 5.4 to 13.2 maf from Central Valley aquifers (DWR 2013); approximately 1.0 to 2.5 maf per year of groundwater depletion. In dry 2014 alone, an additional 5 maf of groundwater pumping is expected (Howitt et al. 2014). This additional groundwater storage depletion has significantly affected surface water courses and groundwater dependent ecosystems in various parts of the Central Valley, and has contributed to reduced inflows to the Delta.

California has approximately 850 maf to 1.3 billion acre-feet (DWR 1975, DWR 1994) of groundwater in storage. However, not all of this groundwater is economically or practically available, since much of it is of poor quality or is too deep for economical extraction. Of this total groundwater volume, approximately 149 to 450 maf is estimated to be useable, meaning that it occurs at depths that can be withdrawn economically and is of suitable water quality for drinking or agricultural use. However, withdrawal of this amount without compensating recharge would likely reduce surface water flows, increase land subsidence, and cause conflicts among existing water users.

Conjunctive management of surface and groundwater storage occurs in many locations and is fundamental for storing additional water in aquifers in wet years. Intentional efforts to conjunctively manage surface and groundwater storage have been very successful since the 1940s in many parts of California, including Southern California, Yolo County in northern California, and Kern County in the Tulare basin (Banks 1953; Blomquist 1992; Jenkins 1990; Vaux 1986). Many conjunctive use efforts rely on "passive" or in-lieu recharge, where farmers use surface water in wetter years which both recharges groundwater with return flows and reduces pumping from the aquifer. More active recharge also occurs, usually using water spreading (recharge) basins or managing water releases in losing reaches of streams. Regional pricing of surface and groundwater use has helped fund the availability, use, and recharge of more variable surface water supplies, as well as reduce groundwater use.

The Orange County Water District's conjunctive use activities since the 1930s have resulted in significant recovery of groundwater levels, and a well-managed aquifer storage system for that region. Santa Clara Valley Water District has implemented conjunctive use since the 1960s, recovering some of their groundwater levels and halting further land subsidence. Yuba County is another good example of successful regional conjunctive use operations, with significant recovery of groundwater levels in a previously overdrafted aquifer (Onsoy 2005).

In some areas, overdrafted aquifers have provided opportunities for regional and local groundwater banking using surplus local or imported surface water , such as in the Tulare Basin (Kern Water Bank, Semitropic Water Storage District), and parts of southern California (Eastern Riverside and San Bernardino counties). Limitations on these banking programs include the availability of surface water and infrastructure for direct or indirect recharge, some water right uncertainties for groundwater banking, access to the banked water during times of Delta shortage, and nearby impacts of water level fluctuations from banking activities.

<u>Snowpack and Soil Moisture</u>

Sierra-Nevada snowpack usually shifts a significant amount of winter precipitation to supply spring and summer runoff. Although snowpack storage provides a significant amount of seasonal water storage, the amount and/or timing and scale of runoff from snowpack cannot be controlled. As the climate warms, seasonal snowpack storage will be reduced, leading to some reoperation of downstream reservoirs (Tanaka, et al. 2006; Medellin et al 2008; DWR 2009).

Another form of seasonal water storage is soil moisture. This is the only form of water storage available to agriculture in non-irrigated areas, where precipitation is stored in the soil for use by natural vegetation or crops, usually over several weeks. In most of California, with its long dry season, soil moisture from winter precipitation has operational significance early in the growing season. However, without resupply from irrigation, soil storage alone is usually insufficient in quantity and reliability to support prosperous agriculture.

Water Storage Challenges

The many local, regional, and statewide purposes of water management in California make oversight, operation, and finance of the system and its many components a complex and ever-changing brew. This characterization applies to both surface and groundwater storage, whose roles within this system have changed, and will continue to change over time.

Water management objectives and conditions continue to evolve, and this evolution will demand changes in expectations for policy, planning, and operations, which are beyond the scope of this study. Major foreseeable changes include changes in climate (particularly warming and sea level rise), population growth, increased urban and agricultural water use efficiency, tightening drinking water standards, additional invasive species, landscape changes in watersheds and parts of the Sacramento-San Joaquin Delta, and changes (tightening, loosening, or both) of environmental regulations (Hanak et al. 2011). These changes will affect all aspects of California's water system, including surface water and groundwater storage.

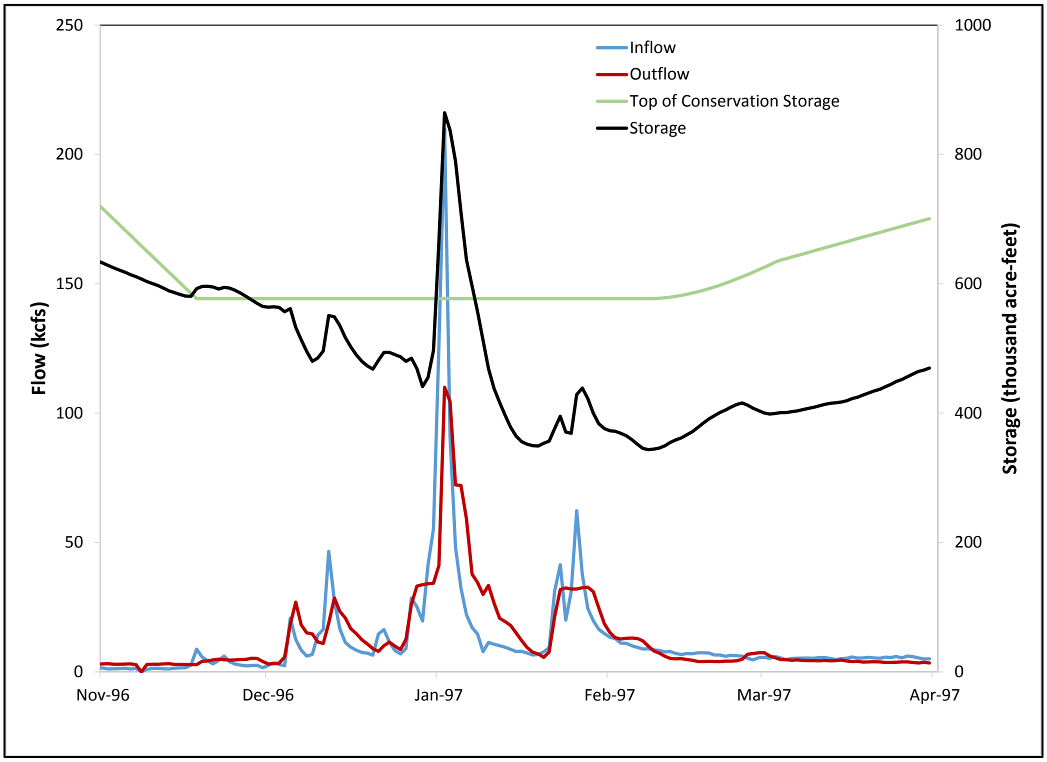
Some particularly important challenges for water storage and storage management include:

- reduced seasonal snowpack water storage with a warmer climate, encouraging some reoperation of dams, aquifers, and water conveyance and recharge; this may include revisiting the reservoir rule curves for some of the reservoirs to increase seasonal water supply pools,
- reduced water availability to fill storage due to changes in climate, increasing overall water use (including environmental uses), and reduced ability to move water across the Delta,
- efforts to restore habitats by removing some dams,
- access to water banked underground, and
- transparency in water rights and water accounting.

How Water Storage Works in California

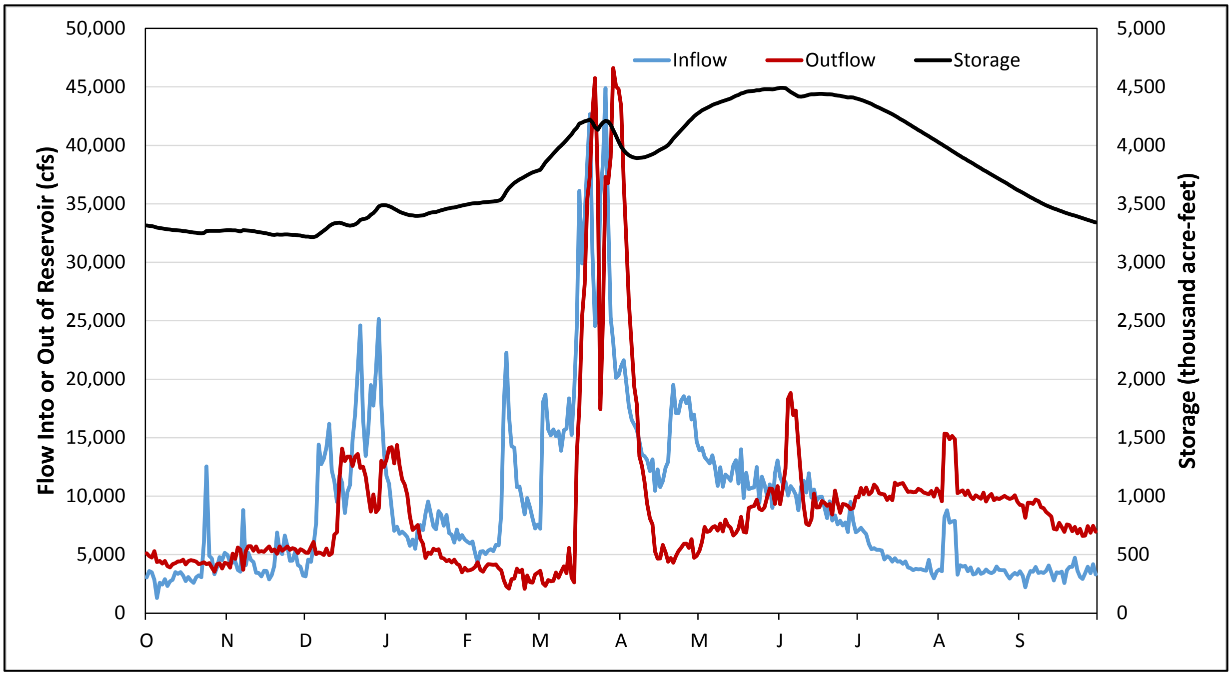
California's climate, economy, and geography drive the need to store water from times of greater abundance to serve demands in times of greater scarcity (Lund 2012; Lund and Harter 2013). Water is generally stored at times when the value of water is relatively low for use in times when the value (and scarcity) of water is relatively high. Figure 4 shows how water storage and release can respond to flood conditions over several days (Figure 4a), wet and dry seasons within a year (Figure 4b), and droughts lasting many years (Figure 4c). Consequently, the value of storage capacity and the value of stored water varies greatly with time, location, and the purposes of storage.

Figure 4a. Folsom Reservoir Storage and Flows during 1997 Flood Event



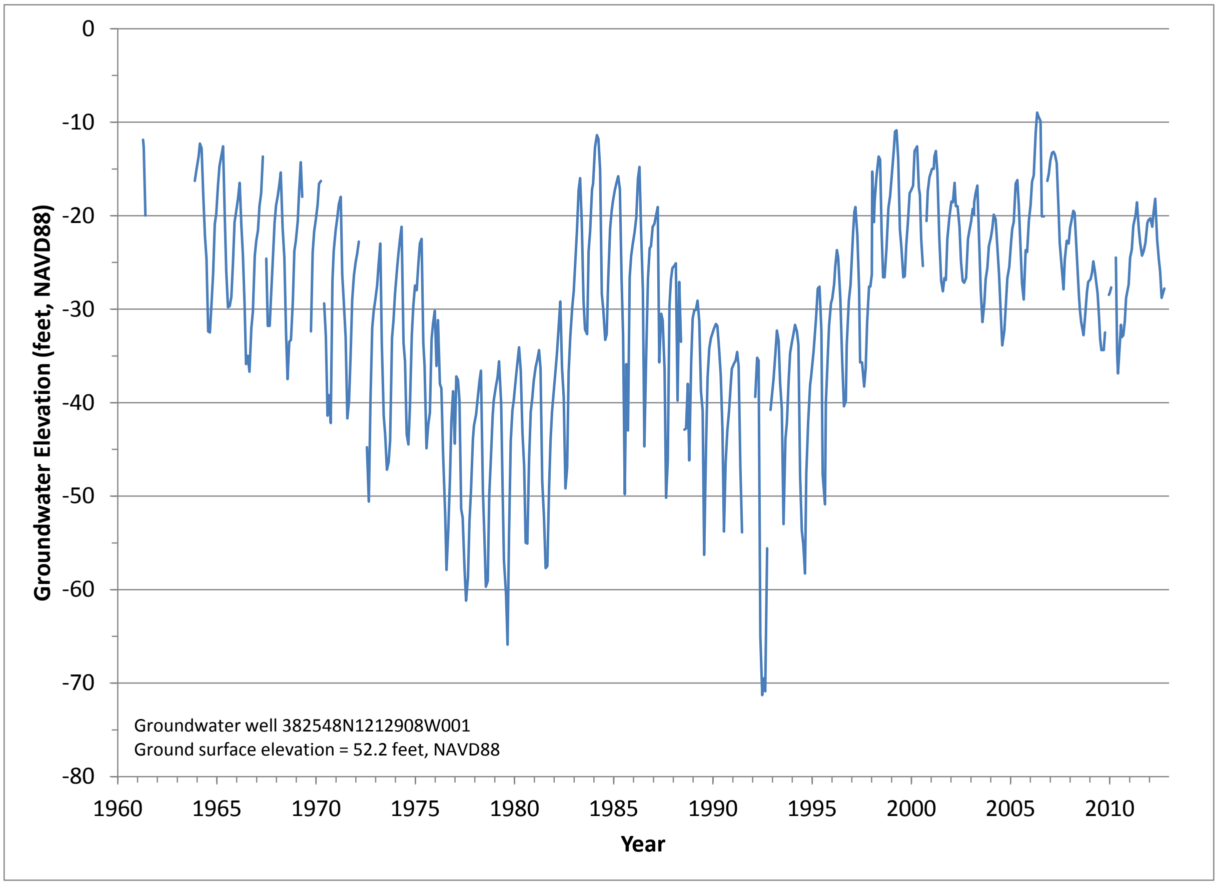
Source: USACE data (2013)

Figure 4b. Typical Seasonal Reservoir Operations



Source: CDEC data for Shasta Reservoir (2013)

Figure 4c. Typical Annual and Decadal Scale Groundwater Storage Levels (Galt, California)



Source: California Water Data Library Well No: 382548N1212908W001

Just as the value of stored water varies with time, all locations and types of water storage are not equal. Natural storage in snowpack and groundwater and managed surface and aquifer storage have important roles, but only the small portion of California's total storage in surface reservoirs and groundwater within the reach of wells can be "managed." Figure 5 summarizes total capacities of surface and groundwater storage and its use in California.

