Climate change and water-related ecosystem services: impacts of drought in California, USA

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Abstract. We investigated the potential impacts of climate change on water-related ecosystem services (WES). Based on the review of the recent literature, we concluded that climate change will have substantial effects on provisioning, regulating, and cultural WES via changes in the distribution and value of water over space and time. However, the effects of climate change on specific WES will be different depending on the extent of the impact of such changes in the distribution of water and the adaptive capacity of the region's biophysical and social system. The 2015 California drought provides an excellent example of the cascading effects of climate change on multiple WES. Declining streamflow and the concomitant rising stream temperatures have immediately threatened the provision of drinking water and hydropower generation and threatened the health of ecosystems that rely on water. The secondary effects of drought on WES are widespread across different water-dependent industries, including water-based recreation. The findings of our study also show that the impacts of climate change will differ by location, suggesting a need for a place-based flexible climate adaptation strategy. We also suggest that future research directions include the examination of: (1) the multiple cascading effects of climate change on potential synergies and tradeoffs among different WES, (2) the specific effects of changing climate and the connectivity of WES from upstream to downstream WES users, (3) the changing value of WES over space and time under changing climates, and (4) the effectiveness of various climate adaptation measures on the whole suite of WES.

Key words: California; climate change; drought; hydrology; water-related ecosystem services.

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Introduction

Water-related ecosystem services (WES) are the benefits obtained from ecosystems for which ecosystem composition, structure, and function are reliant on a supply of water (Brauman 2015). Any waterbodies such as rivers, springs, wetlands, lakes, reservoirs, and swamps offer space for ecosystems and contain specific ecosystem structures and functions. Throughout history, humans have used these water bodies for economic, social, cultural, and spiritual purposes. As such, these water bodies deliver provisioning, regulating, and cultural ecosystem services, and thus have both instrumental and intrinsic values to humans and ecosystems. The value of WES is subject to the spatial and temporal availability of water on the landscape and relative proximity to human populations. Even in relatively water-rich regions, the value of WES can be high during periods of scarcity (Jaeger et al. 2013). While there have been numerous studies investigating land use change impacts on WES (Brauman et al. 2014, Gao et al. 2016), only a few studies examined climate change impacts on WES (e.g., Nelson et al. 2013, Hoyer and Chang 2014, Lorencova et al. 2016).

As climate change modifies the water cycle via changes in the spatial and temporal distribution of precipitation and the form of precipitation (e.g., snow vs. rain) on Earth, WES is projected to change in coming decades (Fig. 1). Even though mean annual water availability may remain the same under a changing climate, the amplified seasonality of water availability and increased frequency of extreme hydrologic events will have substantial effects on WES. For example, in high alpine watersheds, rising air temperatures will bring more rain than snow in winter and result in less snow accumulation and earlier snowmelt (Barnett et al. 2005), thus limiting summer water supply when humans and ecosystems need water most. Additionally, climate change may shift the distribution of rainfall events with more extreme weather events, which may lead to more frequent floods and droughts. According to the IPCC 5th assessment report, flood probability is projected to rise in mid-latitudes where the majority of the world population resides (Jiménez Cisneros et al. 2014). Such extreme weather events may exceed the drainage basin’s capacity to regulate floods, thus damaging
communities that are prone to floods. For example, changes in the amount and timing of freshwater inputs to estuaries change salinity, negatively affecting fish species that have been adapted to salinity for a long time.

Drought frequency is projected to increase under climate change scenarios (e.g., Jung and Chang 2011). The recent California drought is one of the most salient examples that have had substantial impacts on society and environment in the immediately affected regions and beyond (Ashoori et al. 2015). The drought, which has lasted for 5 yr, has also caused major environmental and economic consequences around the country, because California grows more than a third of America’s vegetables and two-thirds of its fruit and nuts (US Department of Agriculture 2016). In this paper, we first provide a general review of the potential effects of climate change on WES from a global perspective, focusing on the regions of Mediterranean climates. We then discuss climate change impacts on an individual WES using the California drought as a case study. Finally, we offer some potential climate adaptation strategies for WES in the California region.

**Effects of Climate Change on WES in the Mediterranean Climate Region**

**Effects on provisioning services**

As climate change will perturb the water cycle via changes in the spatial and temporal distribution of water storage, many provisioning WES will shift in the Mediterranean climate. The specific effects of climate change on WES will differ by region, where the value of WES and local watersheds’ responses to climate change will be mediated by the capacity of the natural and human systems.

**Water provision**

There have been many recent studies focusing on the effects of climate change on water yield in the Mediterranean climates worldwide (Table 1). Regions with Mediterranean climates are considered to be most vulnerable to climate change due to their strong seasonality of precipitation, high irrigation water demand, and dense and growing populations. In Europe, the Mediterranean climate regions will be most vulnerable to climate change. By 2080, 20–38% of the population in these regions will be living in areas of increased water stress. Water supply at peak demand times will be reduced, and the risk of winter floods will increase (Schröter et al. 2005). A study by Bangash et al. (2013) on the Llobregat basin (Catalonia, NE Spain) shows that water provisioning in the basin is highly sensitive to climate change, and water supply and delivery are likely to decline significantly. A subsequent study in the same basin shows that annual water volume in the basin decreased 80% from normal in dry years and increased 160% in wet years, corroborating the sensitivity of the region to severe climate shifts (Terrado et al. 2014).