Groundwater storage capacity in California dwarfs that of surface storage, which is much more actively used. Seasonal storage tends to be more from surface reservoirs and long-term and dry year storage is more from groundwater. Some surface storage reservoirs are operated predominantly for flood control or hydropower reservoirs, although this single-purpose storage sometimes contributes to seasonal water supply storage. The currently proposed new surface storage reservoirs, discussed later in this paper, would add less than ten percent to existing surface storage capacity. Figure 6 shows how not all storage in a reservoir or aquifer is accessible and how different ranges of storage often serve different purposes, sometimes with different seasons.

Figure 5. Surface and Groundwater Storage Capacity in California and Its Seasonal and Drought Use

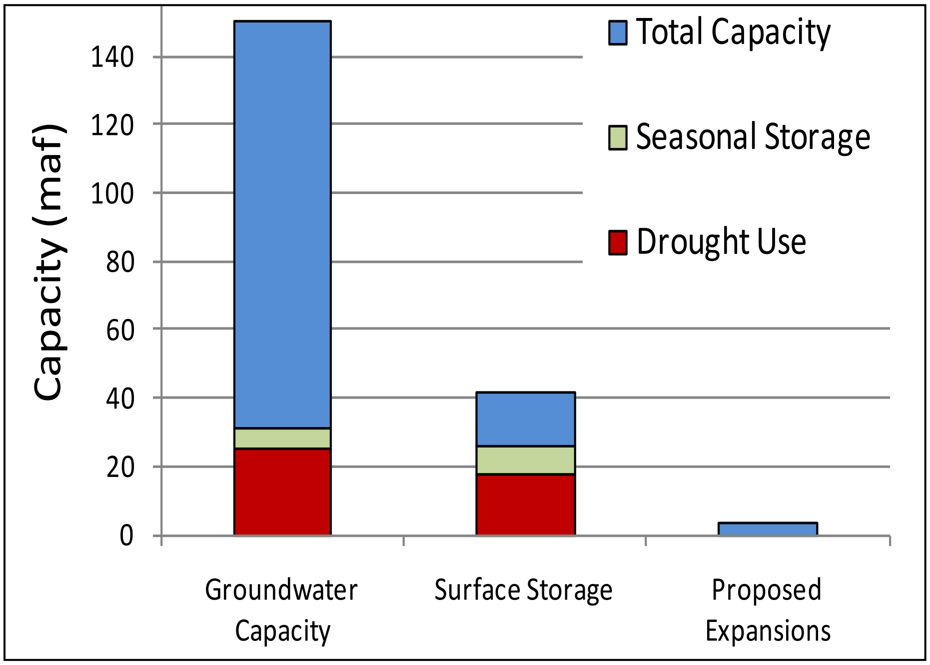
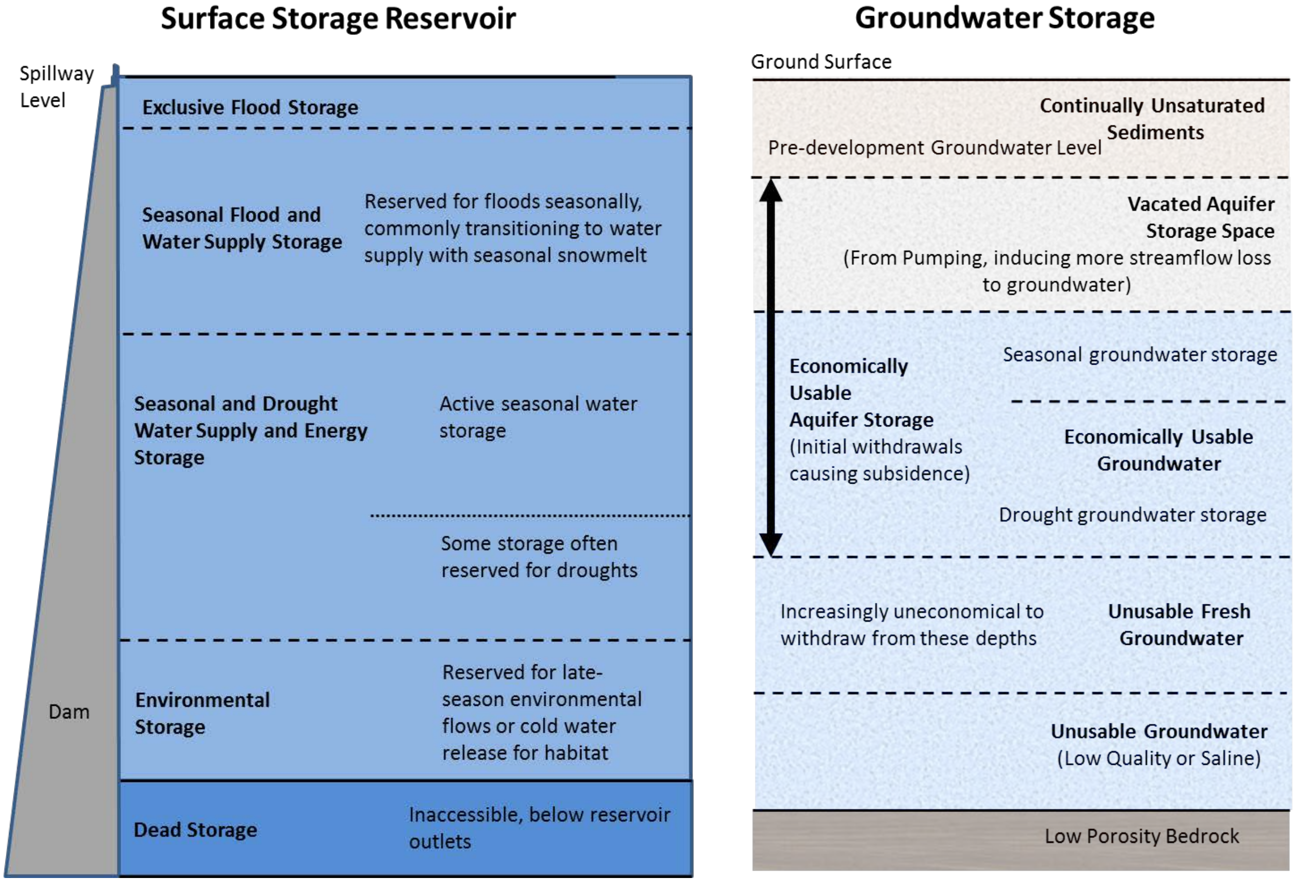


Figure 6. Common Operating Ranges for Surface and Groundwater Reservoirs



Groundwater in storage is primarily from recharge that has occurred over hundreds of thousands of years from surface water bodies (rivers, streams, and lakes), runoff from mountains, and rainfall over the ground surface. In addition, human activities during the past century, such as irrigation, contribute significantly to groundwater recharge through deep percolation of applied water.

Useable groundwater in storage is that portion of groundwater that has reasonable quality for urban or agricultural use and is within an economical depth to pump. Most wells in the Central Valley are 200 to 500 feet deep, although some wells are over 1,000 feet to tap deeper aquifer layers. Other wells are deeper still, such as in some coastal aquifers, where water wells are over 2,000 feet deep to extract deeper groundwater that is somewhat isolated from saline ocean water.

Long-term extraction of groundwater beyond its replenishment rate causes overdraft of the basin. While overdraft can have significant negative impacts, as described above, short-term depletion can provide additional storage space in the basin, providing an opportunity for deliberate underground storage of surface water. Some of California's major groundwater basins currently being overdrafted are shown in Table 2.

The storage space created as a result of historical overdraft contributes to the available groundwater storage capacity. About 250 maf of storage capacity is available statewide, of which the Central Valley comprises approximately 170 maf (DWR, 2003).

Table 2. California's Major Overdrafted Groundwater Basins

Groundwater Basin	Estimated Recent Overdraft rate (taf/yr)	Average Current Pumping (taf/yr)	Percent Pumping from Overdraft
Sacramento Valley	180	1,900	9%
San Joaquin River Basin	480	2,500	19%
Tulare Basin	1,500	5,400	28%
Salinas River Basin	26	496	5%
Pajaro River Basin	12	48	25%

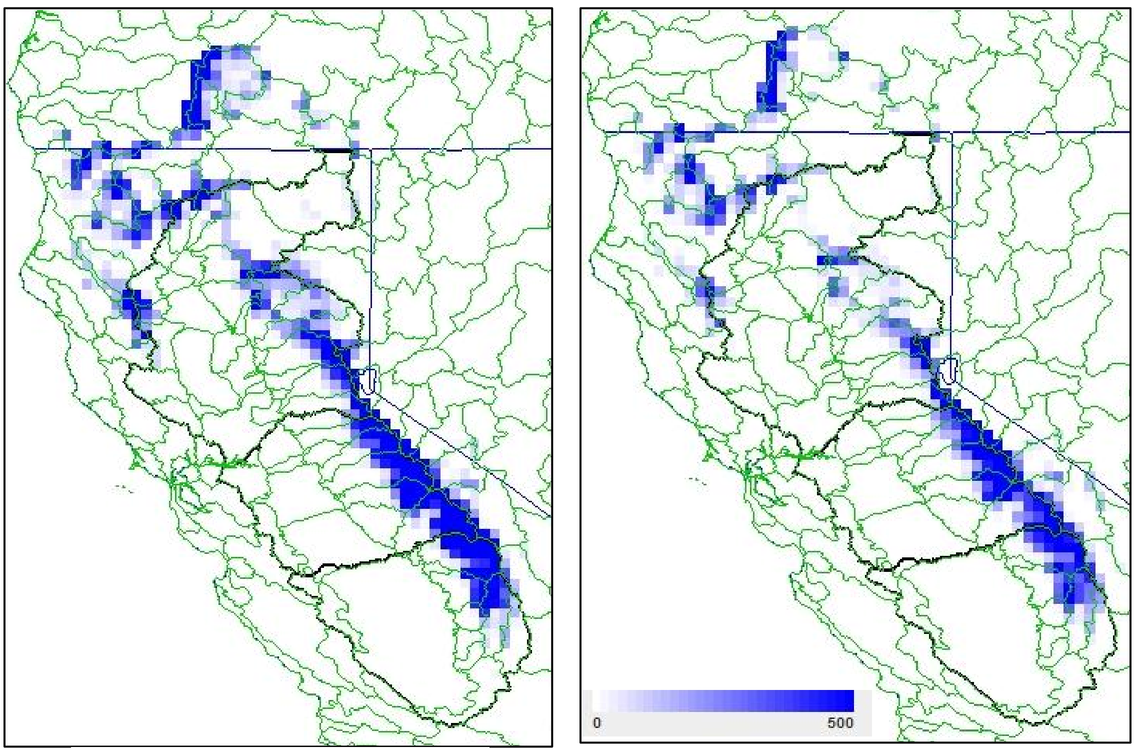
Source: (TNC 2014; MCWRA 2012; PVWMA 2013)

Working as a System

Groundwater and surface reservoirs have important and different storage capabilities. Seasonal storage (within a year) is routinely provided by surface reservoirs, whereas groundwater basins, with their greater storage capacity and generally slower recovery rates, are more important for long-term storage. The seasonal operation of surface reservoirs often supports groundwater recharge downstream, essentially transferring short-term storage into longer-term storage. Both seasonal and drought storage are augmented by natural seasonal snowmelt, soil moisture, and groundwater storage. Short-term storage for flood management and power generation is predominantly by surface water reservoirs. Groundwater alone typically can absorb little floodwater because flood flows are typically contained within the river channels or occur for a duration too short to permit significant percolation to groundwater. However, groundwater can be managed conjunctively with surface storage to increase both flood retention and water deliveries. In this case, the surface reservoir can be used during wet periods and wet years, while reducing groundwater pumping during these periods, which in turn results in increasing groundwater in storage. During dry conditions and dry years, on the other hand, when surface water may be insufficient, water previously stored in aquifers during wet periods can be extracted for beneficial use.