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**Fig. 1.** Cascading effects of climate change on water-related ecosystem services.
Table 1. Potential impacts of climate variability and change on water ecosystem services (WES) in the Mediterranean climates.

| Author (year) | Study area (Elevation/size) | Climate scenarios | Data period | Models | Ecosystem services | Major findings |
|---------------|-----------------------------|-------------------|-------------|--------|-------------------|----------------|
| Williamson et al. (2016) | Lake Tahoe (1897 m, 490 km²), Lake Giles (428 m, 0.47 km²) | Analog historical scenarios (extreme events) | 2014–2015 (Drought), 2013–2014 (Wildfire), 1999–2011 (Flooding) | Literature review, descriptive statistics | Water quality, biodiversity (As a result of UV Radiation levels) | Drought leads to increases in UV radiation penetration in lakes and reservoirs.
Wildfires lead to decreases in UV radiation penetration in lakes and reservoirs.
Floods lead to reductions in UV radiation penetration in lakes and reservoirs. |
| Carvalho-Santos et al. (2016) | Vez Watershed, Portugal (30–1400 m, 252 km²) | Ensemble of 4 RCP 4.5 GCMs (CNRM-CM5, CSIRO-MK3.6, MRI-CGCM3, MPI-ESM-LR) | 2021–2040, 2041–2060 (2003–2008 for model calibration, 1984–1989 for validation of flow) | Soil and Water Assessment Tool (SWAT), Linear regression | Water quantity, Water supply timing, Water quality, Erosion control, Flood regulation | Climate change will reduce annual water yield by 7% and 15%–38% summer, increase soil erosion, and increase nitrates.
The combining effects of land use will increase or decrease changes in the ecosystem services. |
| Leitinger et al. (2015) | Lautaret (France, 1650–2500 m, 12.92 km²), Stubai (Austria, 970–2200 m, 4.93 km²) | Dry vs. normal scenarios (summer precipitation reduced by 43% and 36% of normal) | Historical period | HILLFLOW Hydrological Model | Soil moisture, Water quality | Soil moisture reduced by 23%–43% during dry conditions. Different grassland types can somewhat mitigate these effects.
With drought conditions, soil fertility will decrease and water quality will increase in the short term. |
| Terrado et al. (2014) | Llobregat basin, Spain (4950 km²) | Historical climate variability (extreme wet and dry conditions) | 1950–2000 | Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) | Drinking water, Hydropower production, Erosion control | Average annual water decreased 80% in dry years and increased 160% in wet years.
Nutrient loads decreased in dry years (11.4%) and increased in wet years (6.4%).
The significance of the response varied dramatically throughout the basin.
Erosion increased during wet years (64%–71%), but the effects were not homogeneous in the basin.
Surface water shortages are primarily offset by increased groundwater pumping.
Water shortages of 2.7 million acre-feet will cause $40,000 acres of farm land to be fallowed in 2015.
Drought will have direct costs of $1.84 billion and 10,100 seasonal jobs in 2015. Total economic impact could reach $2.74 billion when other effects are considered. 
Increased groundwater overdraft throughout the drought period will slowly deplete groundwater reserves. |
| Howitt et al. (2015) | California | Historical drought | 2015 drought | The Statewide Agricultural Production (SWAP) Economic Model, surface–groundwater simulation model (C2VSim) | Irrigation water, agricultural production | | |
| Author(s) | Study area (Elevation/size) | Climate scenarios | Data period | Models | Ecosystem services | Major findings |
|-----------|-----------------------------|-------------------|-------------|--------|-------------------|----------------|
| Bangash et al. (2013) | Llobregat basin, Spain (4957 km²) | Precipitation changed from +2 to −16% AET change to −2% to 5% | 2001–2100 | InVEST | Water yield, Water scarcity, Soil loss, Hydropower generation | Water provisioning (3%–42% reduction) and erosion control are highly sensitive to climate change in this basin. Hydropower generation reduced by 5%–43%. Sediment retention will be reduced by 0–23%. |
| Molina-Navarro et al. (2014) | Ompolveda River catchment, Spain (88 km², 718–1137 m) | Temperature increase 1.3–3.9°C; precipitation −2.9 to −11.5% | 2000–2100 (2046–2065 and 2081–2100) | SWAT | Water supply, nutrients | Climate change is projected to decrease discharge by 48.7% in the 2081–2100 period. Most scenarios predict a deterioration of trophic conditions, threatening water quality. |
| Schröter et al. (2005) | Europe | HadCM3 NCAR-PCM CGCM2 CSIRO2 B1, B2, A1FI, A2 2.1–3.4°C increase | 2000–2080 | Macroscale hydrology model | Water supply, Crop area | By 2080, 20%–38% of the population in Mediterranean regions would be living in areas of increased water stress. Water supply at peak demand times will be reduced, and the risk of winter floods will increase. The Mediterranean region will be most vulnerable to climate change—risk of water shortages, forest fires, northward shifting of tree species, and loss of agricultural potential. The economic cost of WES losses in the SA-MDB during the Millennium Drought was nearly $810 million. Most losses were provisioning and regulating services. |
| Banerjee et al. (2013) | Southern Australia Murray Daring basin (SA-MDB), Australia (1,061,469 km²) | Australia’s Millennium Drought | 1997–2010 | Cost-based methods (defensive expenditure, mitigation expenditure, and damage cost methods) M5 model Bivariate habitat duration curves | Water supply, Food production, Water regulation, Soil retention, Turbidity mitigation, Biodiversity recreation, Water quantity, Stream temperature, Habit suitability | 25% reduction in mean summer flow. Increase in water temperature of +4%. Increase in the number of days with less suitable habitat. 10%–30% decline in freshwater resources. Agricultural sector will be mostly severely affected. Proactive adaptation could mitigate negative consequences. Groundwater recharge decrease by 21%–31%. Streamflow decrease by 16%–23%. Wheat yield decrease between 2.2% and 10.4%. |
| Muñoz-Mas et al. (2016) | Cabriel River in Spain (4750 km², 490–1790 m) | CCCma-CanESM2 ICHEC-EC-EARTH (RCP 4.5 and 8.5) | 2011–2040 | | | |
| Koutroulis et al. (2016) | Crete Island (8303 km², 0–2450 m) | EURO-CORDEX (RCP 2.6, 4.5, and 8.5) 2–3°C rise | Mid- and late 21st century | SAC-SMA Sacramento model | Water supply, Water demand, Construction cost | |
| D’Agostino et al. (2010) | Candelaro catchment (1778 km²) | Winter rainfall 5%–10% reduction | 2050 | DiCsSM | Water supply, Groundwater, Wheat yield | |

Table 1. Continued.
Another study focusing on the Ompolveda river catchment in central Spain shows that climate change will have a noticeable impact on flow regime with the period from 2081 to 2100 experiencing a decrease in river discharge of up to 48.7% with a decline in annual precipitation of 11.5% under the A2 emission scenario (Molina-Navarro et al. 2014). Decreases in streamflow will result in further reductions in groundwater recharge in the Candelarocatchment, threatening sustainable supply of water and reducing wheat yield (D’Agostino et al. 2010). In the east Mediterranean island states, 3°C warming is projected to decrease freshwater resources by 10–30% in Crete (Koutroulis et al. 2016).