Seasonal snowpack in the Sierra Nevada, Cascade, and other high mountain ranges provides the most significant seasonal surface water storage. California's water supply, flood management, ecosystems, and general water management infrastructure take advantage of snowpack shifting winter precipitation to spring and summer snowmelt. A warming climate will shift more precipitation to rain from snow and cause earlier snowmelt, significantly reducing seasonal snowpack storage and eroding the effectiveness of the current storage system and operation. Figure 7 depicts the potential loss of April 1 snow water equivalent due to climate warming by mid-century.

Figure 7. Simulated Historical and Future April 1 Snow Water Equivalent



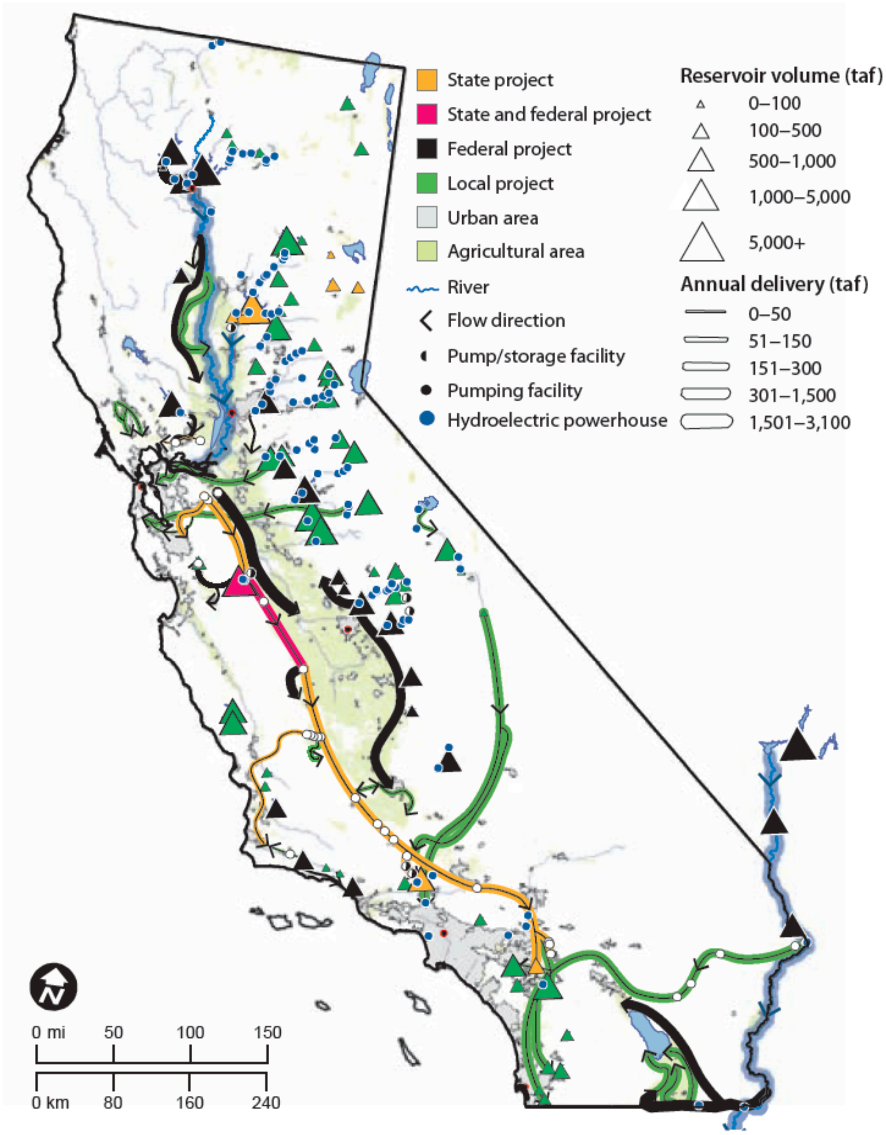
1981-2010: ~ 23.0 maf **2041-2069: ~11.7 maf**

Source: Historical and future VIC hydrological model simulations (CH2M HILL)

Water storage infrastructure and operations function as parts of a large, interacting and dynamic system that serves many purposes (Figure 8). Some implications of these interactions are summarized below.

Storage capacity often serves multiple purposes. Fortunately, storage of winter floods for spring and summer water supply is compatible with California's climate. Storage of seasonal flood and high flows reduces downstream flooding and holds water from the wet season for agricultural and urban uses during California's long dry season. By distributing stored floodwaters over time, the flood storage system also can increase recharge to groundwater, which can be used during dry months and years. In parts of the world where the flood season is also the main water use season, storage capacity for floods has much less ability to serve doubly for water supply.

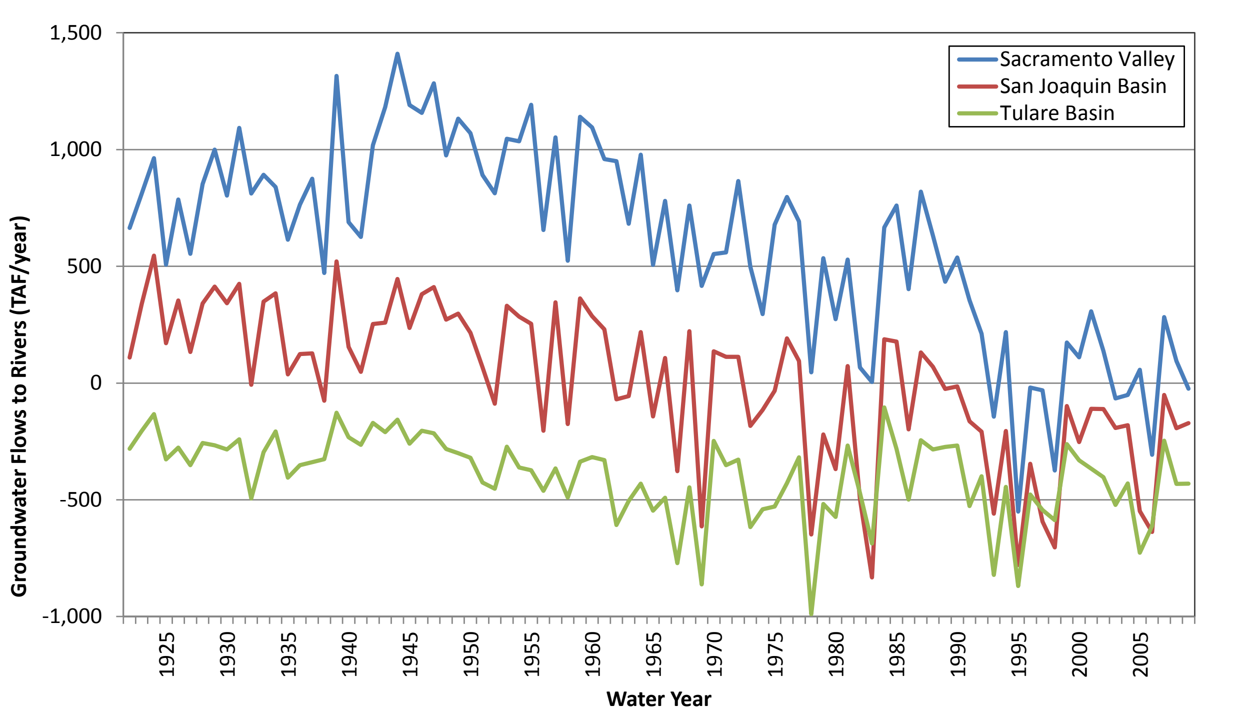
Figure 8. California's Vast Intertied Water System



Source: Hanak et al. 2011

Groundwater and surface water connect and interact in important ways. Surface water and groundwater systems in California are interconnected and substantially operate as an integrated system. During the pre-development era, groundwater levels were high enough to provide a fairly constant base inflow (baseflow) to streams. Groundwater pumping has lowered groundwater levels in many areas, reducing water flow from groundwater to streams and has often reversed these flows to the point that today, in many parts of the state, more water flows from streams to aquifers than from aquifers to streams (TNC 2014; Fleckenstein et al. 2004; Faunt et al. 2009). Figure 9 shows the surface water/groundwater interaction for Central Valley rivers and streams from the 1920s through 2008. As shown in the figure, groundwater withdrawals have reduced streamflow in Central Valley rivers by over 1 maf per year.

Figure 9. Historical Simulations Show Growing Losses from Streams to Groundwater



Source: TNC 2014

Location, location, location. The location of storage, relative to flows from source watersheds, water demands, and conveyance facilities is very important. For storage to be useful, it must be located where it can be replenished and withdrawn in quantities and at costs suitable for its intended demands. Much of California's remaining surface water and groundwater is unavailable for storage because of costs and limits of accessing it for recharge, withdrawal, or conveyance due to its location.

Groundwater is typically drawn from aquifers near the place of use. Overdraft and groundwater depressions are common in areas of concentrated pumping. For managed groundwater storage projects to be successful, the projects need to be located strategically not only in areas with large available storage space, but also where there is access to water for managed recharge, such as from recycled water, storm water, flood flows, and/or imported water. Careful analysis of feasibility of recharge relative to the source water, available storage, as well as recharge rates is required for managed recharge programs.

California has large amounts of empty groundwater storage capacity south of the Delta due to decades of overdraft. This storage capacity is hard to employ fully because of its remoteness from major available water sources. The same principle applies for surface water storage, which cannot provide water without a water supply to fill it first.

Storage capacity does not equate to water supply. Storage space must be at least partially filled before it can provide additional water supply, and numerous operational, physical, institutional, and legal constraints often limit the effective use of available storage space. These constraints include engineering restrictions on the rates at which reservoirs can be filled and emptied for safety and capacity reasons, lack of conveyance capacity to bring stored water to or from reservoirs or aquifers, water rights and contract constraints, and regulatory limitations. For water recharge to groundwater, there is often some loss of water that cannot be recaptured later by extraction wells, so the amount of water recharged exceeds its future deliveries.

Water deliveries do not increase in direct proportion to increases in additional storage capacity. Doubling of reservoir size does not double water deliveries (Hazen 1914). Water deliveries are ultimately limited by the amount of water flowing into a reservoir. A small reservoir in a watershed with variable inflows will greatly improve regular water deliveries. But, as the reservoir size increases, compared with the amount of inflow available to fill the reservoir, the available storage space is filled less and less frequently, which means that the each additional increment of added storage capacity provides less and less water supply benefit. Millerton Reservoir (with 500 taf capacity) on the San Joaquin River (with 1.7 maf/yr average flow) delivers about 800 taf/year; however, adding a 1.2 maf reservoir upstream on this river is estimated to increase deliveries by less than 80 taf (Reclamation 2014a).

Storage Limitations. The performance of California's water system is often limited by the storage and conveyance capacities available at specific times and locations, forcing available water to be under-utilized for some purposes. However these capacity limitations are often not physical, but come from environmental regulations, flood operating policies, and water rights or contracts. Storage restrictions from water rights and contracts sometimes can be loosened with water market transfers. Flood operating policy changes often require prolonged reassessments of trade-offs between flood and other objectives for a particular reservoir site. Environmental protections that affect storage operation can take many forms, including needs to store cold water to support salmon downstream, storage to support minimum or pulse flows for downstream habitat, and avoidance of release patterns that could disrupt downstream habitats.

Climate Change. Climate warming will significantly affect the effectiveness of storage in California's current water system (Buck et al. 2011; Willis et al. 2011; DWR 2009). Five effects of climate warming will be:

1) reduced winter snowpack, shifting annual streamflow from spring to winter months, something that is already happening (Aguado, et al. 1992),
2) higher evaporation and evapotranspiration rates, reducing annual streamflow by several percent and reducing groundwater recharge (Ficklin et al 2013),
3) higher crop growth and evapotranspiration rates and longer growing seasons, with variable effects on agricultural and outdoor landscaping water demands, ranging from no change to modest increases in transpiration by the same or similar crops to large increases from additional double-cropping,
4) higher stream temperatures that reduce the quantity of cold water, particularly in spring, and increase the demand for or reduce the effectiveness of reservoir releases of cold water to maintain cold water habitat downstream of reservoirs, and
5) higher sea levels that increase risk of salinization of coastal aquifers and reduce the ability of the Sacramento-San Joaquin Delta to convey stored water.

In addition, increases in the overall intensity and duration of floods and droughts also can be affected and are important areas of active research and investigation that are beyond the scope of this study.