In southern Australia, climate change will reduce not only streamflow but also recharge, although specific impacts of climate change at a local scale will vary depending on topographic and soil conditions (Dawes et al. 2012). Decrease in water availability in the last decade is associated with the expansion of the Hadley cell, which dampens winter precipitation in southern Australia (Post et al. 2014). In southwest Western Australia, a 13.6% decline in mean annual rainfall is projected to result in 36% decline in annual streamflow in the mid-21st century under the A2 emission scenario. Annual runoff is projected to decline by 74% with a 23.6 reduction in precipitation in the late 21st century. Spatial and temporal variations of rainfall and runoff are also projected to shift. The rate of changes was higher in high-elevation areas compared to low areas, and high rainfall events in the catchment reduced significantly, resulting in further reductions in total runoff.

Additionally, climate change is likely to bring more extreme hydrologic events such as droughts. In mountain rivers of the southwestern Balkans in Europe, due to decreases in summer precipitation and increases in air temperature, minimum flows are projected to decline in the mid- and late-21st century, particularly under the high emission scenario, increasing the risk of droughts (Papadaki et al. 2016). In a study of the influence of drought on national forests and grasslands across the United States, Sun et al. (2015) found that extreme events directly influence the water balance across the country, particularly in the regions of Mediterranean climates. The three-month standardized precipitation index (SPI3) has declined in most of the natural forests in California from 1962 to 2012. During the top five drought years, on average, a 22% decrease in precipitation led to reductions in streamflow by 37%. In California, the decline is much more substantial, with the majority of the stations studied exhibiting more than 75% declines in streamflow during the same period. Drought related to climate change will result in substantial, yet variable, effects across the various climate regions of the United States, and the Mediterranean climates will be mostly severely affected by the drought. The different responses of forest water yield to these droughts are associated with different vegetation characteristics and severity of droughts.

While there have been numerous studies investigating the potential consequences of climate change on water availability, the specific degree and impact on the water supply system are less quantified. In a review of worldwide water suppliers, Staben et al. (2015) stressed a need for a tailored climate adaptation strategy that suits local settings. Climate-induced increases in water demand and changing demographic conditions should be taken into account for future adaptation planning by water utilities (Parandvash and Chang 2016). In a study of a drinking water production system in the Netherlands, Ramaker et al. (2005) called for a flexible approach for potentially solving climate-induced problems. Flexible adaptive strategies include diversifying sources of drinking water and creating more distributed small storage systems, which can minimize large water-providing systems’ failures resulting from climate change. Similarly, adaptive management of headwater forests (e.g., planting pine forests) can help increase water provision via increase in groundwater recharge in Spain (Garcia-Prats et al. 2016).

**Hydropower generation**

With changing runoff amounts over space and time in a warming climate, the potential for hydropower generation is projected to be altered substantially in future, but the specific impacts of changing hydrology on hydropower generation will differ by region. In a study of the future of hydropower across Europe, Lehner et al. (2005) found that severe alterations to discharge regimes will affect which regions of Europe will be most suitable for hydropower. Water availability is expected to increase in northern and northeastern regions as a result of climate change, with Russia and Scandinavia having a significant increase in their hydropower potential. In most of southern and southeastern Europe, however, water availability is expected to decrease, and Portugal, Spain, Ukraine, Bulgaria, and Turkey will likely see significant decreases in their hydropower potential. The hydropower potential of the United Kingdom and Germany is projected to maintain relative stability. As a whole, the gross potential of hydroelectricity generation in Europe is expected to decline by 6% by 2070. At a local scale, hydropower generation is reduced by 5%–43% with reduction in flow by 3%–42% in the Llobregat basin in Spain (Bangash et al. 2013). In the Toce river basin in Italy, with changes in seasonal runoff, hydropower potential is projected to increase in fall, winter, and spring, but it is projected to decline in June and July (Ravazzani et al. 2016).

In North America, changing flow regimes have either positive or negative effects on hydropower generation depending on the region of interest. In British Columbia, Canada, annual hydropower potential is projected to increase more than 10% by the mid-21st century as regional streamflow characteristics are projected to increase (Parkinson and Djilali 2015). However, in the United States, earlier snowmelt combined with declining snowpack due to rising air temperature is projected to
have generally negative impacts on hydropower generation in the Pacific Northwest (Lanini et al. 2014, Lee et al. 2016) and California (Rheinheimer et al. 2013, Madani et al. 2014), particularly in the summer when streamflow is projected to decline.

In a global assessment of hydropower potential in the mid- and late-21st century using five global climate models, van Vliet et al. (2016) identified approximately 29% and 36% of the world will experience declines in hydropower generation potential by 2080s, under RCP 2.6 and RCP 8.5 scenarios, respectively. The regions of Mediterranean climates will experience such declines in hydropower potential by more than 20% under the RCP 8.5 scenario due to declines in annual streamflow.

**Effects on regulating services**

Together with rising air temperature, changes in flow regimes will also negatively affect many regulating WES, notably water purification and flood regulation. The response of each basin’s regulating services to climate change differs, subject to the degree of interactions between land surfaces and atmospheric processes. Studies have found transient rain–snow zones and urban areas, which are the typical characteristics of the regions of the Mediterranean climates, may be more vulnerable to climate change than other regions because the hydrologic regimes can be altered more substantially with modest changes in precipitation and temperature (Dahm 2010).