California's existing surface storage capacity can accommodate some, but not all, seasonal shifts in streamflow from a warmer climate for hydropower, water supply, and flood management (Buck, et al. 2011; Madani and Lund 2010, Willis et al. 2011), although this accommodation comes with some inconvenience and economic losses. With proactive adaptation, groundwater also can be employed to balance shifts in seasonal streamflows by shifting more drought storage from onstream reservoirs to aquifers (Tanaka et al. 2006). Nonetheless, recent studies indicate up to 10% reductions in water deliveries and increased risk to the management of cold water releases from reservoirs for downstream fisheries (cold water pool management) due to climate change through mid-century (Bay Delta Conservation Plan 2013).

The effects of warming on fish are more severe, especially if warmer conditions are also drier. Drier conditions reduce water availability for fish flows, and warmer conditions make it harder to support fish in downstream habitats with cold water stored in reservoirs (Moyle et al. 2013).

Severe and prolonged droughts in California can last for many decades (Kleppea et al 2011). Such droughts would be seen as a drier climate for several generations. These drier conditions would diminish the deliveries and effectiveness of much of California's water storage infrastructure (Harou et al. 2010).

Storage Study Efforts to Date

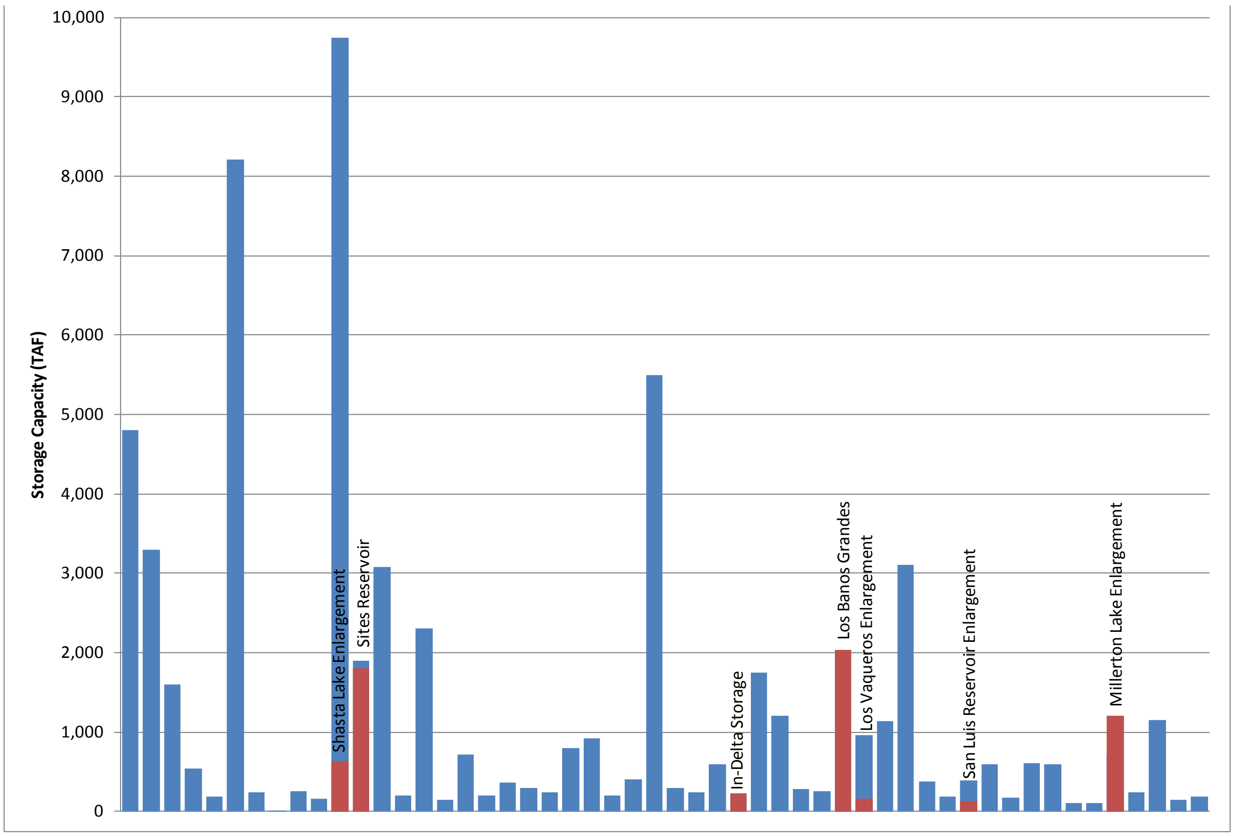
For nearly a hundred years local, state, and federal governments and research institutions throughout the state have studied surface water storage and new or expanded storage facilities in California.

The CALFED program in the early 2000s, drawing on many previous studies, performed a comprehensive screening of additional surface storage options for the Central Valley. The initial screening considered over 50 surface storage locations with a cumulative additional storage capacity of over 60 maf (Figure 10). From these initial storage sites, five potential large projects (Shasta Lake enlargement, Sites Reservoir, Los Vaqueros Reservoir enlargement, In-Delta storage, and Millerton Lake enlargement) with a potential for 4.2 maf of new surface storage were selected for further study. Subsequent investigations of these options are continuing to seek improvements in water supply reliability, water quality, environmental flows, and other benefits.

In addition, regional and local storage continues to be investigated to support local water supply and flood management. For example, the Metropolitan Water District of Southern California completed Diamond Valley Reservoir in 1999, adding 800 thousand acre feet (taf) of storage for southern California. Contra Costa Water District increased Los Vaqueros Reservoir to 160 taf in 2012. Similarly, the San Diego County Water Authority is increasing San Vicente Reservoir to add 152 taf for local supply resiliency to earthquakes. In total, more than 27 maf of new surface and groundwater storage projects are being considered statewide, often by local agencies.

Many state, regional, and local efforts are encouraging more proactive management of groundwater capacity to store surface water during wet years and seasons, known as conjunctive use of surface water and groundwater. Another concept in use of groundwater and surface water resources in a conjunctive mode is groundwater banking opportunities. In this case, local water agencies which have access to surface water use artificial or in-lieu means to recharge the groundwater system and bank the surface water when available, with the premise of using the banked water during times that surface water is not available. Many local agencies are starting to implement such programs. Local groundwater banking provides opportunities to store water in a relatively safe and economic environment, closer to the demand areas. In addition to improving the use and storage of existing water sources, some of these efforts seek to develop some new supplies by treating urban wastewater, stormwater and brackish or poor quality groundwater. Many of these efforts are in Southern California. Up to 1 maf of groundwater storage or conjunctive use was targeted for further study in the CALFED investigations, primarily in the San Joaquin and Tulare basins.

Figure 10. Surface Storage Options Investigated in CALFED Review (Red bars are storage programs now being actively studied by local, state and/or federal agencies)



Source: Data from CALFED (2000)

Much of the potential new storage capacity is in the Central Valley and along the major state and federal water project conveyance systems. The Sacramento and San Joaquin Rivers and Central Valley Project and State Water Project canals are particularly important for making stored water useful over large parts of California.

Table 3 summarizes major on-going surface and groundwater storage studies in California. The CALFED storage programs are currently being evaluated under the Integrated Storage Investigations by DWR and Reclamation. DWR also has several other active storage-related studies underway: the System Reoperation Study, the FloodSafe program, and the California Water Plan. The USACE and local agencies also participate in the FloodSafe program.

A statewide inventory of groundwater management plans shows that many regional and local agencies are leading efforts to evaluate and expand groundwater storage and banking, including Semitropic Water Storage District, Sacramento and San Joaquin counties, Orange County Water District, and Eastern Municipal Water District. In recent years, local banking projects have drawn attention from state, regional, and local groundwater policy makers. Some potential advantages of local groundwater banking programs are that they are constructed and maintained for local agricultural and municipal uses, more supported by local governments, and require lower water transmission and distribution costs due to the proximity of demands.

Table 3. Summary of Major On-Going Storage Investigations

Proposal	Region	Owner/ Proponent and Description	Capacity, taf
Surface Storage Programs			
Shasta Lake Enlargement	Sacramento	Reclamation/DWR - On-Stream Storage to increase regulating capabilities and yield opportunities	Up to 640
Sites Reservoir	Sacramento Valley	DWR/Reclamation/Sites JPA - Off-Stream Storage for local and system-wide yield opportunities	1,200 to 1,900
In-Delta Storage	Sac. -San Joaquin Delta	Island Storage in Central or Southern Delta for Delta flows or exports	230
Los Vaqueros Enlargement	Delta	Reclamation/CCWD - Water supply storage off California Aqueduct or Delta-Mendota Canal	Up to 965
Millerton Lake Enlargement	San Joaquin River	Reclamation/DWR - On-Stream Storage to increase flow regulating opportunities	720
San Luis Enlargement	San Joaquin Valley	Reclamation/DWR - Increased off-stream storage for improved CVP and SWP deliveries	370
Groundwater Storage Programs			
Sacramento Valley Region	Sacramento Valley	Local entities - Local and regional groundwater banking for water supply and the environment.	Up to 3,500
San Joaquin Basin	San Joaquin Basin	Local Entities - Madera Ranch and similar groundwater banking opportunities for water supply storage.	Up to 2,500
Tulare Basin	Tulare Basin	Local Entities - Kern and Semitropic water banks successfully operate, and other groundwater banking are being investigated.	Up to 12,000
Other local and regional Storage opportunities	Southern California, Central and South Coast	Local and Regional Entities - Various local and regional groundwater storage programs	Up to 4,000

The Need for a Different Approach

California's water system has been built piecemeal over many years, with most projects being independently conceived and implemented incrementally. But California has come to manage water infrastructure more as an integrated system. Excess flows in wetter years from streams and reservoirs in northern California are shifted to surface water and groundwater storage in the southern Central Valley and southern California for drought storage. Flood storage to protect Sacramento is augmented by shifting water from Folsom reservoir to other reservoirs. New Bullard's Bar reservoir in Yuba County is coordinated with operation of the SWP's Oroville Reservoir to better protect Marysville and other downstream communities. Aqueducts connect water users to a wider range of water sources and storage locations and facilitate voluntary exchanges among users. Water market transfers increase the system's adaptability to changes in water availability, water demands, and climate.

Yet most studies of potential water storage projects have been "project studies", where a particular proposed project is evaluated in relative isolation from other water storage and non-storage management options regionally and statewide. Such project-level analysis continues today with studies of surface water and groundwater storage projects, such as Sites Reservoir, Temperance Flat, Los Vaqueros, and Madera Ranch water storage projects. Authorizing legislation for project studies often limits the options, locations, and benefits to be evaluated in an integrated context from the onset. Further, much of the surface water storage and delivery facilities have been planned, designed, and developed with little coordination with groundwater supplies or groundwater storage.

The true value of water storage in California is driven by its ability to be useful as a component integrated into a complex and changing system with diverse and evolving purposes for a somewhat uncertain future.

Accordingly, we propose a more integrated approach where "system studies" of water infrastructure would better reflect the integration of various types of storage and other relevant conveyance and distribution facilities. Such studies would also better highlight promising actions of all types for the broad water management purposes of California. Water system improvement studies should move from project justification studies to studies that identify the most promising projects regionally and statewide for a variety of purposes, and those that help improve the adaptability of the system for a range of likely future demands and climatic conditions.

Some potential advantages of identifying candidate water management actions using an integrated system perspective are:

- Lower costs and greater overall effectiveness from
  - better integration of supplies, demands, infrastructure operations, and investments,
  - better integrating local, regional, and statewide management and investments,
  - better use and adaptation of existing facilities, through integration of operations or re-operations to avoid or reduce needs for new capital investments, and
  - better identification and estimation of likely system-wide and local benefits and more complete consideration of alternative costs and policies;
- More adaptable systems, designed and funded to serve multiple purposes and better able to accommodate future changes;
- Broader political and financial support for actions, because a broader range of interests are explicitly considered and balanced in the analysis;
- More flexible integrated water system management that provides more resilience in extreme conditions, such as short-term or long-term droughts; and

- Water operations that are designed to support multiple habitat needs – wetlands, riparian, floodplain and instream flow needs – to optimize environmental water uses in better balance with the agricultural and municipal demands.

Major elements of a system-based approach are:

- Emphasis on managing local, regional, and statewide facilities as an integrated system with local, regional, and statewide consequences;
- Emphasis on integrating the roles and effectiveness of various storage types to supply current and future demands;
- More rigorously evaluating operational flexibility under variable hydrologic and climatologic conditions;
- Use of an integrated operational strategy to optimize the use of the finite resources in a sustainable manner;
- Consideration of multiple water, energy, and ecological purposes that depend on the water system and use of performance measures to ensure benefits from more integrated management;
- Proactive inclusion of ecosystem needs as part of planning and systemwide operations rather than as post-hoc constraints on a system designed primarily for other purposes;
- Recognition and incorporation of uncertainty in analysis and decision-making;
- Quantitative assessment of regional and local water availability, costs, decisions, and performance to provide a common technical basis for discussion and policy-making and trade-offs among alternatives;
- Broad consideration of management options including new supply development, demand management, facility development or modification, system reoperation, and policy/institutional changes and cooperation at local, regional, and statewide levels; and
- Application of simulation and optimization modeling to identify promising alternatives (optimization) and quantify their effectiveness (simulation) under a range of conditions Palmer et al. 1982; Needham et al 2000).