**Water purification**

Many studies have focused on the effects of climate change on one or more water quality parameters around the world (Praskievicz and Chang 2009, van Vliet et al. 2011, Jiang et al. 2014). These parameters include water temperature, dissolved oxygen levels, nutrient loads (specifically nitrogen and phosphorus), and other contaminants. In general, these studies show that climate change is influencing, and will continue to influence, water quality around the world, but each basin’s response to climate change will differ by location. In a study of the relationship between climate variables and river water quality in 14 large rivers around the world, Jiang et al. (2014) found that ammonia concentrations increase with temperature increases, while nitrate and total orthophosphate concentrations increase with precipitation increases in general. The authors also found that other biophysical (climate type and soil type) and human disturbance factors (population and land cover) have secondary effects on the relationship between climate and water quality variables.

At a global scale, monthly stream temperatures are projected to increase by 1–4°C in the mid-21st century (2041–2070) compared to the historical period (1961–1990) under the A2 and B1 climate change emission scenarios (Punzet et al. 2012). In the equatorial zone, large increases in warming occur during winter months, while in temperate zones, including the Mediterranean climate regions, they occur during summer months. In a study of 157 river stations globally, when increases in air temperature and decreases in streamflow are taken into account together, discharge reductions of 20% and 40% would increase stream temperature by additional +0.3°C and +0.8°C, respectively. In several stations located in mid-latitude temperate climates (e.g., San Joaquin, Potomac, Rhine, and Danube), stream temperature is projected to increase more under the combined scenario of +4°C air temperature increase and a 40% discharge decrease than under a +6°C air temperature increase only scenario (van Vliet et al. 2011). This becomes particularly important given that summer streamflow is projected to decline further in these basins. In the Sierra Nevada mountains in California, stream temperatures are projected to decline more than 3°C during the summer months due to reductions in streamflow that result from reduced snowpack and earlier snowmelt (Stewart et al. 2015). Increases in temperature and decreases in precipitation could increase the risk of deoxygenation in rivers (Whitehead et al. 2009).

More frequent high flows, flooding events, and storm events associated with climate change could increase soil erosion, in turn increasing the discharge of contaminants such as heavy metals and other toxic compounds. Climate change is projected to decrease regulating (erosion control) services from the upper to the lower parts of the Llobregat basin in Spain between 5% and 43% (Bangash et al. 2013). With increased precipitation in winter and spring, and a subsequent decline in biomass growth, average sediment loads are projected to increase in the Vez watershed, northern Portugal (Carvalho-Santos et al. 2016). In contrast, sediment loads are projected to decline mildly by 7.9% in the Acheoloos river in Greece due to decline in precipitation (14.6%) and flow (19.5%) under the A1B climate change scenario (Nerantzaki et al. 2016). Another review by Delpla et al. (2009) reached the conclusion that increased temperatures and heavy precipitation events promote the formation and dispersion of disinfection by-products, dissolved organic matter, micropollutants, and pathogens.

Nutrient loads—specifically nitrogen and phosphorus levels—are also projected to shift in a changing climate, largely due to precipitation declines. In a medium-sized watershed in Portugal, nitrate levels will increase due to climate change and could be exacerbated due to land use decisions (Carvalho-Santos et al. 2016). Similarly, phosphorus export is projected to increase 13% under the worst-case scenario of climate change and agricultural land expansion in the Ompolved river catchment in Spain (Molina-Navarro et al. 2014). In the Llobregat river basin in Spain, Terrado et al. (2014) found a positive correlation between nutrient loads and precipitation. In dry years, the total nitrogen load exiting the basin decreased and increased in wet years. They also found a similar
result for total phosphorus loads, with the loads exiting the basin decreasing in dry years and increasing in wet years. With projected climate change, phosphorus targets were exceeded during summer months in a tributary to Lake Simcoe (Portugal) despite reductions in flow and low increases in total phosphorous, which is detrimental to the ecological and trophic statuses of the lake due to the long residency time of phosphorus (Crossman et al. 2012). While climate change leads to increased nutrient loads and reduced retention capacity, land management such as the restoration of riparian areas via tree planting has shown to buffer some of the negative consequences of climate change (Hoyer and Chang 2014).

**Flood regulation**

With expected increases in the frequency of extreme events under a warming atmosphere, the probability of floods is likely to increase worldwide (Milly et al. 2002) as drainage basin capacity to regulate floods will decline. However, the spatial and temporal extent of floods and associated flood risks will differ by specific local physiographic and socio-economic conditions. In Europe, using a threshold-based evaluation of extreme event magnitude and frequency, Alfieri et al. (2015) found that flood risk is projected to increase by an average 220% by the end of the 21st century under a 4°C warming scenario. With continuous socio-economic development, nearly a million people will be affected by floods. However, in a follow-up study, Alfieri et al. (2016) showed that when adaptive strategies are implemented (as opposed to traditional raising of flood protections in a piecemeal way), flood risk and damage could decline, with different degrees of impacts in reducing such risks depending on the type of adaptation measures. Based on their simulation study, they recommended the further development of relocation and vulnerability measures first, followed by increasing natural retention capacity in upstream areas to reduce peak flow, and rising flood protections as a last resort.

In the United States, even though total precipitation amount is projected to decline, flooding may intensify in some regions (Georgakakos et al. 2014). In particular, coastal cities are vulnerable to flood risks when storm surges and high precipitation events occur simultaneously. While individual events may not be extreme on their own, the combination of the two events may exponentially increase the potential flood damages. The number of these compound events increased in the past century, and such events are likely to increase in a warming climate. Such flood risks are much higher in the East and Gulf coast cities than in west coast cities because hurricanes and other big storms hit more on the East and Gulf coasts (Wahl et al. 2015). However, the long-term sea level rise is the main source of increasing flood risks in coastal cities, including major cities located in the Mediterranean climate (e.g., San Francisco, Los Angeles). When future population projection is considered, approximately 4.2 million people living in US coastal counties are at risk of flood with a projected sea level rise of 0.9 m by 2100 (Hauer et al. 2016).