Elements of a system-based approach have been employed in California by regional water agencies, university researchers, and private companies. Examples of efforts that embody a system-based approach include:

- Statewide economic optimization of California's water system using the CALVIN model (Draper et al 2003; Jenkins et al. 2004; Pulido et al. 2004; Tanaka et al. 2006; Harou et al. 2010; Buck et al. 2011; Ragatz 2013; Chou 2013; Nelson 2014),
- Metropolitan Water District of Southern California's Integrated Resource Plan Analyses,
- Reclamation's Colorado River Basin Study and Sacramento-San Joaquin Rivers Basin Study,
- San Diego County Water Authority's Regional Facilities Master Plan, and
- Santa Ana Watershed Project Authority's (SAWPA) IRWM & One Water One Watershed (OWOW) Program.

Some of these analysis and planning efforts have been quite thorough and illuminate the promise of the approach we propose.

Economic Optimization Analysis of Reservoir Value: Pointing towards Integrated Analyses

Example storage valuation results from an integrated system optimization model are in Table 4 (Ragatz 2013). The CALVIN hydroeconomic model of statewide water supply coarsely integrates statewide hydrology, storage, conveyance, and treatment infrastructure, environmental flows, and economic values of agricultural, urban, and hydropower water uses (Draper et al. 2003). The model maximizes overall economic performance over a 72-year period.

Table 4 shows estimates of the economic value of expanding selected reservoirs ($/year per unit of expanded storage capacity) under various climate, Delta water export, and urban water conservation conditions. Similar results are available for infrastructure and demands statewide.[1]

Table 4. Estimated annual economic water supply values of expanding surface reservoirs under different climate, Delta export, and water conservation conditions, CALVIN, $/yr per acre-ft of expanded storage capacity (Ragatz 2013).

	Historical climate				Warmer, drier climate			
	0% urban conservation		30% urban conservation		0% urban conservation		30% urban conservation	
Reservoir	Full exports	No exports	Full exports	No exports	Full exports	No exports	Full exports	No exports
Claire Engle	3	3	3	3	39	30	32	32
Shasta	8	8	8	8	67	34	51	34
Oroville	15	11	13	10	78	18	66	17
N. Bullard's Bar	18	17	17	17	156	19	90	19
Folsom	13	10	11	9	153	20	85	15
Pardee	2	5	1	1	14	32	20	41
New Melones	9	10	9	10	3	3	3	5
Hetch Hetchy	6	7	5	7	7	6	5	7
New Don Pedro	8	9	8	8	4	3	4	5
Millerton	6	95	5	62	37	120	56	33
Pine Flat	6	95	5	62	20	103	51	95
Kaweah	56	457	47	379	269	263	225	254
Success	49	403	42	340	361	361	308	357
Isabella	4	46	1	15	32	76	32	5
Grant Lake	52	116	44	76	0	0	0	0

In these results, the value of increasing water storage north of the Delta (purple) is heavily influenced by the ability to export water to drier parts of the state with greater water demands. Greater water conservation modestly reduced the value of expanded storage, and a warmer drier climate greatly increases the value of expanding storage capacities, unless Delta exports capacity is eliminated.

South of the Delta, eliminating Delta export conveyance increases the value of increased storage capacity. Reducing urban water demands again reduced the value of increasing storage capacity. But a warmer drier climate increases the value of additional storage on some rivers, but decreases the value of water storage on streams that already have considerable storage capacity relative to inflows. In effect, for New Melones, New Don Pedro, and Grant Lake reservoirs (yellow), the drier climate makes full utilization of existing storage capacity more difficult and rare, reducing the average annual value of expanding storage.

These results illustrate many of the principles of water storage use and value in an integrated system. Storage value varies greatly with location, inflow climate, and water demand conditions.

A System-Based Pilot Simulation Analysis

To illustrate elements of our proposed systems-based approach using existing simulation models, we developed a pilot study of storage options in the Central Valley has been developed. The pilot analysis considers two simplified surface storage and two groundwater storage configurations, each facility having approximately 2 maf of storage capacity. One surface storage facility and one groundwater facility were located north of the Delta (in the Sacramento Valley), and one each south of the Delta (in the San Joaquin Valley). The hypothetical storage facilities were analyzed as integrated facilities within the intertied state and federal water system. For this pilot analysis, the size of the facilities was selected for illustration purposes and based on the authors' general sense of the size of additional storage that might be considered or proposed. The locations were selected not to mirror any specific storage proposals but to represent a range of geographic possibilities and general operational mechanisms within the intertied state system. For the analysis, the storage configurations are operated for both water supply and environmental flows. Management of the new storage is integrated with existing storage and conveyance to improve overall system efficiency. The pilot study's main assumptions are summarized in Table 5. Detailed assumptions are in Appendix A.

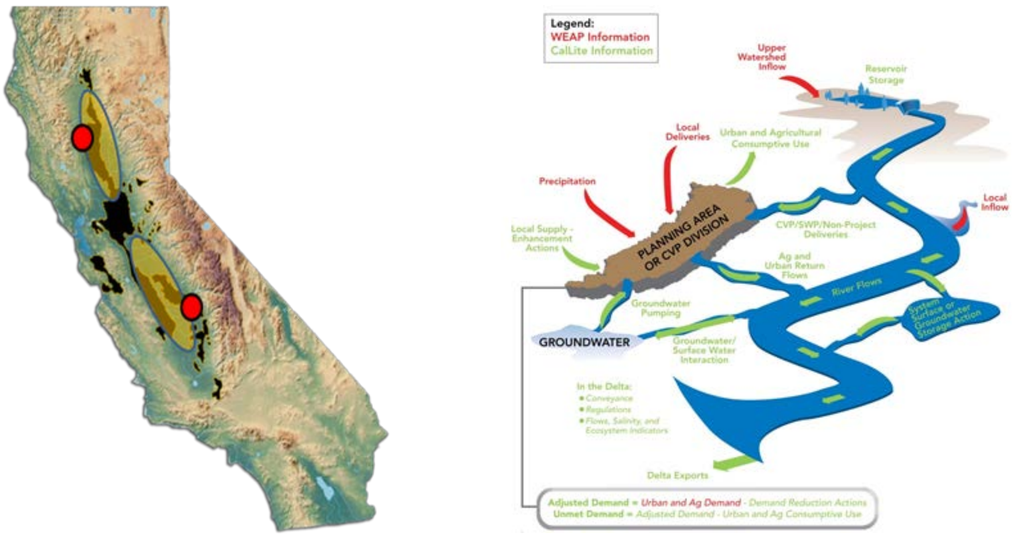
Table 5. Summary Description of the Pilot Study Storage Analysis

Characteristic	Description
Objectives	1. Improve dry-year water delivery reliability 2. Improved ability to meet Delta environmental flow and Sacramento River temperature objectives
Period of Evaluation	82 years of historical hydroclimate 1922-2003
New Surface Storage options	1. North of Delta off-stream surface storage of 2 maf with diversion from/to the Sacramento River; 2. South of Delta off-stream surface storage of 2 maf with conveyance from/to the California Aqueduct and Delta Mendota Canal
New Groundwater Storage options	1. Management of up to 2 maf of groundwater storage in the Sacramento area with conveyance integration with the American and Sacramento Rivers; 2. Management of up to 2 maf of groundwater storage in Madera County with conveyance integration with the San Joaquin River, Delta Mendota Canal, and Friant-Kern Canal
System Operational Assumptions	1. Diversions to new storage allowed only when environmental flows are already satisfied. 2. Allow pre-release from existing storage to new facilities to improve storage balancing. 3. Release storage from new facilities to increase performance against the two main objectives.
Future Climate and Socio-economic Cases	Historical hydrology, *Current Trends* socioeconomic conditions
Future Regulatory/ Delta Conveyance Assumptions	1. Existing Delta conveyance and regulations as described in BDCP No Action 2. Future Delta conveyance and regulations in the BDCP Alternative 4
Resources Evaluated	Water delivery, ecological, water quality, flood control, hydroelectric power, and recreation resources

The pilot study examined storage options with the CalLite water resources model as described in Appendix A. Historical hydrologic conditions were adopted from the Sacramento-San Joaquin Basins Study (Reclamation 2014b). Groundwater storage capacity and the ability to recharge and extract water from the aquifer was developed from California's C2VSIM groundwater-surface water system model (Brush et al. 2013) analyses and simplified for integration in the CalLite model simulations. C2VSIM is an application of the Integrated Water Flow Model (IWFM) to the Central Valley. A new version of the model with refined spatial discretization and grid network has been developed and is used for this study (Taghavi et al. 2013). Figure 11 depicts the general location of the surface and groundwater storage programs and the integrated hydrologic system included in the CalLite model.

A discussion of results from the model simulations is provided below to illustrate the types of insights that can come from more integrated system analysis.

Figure 11. General Location of the Surface and Groundwater Storage Programs and the Integrated Hydrologic System included in the CalLite Model



How Much Storage can be Effectively Used? (Use of Surface and Groundwater Storage).

The pilot analysis included simulations of each of the four storage options (two surface storage and two groundwater storage options) described above. An 82-year trace of storage in the surface facilities appears in Figure 12 for the historical climate. The additional Sacramento Valley surface storage fills during wet periods and is released during dry periods to improve water delivery reliability or to preserve coldwater pool reserves in existing reservoirs during these years. Most of water made available from the additional storage is used to provide otherwise unmet needs during drier years. This operation is typical for offstream reservoirs in California.

For the additional San Joaquin Valley (SJV) surface storage option, only about 300 to 400 taf, of the additional 2 maf of storage capacity made available in that region was effectively used. Storage up to approximately 1 maf is used once during an extended wet period. The limited use of SJV surface storage is largely due to limited availability of water from the Delta to fill the reservoir (assumed conveyance was limited to that which could be provided via California Aqueduct and Delta Mendota Canal). During wet periods, water must first meet existing demands and environmental requirements before diversions to the new storage can be considered. In addition to upstream demands, existing Delta conveyance limitations further constrain wet period diversions that might have helped fill the 2 maf of additional surface storage capacity in the San Joaquin Valley.

Figure 12. Simulated Use of Additional Sacramento Valley and San Joaquin Valley Surface Storage: ***Sacramento Valley can better use new surface storage alone than the San Joaquin Valley***, CalLite simulation results with the historical climate

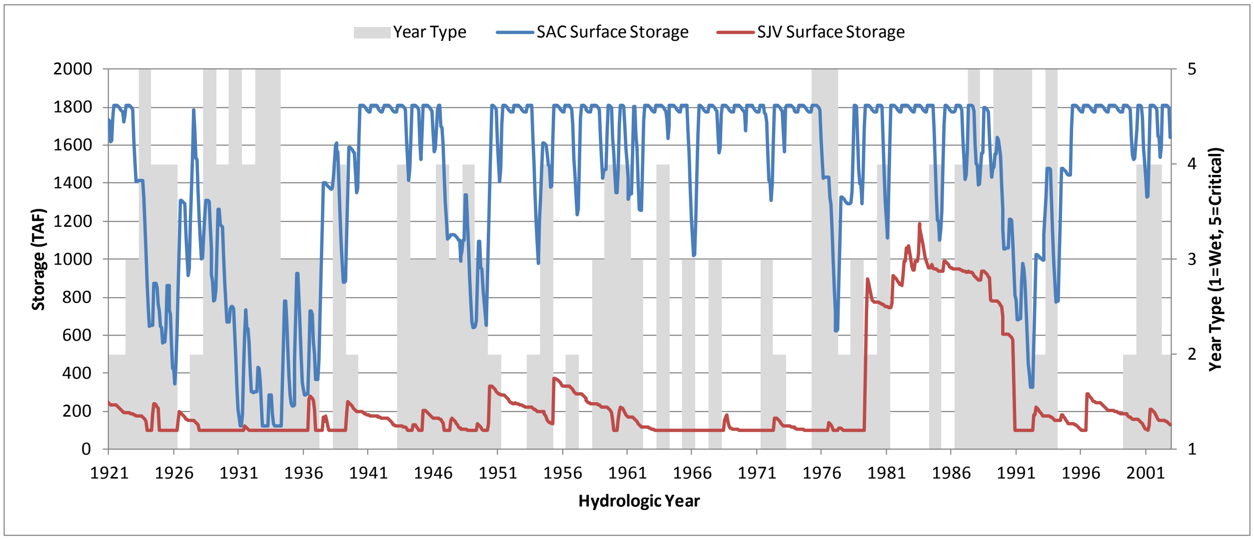
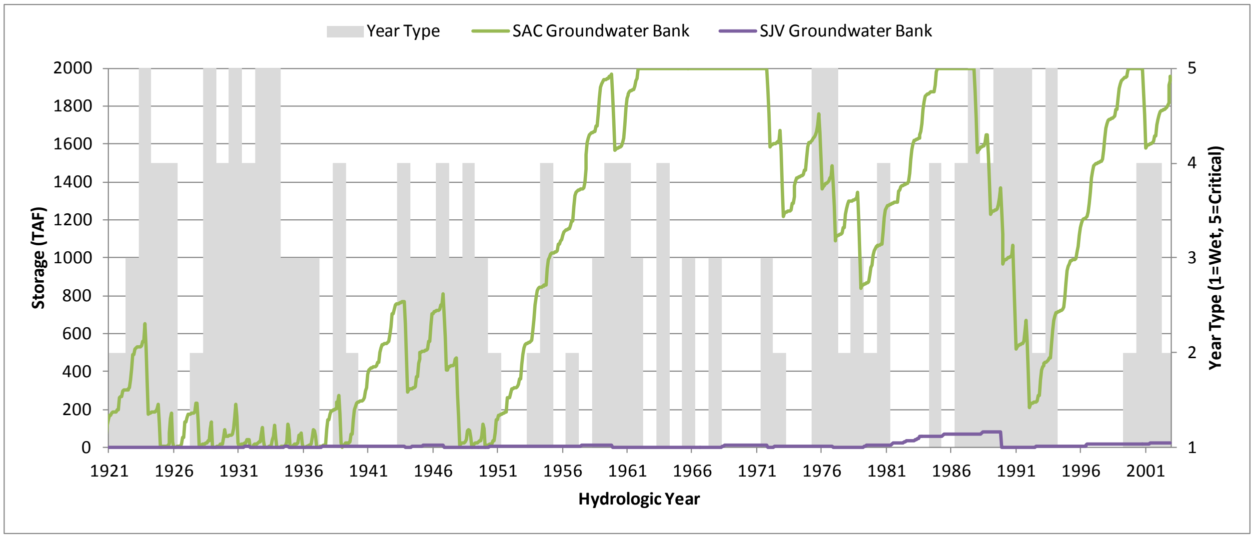


Figure 13 shows the similar 82-year period trace for the groundwater storage options considered in the Sacramento and San Joaquin Valleys for the historical climate. To get the maximum groundwater storage with minimal recharge facilities (and expense), of the three typical groundwater recharge methods (surface spreading, direct injection, or in-lieu recharge), the in-lieu recharge method was selected for this pilot study. "In-lieu" recharge programs supply existing groundwater users overlying a depleted aquifer with surface water during wetter years to increase groundwater levels due to reduced pumping in those times. Reduced groundwater pumping during the surface water delivery period allows groundwater that would have been pumped, to stay in storage and increase storage over time. During dry periods or periods with limited surface water supplies, banked groundwater becomes a source of supply. The seasonal operation of in-lieu groundwater banking depends on seasonal water demands and water availability. Since most water use for in-lieu operation is for agricultural purposes, surface water can be delivered in lieu of groundwater use only during the irrigation season. However, winter and spring is when excess surface water is most available, and when irrigation demands are the lowest. This seasonal mismatch between supply and demand limits in-lieu-based groundwater banking, especially if the operation is not integrated with larger system operations. As seen in Figure 13, about half of the available new groundwater storage capacity (about 1 maf) was used in the Sacramento Valley, until a long sequence of wet periods allowed the groundwater storage to fill. It is likely that an improved operation of the Sacramento Valley groundwater storage operated in this way would effectively use no more than 1.2 to 1.5 maf of storage capacity. In the San Joaquin Valley, however, less than 50 taf of groundwater storage capacity could be used due to inability to provide water for in-lieu demands, which do not coincide with the timing of greatest water availability from the Delta.

There are clear physical limits on useable additional surface and groundwater storage capacity in different parts of California under today's conveyance, climate, and policy and regulatory conditions. Under these conditions, larger amounts of storage capacity could not be utilized and would likely not be cost-effective.

Figure 13. Simulated Use of Sacramento Valley and San Joaquin Valley Groundwater Bank Storage: ***Sacramento Valley can better use expanded in-lieu groundwater storage alone than the San Joaquin Valley***, CalLite simulations for the historical climate



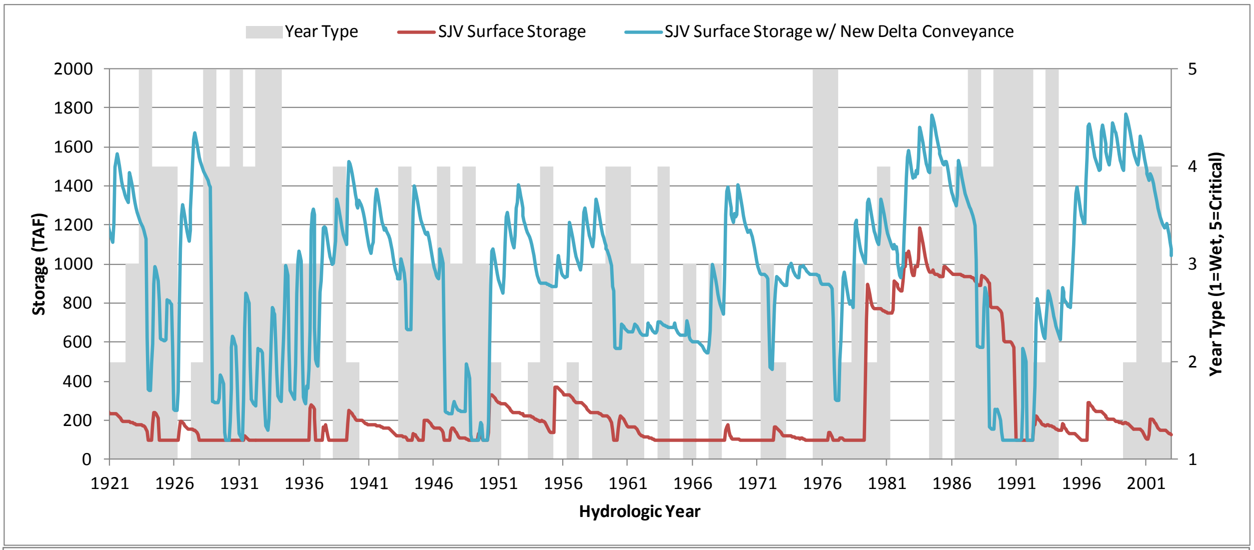
System Integration is Key (Sensitivity of Storage Operations to Delta Conveyance)

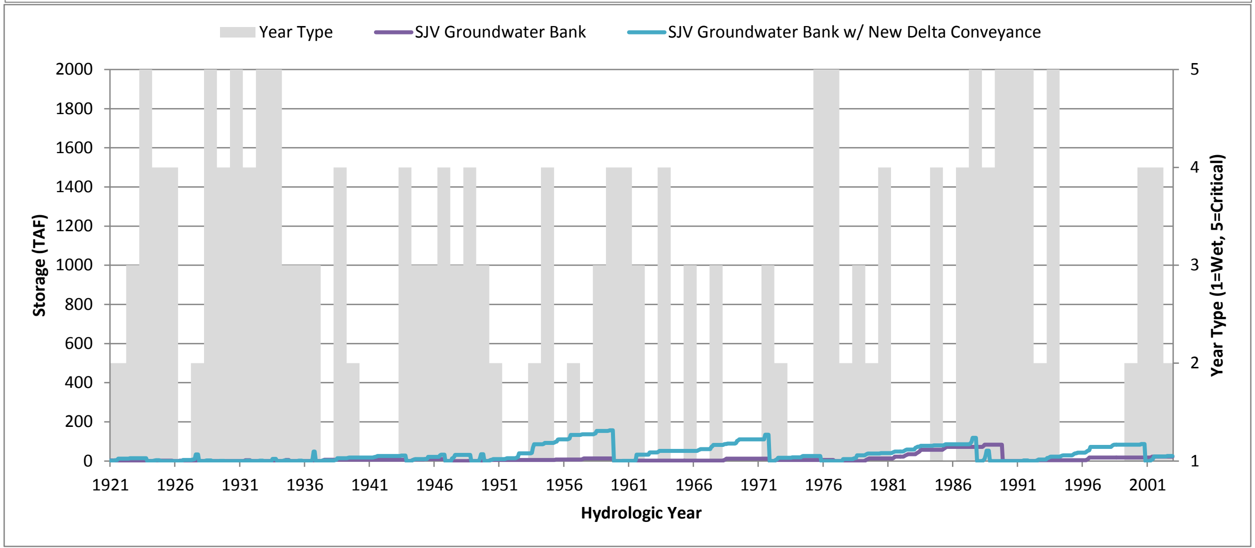
The use and benefits of storage depend strongly on other parts of the system. For this pilot we explored two major integration aspects that help us understand linkages with other infrastructure and conjunctive use options. First, we consider changes in the value of surface storage in the San Joaquin Valley with improved Delta conveyance. Second, we consider operating surface and groundwater storage in tandem to capitalize on their combined relative strengths.

Figure 14 shows the use of San Joaquin Valley surface storage under existing conveyance and with new conveyance similar to that described in the Bay Delta Conservation Plan (BDCP). While only a maximum of 1.2 maf of capacity was used with existing conveyance, nearly 1.8 maf could be used (and used much more frequently) in simulations with improved Delta conveyance. Improved conveyance allows more diversion of flows during wet periods and the new surface storage allows this water to be captured. While significantly more limited than surface storage use due in large part to the mismatch between when water was available and when it could be used for in-lieu recharge, SJV groundwater storage also was used more with improved Delta conveyance, with maximum use growing from 50 taf with existing conveyance to approximately 200 taf of new storage capacity with improved Delta conveyance.

Sacramento Valley storage utilization was relatively insensitive to Delta conveyance assumptions since current conveyance conditions in the Delta do not significantly constrain moving available water into the new Sacramento Valley storage locations.

Figure 14. Simulated Use of Additional San Joaquin Valley Surface Storage (top) and Groundwater Bank Storage (bottom) with Existing and New Delta Conveyance: *New Delta Conveyance makes San Joaquin Valley Surface Storage and Groundwater Bank Storage more useful*, CalLite with the historical climate





Integration of Surface and Groundwater Storage (Integration Magnifies Performance)

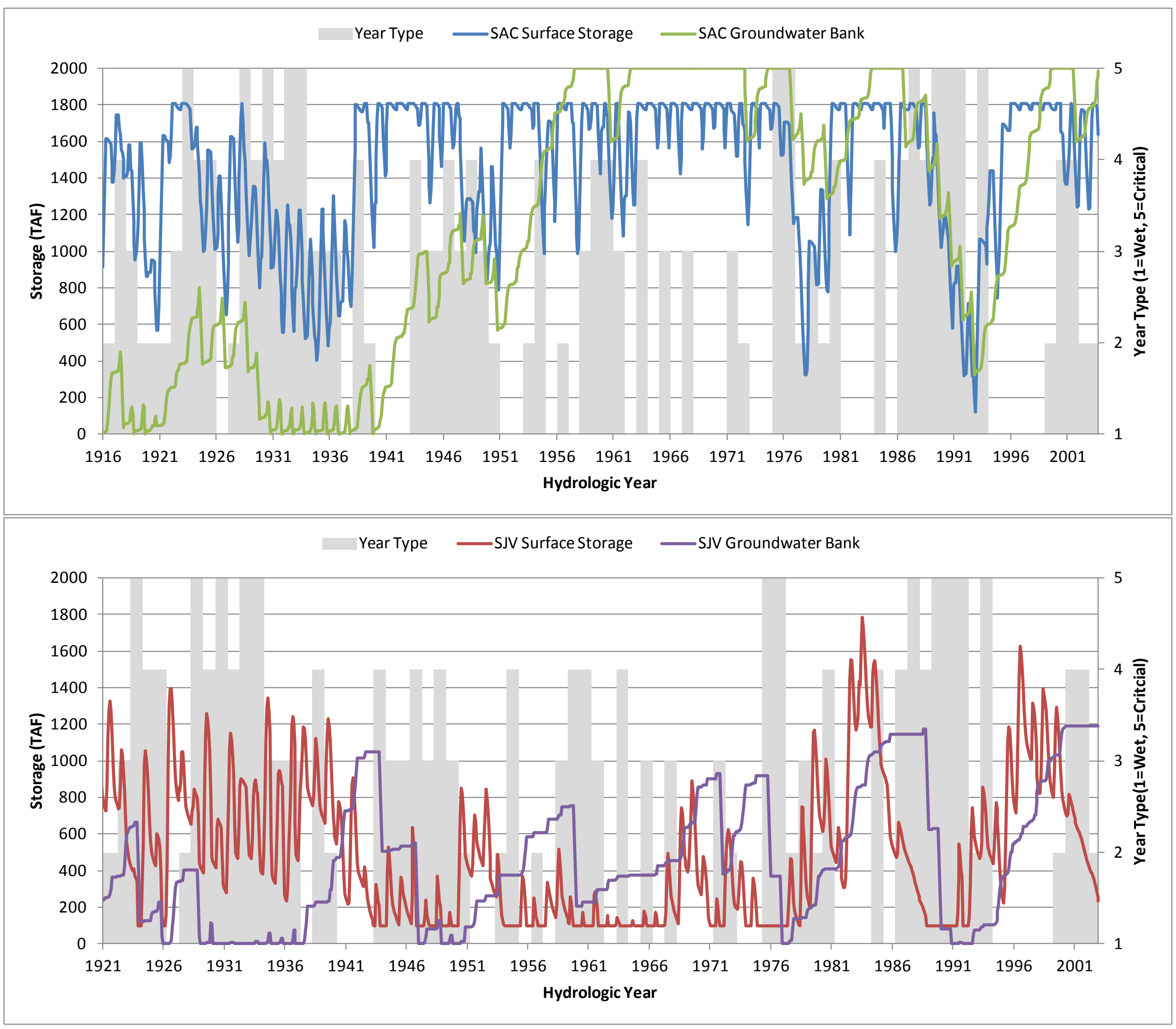
Surface and groundwater storage have historically been planned and managed as relatively independent resources.[2] However, enhanced integration of surface and groundwater storage could significantly improve water management, reduce rates of groundwater declines, adapt to climate change, and optimize new infrastructure investments (Jenkins et al 2004; Tanaka et al.