Climate change also will indirectly affect flood regulation via changes in wetland size. With projected sea level rise, many coastal wetlands will disappear, reducing the buffering effects of storm surges. Inland wetlands will also be affected by changing flow regimes and rising air temperatures. With reduction in size, the capacity of wetlands to store carbon in boreal regions and sequester carbons in temperate and tropical wetlands is also reduced (Mitsch and Hernandez 2013).

The increasing probability of floods will also negatively affect water infrastructure, including drinking water intake and sanitation facilities. With a rise in turbidity during high flow events, the cost of drinking water treatment will increase as natural sediment settling methods will not work. Drinking water facilities themselves may malfunction when flooded during flood events. Additionally, combined sewer overflow resulting from high flow events will pose human health risks (WHO 2009). While long-term increases in rainfall may increase groundwater recharge and hence raise groundwater levels in some parts of the world, it may decrease the efficiency of natural purification process, thus increasing the risk of infectious disease (WHO 2009).

**Effects on cultural water-related ecosystem services**

Information on the effects of drought on tourism and recreation is limited, despite these being the most critical economic sectors in many areas. Existing drought indices do not consider recreation and tourism in their calculations. Lower water levels or snowpack can have dramatic effects on activities such as boating, rafting, canoeing, fishing, snowmobiling, and skiing (Thomas et al. 2013). For example, the snow sports industry contributes $12.2 billion to the US economy every year (Burakowski and Magnusson 2012). However, with rising air temperature of an average of 0.3°C per decade since 1970 (NOAA 2016), the number of ski areas in the United States has dropped nearly 20 percent in the last two decades, from 546 in 1992 to 470 in 2015 (National Ski Areas Association 2016). With air temperature rises of a 2.2–5.6°C by the end of the 21st century, snow depth is expected to decline by 25–100% in the western United States (Peacock 2012), and the length of the snow season in the northeastern United States is expected to shorten by as much as 50 percent (Burakowski and Magnusson 2012). These changes in snow depth and snow season will hurt ski industries that are located in low elevations.

The effects of declining reservoir levels on recreational values during droughts are potentially high, but the effects are site-specific. During the California drought of 1985–1991, decreases in water levels in a reservoir that had high recreational values under normal conditions led to significant losses in recreational value, while those...
reservoirs that had low recreational values under normal conditions were only slightly impacted by lower levels (Ward et al. 1996). These results suggest that water managers should make efforts to maintain water levels at the high value locations and may partially accomplish this by letting the levels drop more significantly at the low value locations (Ward et al. 1996).

**Impacts on aquatic species and biodiversity**

While the effects of climate change may not be seen yet on most fish populations, stream temperature increases, decreased dissolved oxygen, changing sediment and nutrient loads, and changes to hydrographs could lead to decreased productivity of native fish populations and eventually extinction of fish species around the world (Ficke et al. 2007). In northeast Spain, the disappearance of native aquatic species in the past 30 years is attributed to decline in flows that resulted from warming climate and upload forest land conversion (Otero et al. 2011). In southwestern Balkan mountain rivers in southern Europe, with declines in summer flow and rising stream temperatures, the western Balkan trout population and other bio-
ta are projected to decline substantially in the latter half of the 21st century (Papadaki et al. 2016). Similarly, as a result of decreased flow (20%–29%) and increased water temperature (4–4.2°C), habitat suitability for large brown trout is also projected to decline in the near future (2011–2040) in the Cabriel river in Iberian Peninsula (Muñoz-Mas et al. 2016). Together with other human stressors (e.g., watershed degradation, human use of river water), climate change is projected to decrease most of California’s salmon species in the 21st century (Katz et al. 2013).

These types of changes could have significant eco-
nomic impacts, particularly in the coastal regions of Mediterranean climates where commercial and recre-
ational fishing activities are abundant. Together with overfishing, ocean warming and acidifications will have negative consequences on shellfish fisheries, aquacul-
ture and corals, leading to shifts in tourism flows and thus revenues associated with the industry (Weatherdon et al. 2016).

**Synthesis**

As discussed above, the regions of Mediterranean cli-
mates will experience the most dramatic changes in WES in a changing climate. There has been ample evi-
dence of the warming and drying of streams in these regions in the past century. With the projected rise in air temperature and diminishing summer precipitation in future, the storage capacity of mountain snows and groundwater systems will decline, resulting in further declines in summer flow in these regions, which will have huge consequences on water-dependent ecosystems and related services. The studies reviewed also suggest that there are potential non-linear responses of water-dependent ecosystems to climate change. Runoff is projected to decline further with modest declines in precipitation due to higher evapotranspiration resulting from higher air temperature. High-elevation areas are projected to experience the most climate-related stresses on WES, including substantial declines in suitable habitats for cold-water species with the projected rise in stream temperature. Low-elevation areas may experience other water quality problems as non-point source pollution loads could either increase or decrease, depending on flow changes projected by different climate change scenarios. Other ongoing human stressors (largely related to land cover change and management practices) have contributed to the declines in WES in the region. However, opportunities exist to reduce potential negative consequences of climate change on WES by implementing best land management practices, including upland and riparian reforestation to help store water over a prolonged time.

**California Drought as a Case Study**

**Synopsis of California droughts**

Entering 2016, California completed its fourth consecu-
tive year of below-average runoff and snowpack, mak-
ing it the eighth year (out of the last nine) with below-average runoff levels. These recent drought con-
ditions marked the lowest four-year period (2012–2015) statewide precipitation level in the record since the late 19th century. Additionally, the last 2 years, 2014 and 2015, were the hottest years on record, creating hot drought (Overpeck 2013). The year 2015 also produced the least amount of snowpack in the Sierra Nevada range on record (5% of average since 1950), and there is evidence that it may have been the lowest level in more than 500 yr (California Department of Water Resources 2016). The consequences of this sustained drought vary drastically across the state and sectors as the drought has different impacts on farmers, industry, cities, and ecosystems that depend on water availability and quali-
ty (Gleick 2016). Urban areas have to learn to improve supply reliability by focusing on water conservation, reuse of wastewater, and capturing stormwater (Lund 2016a). With these conditions and the potential for them to continue into 2016, the state produced a substantial 2016 Drought Contingency Plan. The main goals of this plan were to meet the essential health and human safety needs in water provision, manage saltwater intrusion into remaining freshwater supplies, protect threatened and endangered species (as well as other fish and wild-
life resources), and consider flexibilities in management practices to maximize the benefit of the limited water supply (California Department of Water Resources 2016). While El Niño in winter 2016 brought more pre-
cipitation and thus snowpack, it was not enough to allevi-
ate the drought. As global climate models project
hotter and drier summers in California, the 2015 drought can be used as a future analog scenario.

Annual precipitation and temperature

As shown in Fig. 2, only 4 yr (2005, 2006, 2010, 2011) had higher than normal precipitation since 2001 in the San Joaquin River basin. During the period, the below normal dry years generally correspond to warmer years. The correlation between water year annual precipitation and annual temperature is statistically significant ($r = -0.58$, $p < 0.05$). Diffenbaugh et al. (2015) has shown that anthropogenic climate change has likely increased the chance of high temperatures coinciding with low precipitation across California, which has been shown to have led to historically severe drought conditions in the state.

Effects on water provision

Mean daily streamflow in 2015 substantially departed from the long-term mean streamflow of the 1981–2010 period in the majority of the stations studied (Fig. 3). Most significant departures are ($Z < -1.65$, $p < 0.1$) found in low-elevation streams located in coastal basins or central valley areas. Four out of the seven stations that have long-term stream temperature records also exhibit statistically significant warming from the reference period ($Z > 1.65$, $p < 0.1$). As shown in Fig. 4, except for 7 yr (1982, 1983, 1995, 1998, 2005, 2006, 2011), streamflow has been consistently lower than the 30-year average (1981–2010). In particular, the last 4 years from 2012 to 2015 show consecutive low streamflow years. The trend of low precipitation levels since the mid-1990s led to low storage levels in reservoirs throughout the Sacramento River and San Joaquin River watersheds in 2015. The Folsom Reservoir set a record low level on November 30, 2015, while the Shasta Reservoir, Oroville Reservoir, Trinity Reservoir, and New Melones Reservoir were at 50%, 47%, 30%, and 22%, respectively, of their average levels at that time of year. The consecutive years of drought have led to cumulative effects that have kept upstream reservoirs near historic lows (California Department of Water Resources 2016). To deal with this drought, statewide mandatory water restrictions were first imposed, calling for a 25% reduction on municipal water use supply from 2013 levels (Nagourney 2015). In response to these restrictions, major municipalities introduced aggressive water conservation measures by increasing water prices or banning outdoor water lawn
irrigation (Lee 2016). Such measures have been largely effective, reducing statewide residential water use by 13.5% from April 2013 to April 2015 (Park et al. 2015). A future adaptation strategy is to increase natural water storage capacity in upland forests by restoring meadows and forest treatment, particularly in the Sierra (California Emergency Management Agency and California Natural Resources Agency 2012).

**Effects on hydropower generation**

Drought has negative impacts on hydropower generation. Over the last 15 years, hydropower has steadily declined in the state of California primarily due to ongoing droughts. Based on data from 1983 to 2014, hydropower generation correlates directly with runoff amounts in California rivers. The 2007–2009 California drought led to hydroelectricity accounting for 13% of the states’ total power generation (below the average level of 18%), and the current drought (2011–2015) resulted in even lower levels at 10.5%, and accounted for only 7% in 2015 (Gleick 2016).

As shown in Fig. 5, hydropower generation is highly associated with runoff volume in the San Joaquin River. During the period from 2001 to 2015, hydropower was least generated in 2014 and 2015 when runoff amounts were lowest in the basin. Years with high hydropower generation (2005, 2006, and 2011) directly correspond to wet years. Even though 2011 was the wettest year during the 2001–2015 period, hydropower generation was not the highest, indicating that the energy sector may have adapted to the previous 3 years’ drought. Hydropower plants located in high-elevation areas (above 300 m) are particularly vulnerable to climate change. In the study

**Fig. 3.** Departure of 2015 daily streamflow and 7 days moving average of daily maximum stream temperature (7DA Tmax) from the 1981–2010 period. Z score is a standard score, measuring how many standard deviations below or above a given score is. If the absolute value of Z score is higher than 1.65, the score is 90% higher (10% lower).

**Fig. 4.** Annual streamflow anomaly from the average of 1981–2010, Sacramento-San Joaquin river.
of potential shifts in hydropower generation under warming scenarios (2–6°C) in the Upper west slope of Sierra Nevada, the largest reductions are found in the highly productive northern Sierra Nevada, while smaller reductions are reported in less productive central and southern watersheds (Rheinheimer et al. 2014). The high-elevation systems may not be able to store as much water as they used to because snowpack is projected to decline substantially in a warming climate in these areas (Madani et al. 2014). One way to adapt to climate change and potentially maximize revenue from hydropower is to increase water storage capacity of these high-elevation systems. Such storage projects could be constructed at a relatively small scale so as not to have profound consequences for water management downstream. However, when storage is a limiting factor (either due to local topography or declining snowpack resulting from climate change), such adaptation strategies may not be effective.

Effects on irrigation water and agricultural production

California agriculture relies on groundwater for approximately 40% of its water supply during normal weather years (Cooley et al. 2015). With reduced surface water supply during dry years, groundwater pumping increases. According to a recent estimate by Cooley et al. (2015), cumulative groundwater loss has been substantial, reaching approximately 100 km³ since 1962 due to over mining of groundwater. Increasing groundwater withdrawals to offset reduced surface water is not sustainable. The depletion of aquifers has forced individuals and communities to dig deeper wells or find alternative drinking water sources, increasing the cost of energy needed for pumping or water diversion. Additionally, there is evidence of infrastructure being damaged due to subsidence (Cooley et al. 2015). Despite challenges for supplying adequate amounts of irrigation water, the California agricultural sector appears to use water more efficiently by switching from flood to drip irrigation. Additionally, while harvested acreage has declined since 2000, most notable decreases were found in vegetables and melons that are water-intensive crops. By switching to less water-intensive crops and fruits (e.g., almond and nuts), total revenue did not necessarily decrease regardless of persistent droughts until 2014 (Cooley et al. 2015).