[2] A major exception is the Friant project which explicitly considered groundwater replenishment for parts of its service area.

2006). The pilot analysis included two simulations that specifically targeted integrated surface-groundwater storage operations to improve the combined use of these assets. In these simulations, surface storage was operated to store water that was available during wet periods (wet months or wet years), but then released water in late spring and summer and during dry periods as in-lieu supply for existing groundwater users. This operation increases the use of available groundwater storage capacity by employing surface storage as a "regulating" reservoir for short duration capture of surplus flows. Collectively, the integrated storage operation increases water deliveries significantly more than each storage type operated independently.

Figure 15 shows simulated use of the new storage options for integrated surface and groundwater storage operation in the Sacramento Valley (top panel) and San Joaquin Valley (bottom panel). Surface storage helps capture pulses of available supply such as in 1921-1923 and 1993-1999 periods. Water is then transferred from surface storage to supply existing groundwater users, who "augment" groundwater storage by reducing groundwater pumping. This integrated surface and groundwater bank storage operation reduces need for surface storage capacity while greatly increasing use of underground storage capacity.

Figure 15. Simulated Integrated Use of Sacramento Valley (top) and San Joaquin Valley (bottom) Surface and Groundwater Bank Storage with New Delta Conveyance, CalLite with historical climate



Integrating Surface and Groundwater Storage and Improving Conveyance

To show how other facility improvements, such as improved conveyance, affect the use of new storage capacity, we evaluated the new storage options with improved Delta conveyance and a more integrated operation of the surface and groundwater storage options. Table 6 summarizes storage capacity utilization for different combinations of surface and groundwater storage and Delta conveyance and integrated storage operations.

Use of additional Sacramento Valley storage capacity is less affected by Delta conveyance assumptions. Nearly 2 maf of new surface storage and 2 maf of new groundwater storage located in the Sacramento Valley can be utilized. However, use of additional storage located in the San Joaquin Valley is highly sensitive to the Delta conveyance assumptions. Surface storage use is nearly two times higher with new Delta conveyance than with existing Delta conveyance. Additional groundwater bank storage utilization in the San Joaquin Valley is relatively small with existing conveyance and regulations, but increases greatly with improved Delta conveyance. Conveyance and integration affect the ability to make use of storage capacity in different parts of the state.

Table 6. Summary of Maximum Storage Utilization for Different Delta Conveyance and Integrated Surface and Groundwater Storage Combinations, CalLite with historical climate (Values in parentheses are storage utilization computed as the storage use exceeded in only 10 percent of years)

Storage	Existing Delta Conveyance	Integrated SW and GW Operations w/ Existing Delta Conveyance	New Delta Conveyance	Integrated SW and GW Operations with New Delta Conveyance
Sacramento Valley				
Surface Storage	1.8 maf (1.8 maf)	1.8 maf (1.8 maf)	1.8 maf (1.8 maf)	1.8 maf (1.8 maf)
Groundwater	2.0 maf (2.0 maf)	2.0 maf (2.0 maf)	2.0 maf (2.0 maf)	2.0 maf (2.0 maf)
San Joaquin Valley				
Surface Storage	1.2 maf (800 taf)	900 taf (100 taf)*	1.8 maf (1.5 maf)	1.4 maf (1.0 maf)
Groundwater	< 50 taf (<50 taf)	<200 taf (<200 taf)	<200 taf (<100 taf)	1.1 maf (1.0 maf)
Total				
Total Storage Utilization	5.0 maf (4.6 maf)	4.9 maf (4.1 maf)	5.8 maf (5.4 maf)	6.3 maf (5.8 maf)

*When SAC storage is integrated with SJV storage, excess Delta supply that would have been stored in SJV is diverted to SAC storage. Existing conveyance limits opportunities to use BOTH surface storage options effectively.

Performance of Storage Programs for Water Delivery and Ecological Metrics

So far our results have only reported storage utilization, but storage utilization is not a fundamental objective for a water system. More useful measures of the value of storage are based on how much additional water it provides for beneficial uses. Accordingly, we turn next to more relevant metrics of water delivery and ecological performance.

Each storage option also was evaluated for improvements in water delivery and ecological metrics. Figure 16 shows a summary of the increases in SWP and CVP water deliveries south of the Delta for each storage and conveyance case. The left group of columns show simulated delivery improvements for the different storage options with existing Delta conveyance. The expanded Sacramento Valley storage increases water deliveries by 200 to 400 taf/yr, with larger increases in the driest years. Expanded San Joaquin Valley surface storage capacity shows benefits of up to 100 taf/yr while delivery improvements are very small with San Joaquin Valley groundwater storage with existing Delta conveyance.

Combining storage expansion options with improved Delta conveyance, shown in the group of columns to the right, increases deliveries by 600 to 900 taf/yr beyond the individual storage options. Integrating the operation of surface and groundwater storage options together with improved Delta conveyance improves water deliveries by of over 1 maf/yr.

These increases in water deliveries were achieved while maintaining ecological flows (as defined) in the Sacramento River and Delta. Critical storage levels in Shasta Lake and Folsom Lake, which indicates coldwater pool management capability, were similar in most storage simulations. Simulations with expanded Sacramento Valley storage generally made small improvements in the frequency of achieving these critical cold water storage levels in Shasta Lake (less than 5 percent increases). Future work could refine operations modeling with an aim to achieve greater upstream cold water storage protection with limited impacts on water delivery.

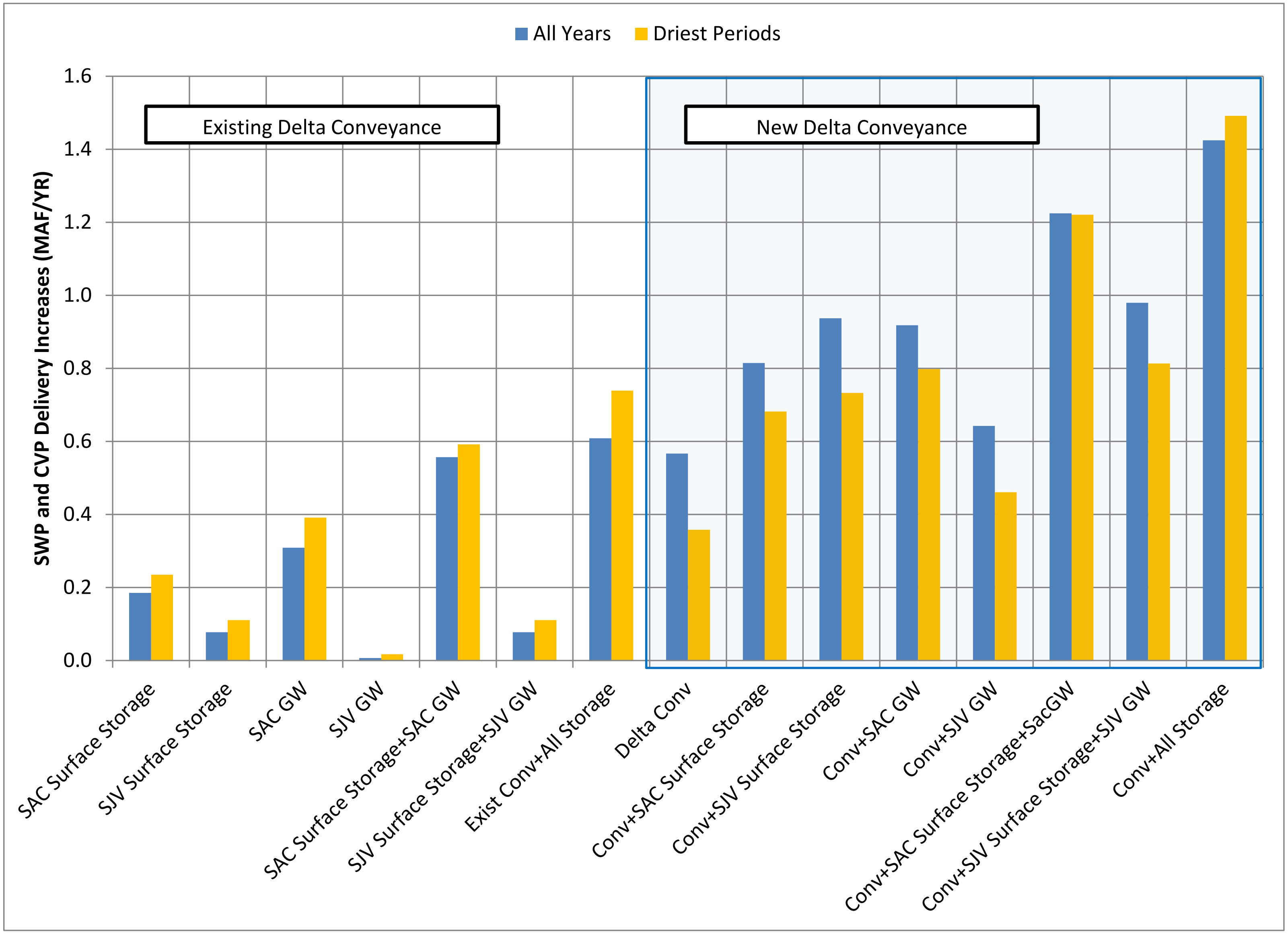
For convenience and ease of interpretation in this pilot study, water delivery improvements are analyzed and reported in terms of how much additional water might be supplied to known demands, and in the case of Figure 16, demands south of the Delta. Portions of these additional water supplies also could be provided to environmental needs such as Delta outflows and Central Valley wetlands. Future work, beyond the scope of this study, could investigate more fully the possibilities for additional storage to provide water supplies for environmental needs.

Expanding an Integrated Approach

For broader application, designed to explore and design particular portfolios of storage and other actions, it would be desirable to expand this type of analysis to include several other aspects of integration. These additional features would include:

- Examination of anticipated or likely climate changes
- Identification and evaluation of ecological implications of surface and groundwater management actions
- Additional conveyance and groundwater alternatives
- Evaluation of local groundwater banking opportunities
- Water demand management activities
- Economic costs and values of alternatives
- Ecological implications of various storage alternatives.

Figure 16. Average South of Delta Water Delivery Increases for Various Storage Options and Delta Conveyance Assumptions: *More integrated water management greatly increases Water Deliveries for Various Storage and Conveyance Conditions*, CalLite with historical climate



Insights from an Integrated Approach

A systems-based approach can offer new insights for understanding the value and limitations of water storage and for developing future storage strategies in the context of a more comprehensive water management vision. The major insights from our pilot simulation analysis include:

- Benefits of expanded storage depend strongly on its location and connections with the integrated system.
- Additional surface and groundwater storage in the Sacramento Valley, when operated as integrated storage units, can increase water deliveries and improve coldwater pool conditions.
- Additional surface storage in the San Joaquin Valley can improve dry-year water deliveries, but it is only effectively utilized with improved Delta conveyance.
- Additional groundwater storage helps improve seasonal and long-term water availability and drought protection in the Sacramento Valley and San Joaquin Basin.
- Integrating storage operations greatly improves benefits north and/or south of the Delta for short-term water deliveries and long-term drought reliability.
- Large scale in-lieu groundwater banking is more productive if planned and operated in coordination with surface storage to regulate wet period surface supplies to improve dry period groundwater deliveries. Peak seasonal flows alone are too infrequent and short in duration to provide much groundwater recharge benefit. Surface storage provides regulating capacity to improve groundwater recharge. Some investment in surface storage can expand groundwater recharge, within limits of water availability.
- Total surface and groundwater storage capacity increases of 2 to 4 maf in the Sacramento Valley and 1 to 2.5 maf in the San Joaquin Valley can be utilized to provide additional water deliveries. New storage capacity beyond these levels seems unlikely to substantially increase water deliveries.
- System-based integrated approaches allow for multiple purposes and highlight their tradeoffs and synergies of different types of projects, particularly groundwater and surface water storage possibilities.
- Groundwater recharge seasons and rates significantly constrain large scale use of in-lieu recharge for agricultural pumpers. Some additional recharge can occur using surface storage as a forebay for delivering water for in-lieu recharge. Further analysis of potential aquifer recharge system-wide, such as considering winter recharge over agricultural lands and artificial recharge, might provide additional local and regional opportunities to make use of existing groundwater storage capacity.
- These simulation results agree well with similar results from less constrained optimization modeling.