Effects on regulating services and aquatic habitat

As streamflow reduced, several regulating WES also declined. For example, in 2015 stream temperature increased over 3°C with less than 100 m³/s decline in streamflow. Smaller water bodies can be particularly vulnerable as they can absorb heat more rapidly than higher volumes of water. As shown in Fig. 6, summer stream temperature anomaly years are negatively associated with summer stream flow anomalies, while the relationship is curvilinear. The highest stream temperature anomaly years (e.g., 1991–1993; 2001–2002; 2013–2015) correspond to low flow years (shown in upper left), while low stream temperature anomaly years correspond to high flow years (shown in lower right 1982–1983, 1995, 1998, 2006, 2011). These wet years are typically El Niño years that brought excessive amounts of precipitation through winter and spring. Spring and summer stream temperatures are projected to increase by 1–5.5°C under a high greenhouse gas emission scenario by the end of the 21st century, with the highest projected increase in the low-elevation subbasins of the southern Sierra Nevada and moderated increases in the northern Sierra Nevada that is affected by snowmelt and subsurface flow (Ficklin et al. 2013).

Drought is also highly associated with increased concentrations of total dissolved solids and specific conductivity (Fig. 7). Specific conductivity is one of the most commonly measured water quality parameters as it serves as an early indicator of potential pollution in a water system, whether it is driven by anthropogenic or natural factors. As shown in Fig. 7, specific conductivity shows seasonal cycles following flow variability. There were record high levels of salinity in the Sacramento-San Joaquin Delta in November 2015, directly linked to the record low inflow to the delta resulting from low rainfall in fall 2015 (California Department of Water Resources 2016). After a prolonged drought, the first fall storm event is likely to flush pollutants that have been accumulated during the dry period, increasing the concentration of pollutants and thus impairing water bodies (Chen and Chang 2014). As extreme drought is likely to occur more frequently in a warmer world, understanding the changing discharge–concentration relationship throughout the year becomes important (Burt et al. 2015).

Together with changes in streamflow, such changes in stream temperature and concentrations of ions and solids will have negative consequences on aquatic habitat. As
stream temperature warms up, many cold-water species are exposed to stream temperatures well above survival temperature thresholds (Null et al. 2012). Species living in water-limited small headwater streams will be particularly vulnerable to changes in streamflow and stream temperature, while species living in estuaries will be vulnerable to changes in salinity as it affects the solubility of dissolved oxygen. Higher salinity is associated with lower dissolved oxygen content in water. These findings suggest that spatially targeted different adaptive management strategies are needed in a warming climate.

**Effects on water-related cultural services**

Low water levels in streams and reservoirs have had negative impacts on water-dependent recreation activities across the state. For example, kayaking and canoeing on the Stevens Creek and Lexington reservoirs were prohibited. Boating ceased on Folsom Lake where six of nine boat ramps were closed due to low water levels. During the 2014 salmon and steelhead migrations, fishing was temporarily shut down on several coastal streams (Cuff 2014). In the spring of 2014, state officials closed portions of about 20 rivers to sport fishing and indicated that other rivers may see the same restrictions in future (Martin 2014). The popular swimming lagoon at Castaic Lake was also closed. San Mateo County Park had to close its campground for the first time in 90 years due to the water supply in Pescadero Creek being too low and filled with algae. Additionally, several locations have closed access to flush toilets (replacing them with chemical toilets) due to low water levels (Cuff 2014).

Winter recreational activities have also been severely impacted by the drought. As shown in Fig. 8, April 1st snow water content in Mount Rose Ski resort is highly associated with inter-annual climate variability. During the dry periods (1986–1992, 1999–2004, 2005–2009, 2011–2015), April 1st snow water contents were significantly lower than those during the wet periods. For example, in 2013, ski resorts across the state had to close weeks early, with the number of visits to ski resorts dropping to 4.9 million, well below the five-year average of 6.8 million. Even Mammoth Mountain, which is the highest elevation resort in the state, reported losses of 10% in visitors from the prior season. In southern California, Bear Mountain and Snow Summit resorts had a combined drop of 20% from the previous year (Martin 2014).
Fig. 7. Temporal variation of total dissolved solids and specific conductance, 1998–2016. The wet and dry periods are defined in Cooley et al. (2015).

Fig. 8. Change in snow water depth, Mount Rose Ski Resort, California. The wet and dry periods are defined in Cooley et al. (2015).
WES tradeoffs across space and time during drought

One of the most challenging issues in water resource management in California is the uneven distribution of water resources over space and time. California receives most of its precipitation during the winter (October to April), but the state needs the majority of its water during the dry summer months when irrigation and urban water demand is high. Snow in the northern and eastern mountainous part of the state melts gradually during spring and summer months, providing the needed water to downstream users such as the San Joaquin Valley, the Sacramento Valley, and coastal urban areas (e.g., Los Angeles). To meet the growing demand for irrigation and urban water, river water has been diverted from the Sacramento-San Joaquin Delta to the Central Valley and to cities in southern part of the state. As cities have grown, competition among different water users has increased over time. Since 1956, water diversions from the delta have increased significantly, while delta inflows have declined (though not statistically significant due to natural climate variability) (Lund 2016b). The diverted water from the delta provides drinking water supply for 25 million people and irrigation water for approximately 1.2 million hectares of irrigated farmland (Culberson et al. 2008).