Conclusions

Both surface water and groundwater storage are important for water management in California. As a result of passage of Proposition 1, the 2014 Water Bond, the potential and value of additional water storage in California is an area of vigorous discussion. This paper reviews the roles of storage in California's integrated water system and provides some insights from a systems-based approach for evaluating additional storage capacity. The pilot study in this paper is a "proof-of-concept" demonstration of a systems-based approach, which yields insights on storage opportunities and challenges. Further application of such a systems-based approach will further improve understanding of surface and/or groundwater storage as part of addressing California's larger water management challenges.

Overall, the pilot study results indicate that integrated water infrastructure programs are likely to significantly outperform individual projects in achieving multiple water management objectives, including water supply reliability, healthy ecosystems, and flood protection. A system analysis approach will best identify specific storage and other projects to meet these objectives.

Several additional high-level conclusions can be drawn from the results:

1. In California, additional surface water and groundwater storage capacity will be more effective if planned, designed and operated as components of an integrated state-wide system. Additional surface storage and groundwater storage capacity and locations must be integrated with other conveyance, operating, and conservation decisions and policies to serve California's diverse present and changing water needs.
2. A systems-based analytical approach, where new projects are evaluated in conjunction with re-operation of many parts of the state water system, can identify promising and effective actions to achieve multiple objectives.
3. Conveyance limitations in the Delta are a major impediment to the state's ability to achieve its "co-equal" water management goals of reducing reliance on the Delta as a water supply source and conserving habitat and species in the Delta, and the ability to make full utilization of surface water and groundwater storage capacity. Improving Delta conveyance and integrating operations greatly increase the additional deliveries possible per unit of additional storage capacity.
4. There is some potential for expanded storage to improve cold water pools and flows for fish in dry periods.
5. No more than 5 to 6 maf of expanded groundwater and surface water storage capacity (2 to 4 maf north and 1 to 2.5 maf south of the Delta) can be effectively utilized in the Central Valley for large-scale water delivery. However, the economic and environmental impacts and benefits of such expansions might not justify the costs of such projects.
6. Storage is one component of a very integrated water system, and integrated water management requires that water supply, water demand, and system improvements be considered together.

Recommendations

Water storage and infrastructure re-configuration are topics of active and animated discussion in California, particularly during the current drought. This study suggests several promising actions for stakeholders and agencies interested in integrated performance-oriented analysis of potential storage and other infrastructure changes for California's water supply system.

1. Studies examining water storage, and water management more generally, should explicitly consider potential for integrating surface and groundwater storage, as well as conveyance and water demand management. Given the demonstrated benefits of integrated management, a transformation is needed in how agencies and stakeholders think about conducting water infrastructure studies. Recent state groundwater legislation could be instrumental in supporting such coordination at regional and local levels.
2. There is a need for more explicit and proactive consideration of potential ecological benefits of surface and groundwater storage in studies of water management infrastructure and operations. Active engagement of environmental advocates and wildlife resource agencies in shaping the exploration and development of infrastructure and operations proposals is critical for strengthening the ecologic function of future projects.
3. Recent studies of water management infrastructure have not proceeded in timely, transparent, collaborative, or cost-effective ways. It may be time to develop an independent, alternative entity with the business and technical capability to bring together state and federal regulatory and project agencies with local benefitting agencies and independent and academic technical expertise to conduct more systematically integrated studies of water infrastructure and operations for multiple purposes.

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Appendix A
Pilot Study Storage Options and Assumptions

Introduction

To illustrate elements of the proposed systems-based approach, a pilot study of storage options in the Central Valley has been developed using the CalLite water resources model. The pilot analysis considers two simplified surface storage and two groundwater storage configurations in the Sacramento and San Joaquin Valleys, and illustrates the potential range of benefits that could be derived from the integration of storage features under alternative system assumptions. Various combinations of surface and groundwater storage options combined with Delta conveyance assumptions were evaluated to illustrate the dependence of the storage operation and benefits on the ability of the conveyance system to integrate such new features.

CalLite Water Resources Systems Model

The CalLite water resources system model was used to evaluate the operation and integration of potential storage options. The CalLite model is a screening model of the Central Valley intertied water resources system and includes the major rivers and water management features in the Sacramento Valley, San Joaquin Valley, and Tulare Lake watersheds (Reclamation 2014b). Operation of all major SWP, CVP, and local project reservoirs, Delta diversion facilities, and the California Aqueduct and Delta Mendota Canal are explicitly simulated in the CalLite model. The CalLite model includes dynamic accounting of flow-salinity relationships in the Delta, Delta requirements under various regulatory conditions, and dynamic allocation decisions for water deliveries to municipal, agricultural, and environmental uses. Groundwater is dynamically integrated with the surface water system in the CalLite model through the inclusion of groundwater basin elements that transmit flow to and from the surface water system.

The current version of the CalLite model utilizes projected water demands based on planning area estimates of population, land use, and irrigated acreage through 2100. The socioeconomic assumptions are generally consistent with those described as *Current Trends* scenario in the 2013 California Water Plan. Hydrology assumptions were based on a repeat of historical 1915-2003 hydroclimate with future projected land use assumptions. The assessment of future demands and upper watershed river flows were derived from WEAP modeling using the socioeconomic and climate assumptions.

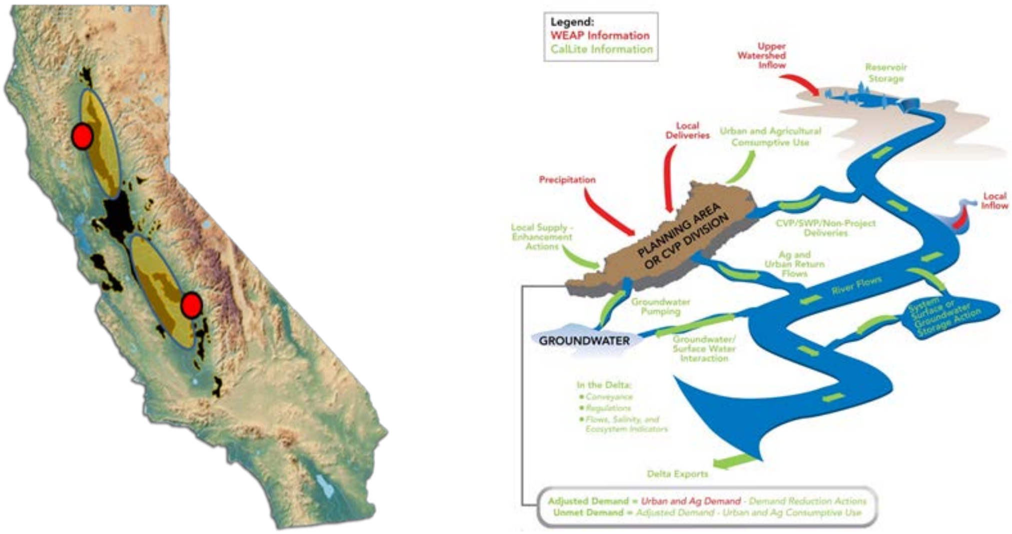
For this evaluation, the CalLite model was improved to include new offstream surface storage reservoirs and groundwater storage banks in the Sacramento Valley and San Joaquin Valley. Groundwater storage capacity and the ability to recharge and extract water from the aquifers was developed from California's C2VSIM groundwater-surface water system model (Brush et al. 2013) analyses and simplified for integration in the CalLite model simulations. These new storage features were simulated as being integrated with the SWP and CVP system in the Central Valley. Assumptions related to these new storage features are included in the following section.

Storage Options and Assumptions

The pilot study evaluated the addition of up to four new storage options integrated into the Central Valley water resources system. Each storage facility was assumed to be sized to permit up to 2 maf of storage capacity. One surface storage facility and one groundwater facility were located north of the Delta (in the Sacramento Valley), and one each south of the Delta (in the San

Joaquin Valley). The storage facilities were analyzed as integrated facilities within the intertied state and federal water system. For this pilot study, the storage configurations are operated for both water supply and environmental flows. Figure A-1 depicts the general location of the surface and groundwater storage programs and the integrated hydrologic system included in the CalLite model.

Figure A-1. General Location of the surface and Groundwater Storage Programs and the Integrated Hydrologic System included in the CalLite Model



The pilot study's storage option assumptions are summarized below:

<u>New Sacramento Valley Surface Storage</u>

- Up to 2 maf of new offstream storage located in the Sacramento Valley
- Sacramento River diversion physical conveyance of up to 6,000 cfs during November through March
- River diversion (reservoir fill) permitted only during November through March high river flow periods and after downstream environmental flows are satisfied
- Releases from storage back to the Sacramento River for SWP and CVP integration were limited to 3,000 cfs and only when either Oroville storage fell below 2.2 maf or Shasta storage fell below 3.0 maf. The Oroville and Shasta storage triggers were used as surrogate indicators when the SWP and CVP upstream storage operations would most greatly benefit from additional supply.
- Release from storage to meet local Sacramento Valley demands was limited to 1,500 cfs during April through October

<u>New Sacramento Valley Groundwater Storage</u>

- Up to 2 maf of groundwater storage in the southern end of the Sacramento Valley

- Sacramento River diversion physical conveyance of up to 2,000 cfs during November through March to provide "in-lieu" supply to overlying groundwater users. This is the "in-lieu" groundwater banking operations. Up to 75% of overlying groundwater demands assumed could be provide with "in-lieu" surface water when available.
- Groundwater bank was allowed to accrue water only when overlying demand could be supplied by alternative surface water supply.
- Releases from storage back to the American River or Sacramento River during July through August to support SWP and CVP integration were limited to 3,000 cfs and only when either allocation to water delivery contractors fell below 70%.

<u>New San Joaquin Valley Surface Storage</u>

- Up to 2 maf of new offstream storage located in the San Joaquin Valley and connected to the California Aqueduct and/or Delta Mendota Canal conveyance
- Diversion to storage required available supply and conveyance capacity at the Delta diversion facilities (existing and proposed)
- Diversion to new storage only permitted with surplus water after all Delta flow requirements were satisfied, existing San Luis Reservoir was filled, and SWP Article 21 demands were met.
- Releases from new storage to the California Aqueduct or Delta Mendota Canal were provided (if water was available in storage) July through August when the allocation to water delivery contractors fell below 70%.

<u>New San Joaquin Valley Surface Storage</u>

- Up to 2 maf of groundwater bank storage located in the San Joaquin Valley and connected to the California Aqueduct and/or Delta Mendota Canal conveyance
- Diversion to storage required available supply and conveyance capacity at the Delta diversion facilities (existing and proposed) to provide "in-lieu" supply to overlying groundwater users. This is the "in-lieu" groundwater banking operations. Up to 75% of overlying groundwater demands assumed could be provide with "in-lieu" surface water when available.
- Diversion to the groundwater bank only permitted with surplus water after all Delta flow requirements were satisfied, existing San Luis Reservoir was filled, and SWP Article 21 demands were met.
- Releases from new storage to the connected users of the California Aqueduct or Delta Mendota Canal were provided (if water was available in storage) July through August when the allocation to water delivery contractors fell below 70%.

<u>Delta Conveyance Assumptions</u>

Two sets of assumptions were included depending on the scenario:

1. Existing Delta conveyance facilities and regulatory requirements
2. Proposed future north delta conveyance of up to 9,000 cfs diversion with bypass flows as assumed under the Bay Delta Conservation Plan, and existing regulatory requirements

<u>Integrated Surface-Groundwater Storage Operations</u>

In scenarios in which new surface storage was operated conjunctively with new groundwater banks, the surface storage was used as the primary storage location for available surface supply. Water was then released from surface storage to meet the overlying groundwater demands through and "in-lieu" operations. Essentially, the surface storage was operated as a regulating reservoir to maximize the benefits of the in-lieu groundwater operation.

<u>Limitations</u>

The CalLite storage options and scenarios developed as part of this pilot study should be considered conceptual in nature, and were developed to demonstrate the value of a systems-based approach toward storage evaluations. Specific storage sites, connectivity with existing and proposed conveyance, and access to additional supplies will significantly influence the operations and benefits of storage features. This pilot study should be viewed as demonstrative of the types of further evaluations that may be undertaken to better inform the role of storage, but more detailed evaluations would necessarily need to be performed to refine any operations or estimates derived from this pilot study.