The 2015 California drought further exacerbated the existing problem of complex water allocation across the state and sectors. In the northern part of the state where most runoff is generated, farmers with senior water rights were entitled to, and wanted to keep more water during the low flow period. This has created tensions between farmers in north and south and between farmers and environmentalists, negatively affecting agricultural production and other water ecosystem services (e.g., stream temperature regulation and water pollution control) downstream (Goode 2015). Compared to the wet year 2011, the combined water diversions for State Water Project and Central Valley Project were 73% lower in 2015 (Lund 2016b). As water export from the delta substantially declined, farmers in the lower Central Valley heavily relied on groundwater for irrigation to maintain agricultural production. Overdraft of groundwater has caused a dry-up of nearby small streams, stressing aquatic ecosystems, and other related WES. This case clearly illustrates that sustaining a specific WES in one place is likely to have negative consequences in different WES in other places.

However, maintaining downstream delta flows has potential synergistic effects. Maintaining minimum environmental flow requirements during droughts can dilute concentration of pollutants, benefitting not only aquatic ecosystems but also recreationalists and farmers (due to maintaining water quality needed for irrigation). Additionally, maintaining delta flows will prevent salt water from intruding to groundwater systems in estuaries, lower reaches of the San Joaquin and Sacramento rivers, and coastal urban areas, which will not cause an increase in the cost of drinking water treatment and the formation of disinfection by-products (Dahm 2010). Considering that the delta water is the major source of drinking water for southern California and the San Francisco Bay area, maintaining good water quality has direct human benefits. Such tradeoffs and potential synergies among

![Fig. 9.](image_url) A hybrid approach to climate adaptation in sustaining water ecosystem services (some key ideas are based on Armstrong et al. 2015).
Table 2. Potential climate adaptation strategies for maintaining water-related ecosystem services (WES) during drought and their direct and indirect impacts on other WES.

| Water-related ecosystem services | Potential adaptation strategies | Direct impacts | Indirect impacts | Current California strategies | Proposed future strategies |
|----------------------------------|---------------------------------|----------------|-----------------|------------------------------|---------------------------|
| Water provision                  | Increase storage capacity       | Supply stable amount of water | Reduce return flow | Water transfers | Extensions to the water transfer window |
|                                  | Find new water sources          | Use water more efficiently | Increase energy cost | Wastewater reuse | Increase “above-the-dam” regional natural water storage systems |
|                                  | Reuse or recycle water          |                             |                  | and reclamation | Solve urban water demand |
|                                  | Replace old infrastructure      |                             |                  |                  | Expand water infrastructure |
|                                  | Revise dam operation rule       |                             |                  |                  | Increase “above-the-dam” regional natural water storage systems |
|                                  | Increase storage capacity       |                             |                  |                  | Solve urban water demand |
| Hydropower generation            | Maintain power generation       |                             |                  |                  | Expand water infrastructure |
|                                  | Decrease downstream ecosystem   |                             |                  |                  | Increase “above-the-dam” regional natural water storage systems |
|                                  | Increase use of natural gas and out-of-state purchases |                             |                  |                  | Solve urban water demand |
|                                  | Expand wind and solar power generation |                             |                  |                  | Increase “above-the-dam” regional natural water storage systems |
|                                  | Groundwater used to offset 70% of surface water shortages |                             |                  |                  | Increase “above-the-dam” regional natural water storage systems |
|                                  | Water trading and operational flexibility |                             |                  |                  | Increase “above-the-dam” regional natural water storage systems |
|                                  | Shift to drought-resistant crops |                             |                  |                  | Increase “above-the-dam” regional natural water storage systems |
|                                  | Desalinization of agricultural water |                             |                  |                  | Increase “above-the-dam” regional natural water storage systems |
| Agricultural production          | Reduce required irrigation water |                             |                  |                  | Reduce reliance on natural gas |
|                                  | Improve downstream water quality |                             |                  |                  | Continue expansion of renewable energy resources |
|                                  | Limit other water uses (e.g., energy) |                             |                  |                  | Reduce reliance on natural gas |
|                                  | Groundwater used to offset 70% of surface water shortages |                             |                  |                  | Increase “above-the-dam” regional natural water storage systems |
|                                  | Water trading and operational flexibility |                             |                  |                  | Increase “above-the-dam” regional natural water storage systems |
|                                  | Shift to drought-resistant crops |                             |                  |                  | Increase “above-the-dam” regional natural water storage systems |
|                                  | Desalinization of agricultural water |                             |                  |                  | Increase “above-the-dam” regional natural water storage systems |
| Flood mitigation                 | Improve forecast and warning    | Reduce flood risk          | Improve water quality | Improve flood forecast warning system | Speed the implementation of 27-year timeline for stabilizing groundwater basins |
|                                  | Restore floodplains and wetlands | Control excessive runoff   |                  |                  | Create central clearinghouse of water trade information (Water ISO) |
|                                  | Upgrade infrastructure          |                             |                  |                  | Widespread use of trading risk and uncertainty for use reduction |
| Nutrient retention               | Implement best management practices | Improve and maintain current nutrient concentrations | Use water more efficiently | Maintain Delta Cross Channel gates in an open position longer to reduce salinity | Amend city and county land use plan |
|                                  | Increase source water protection from pollution | Increase aquatic biodiversity and cultural WES | Increase environmental flow | Salinity control barriers | Restore existing flood control and riparian corridors |
| Cultural WES                     | Modify recreational timing and areas | Optimize recreational activities | Increase potential congestions over the use of recreational areas | Closure of low-elevation winter recreation areas | Minimize development in flood-prone areas |
|                                  |                                  |                             |                  | Limiting recreational activities on low-level reservoirs | Adjust Delta Cross Channel gate openings in response to increased salinity |
|                                  |                                  |                             |                  |                  | Construct additional salinity control barriers |
| Aquatic biodiversity             | Increase shading riparian areas | Cool water temperature     | Increase food provision | Controlled reservoir releases, to control water temperature and minimize red | Relocation/reopening of winter recreations at higher elevations |
|                                  | Improve hydrological connectivity | Maintain diversity         | Improve water quality | dewatering | Intentionally lower water levels in reservoirs that are unpopular for recreation, allowing reservoirs popular for recreation to maintain higher levels |
|                                  | Modify instream habitat          | Remove disruptive structure | Increase other cultural WES | Increase winter-run broodstock collection | Maintain CVPIA refuges, strive to deliver refuge supplies at requested times |
|                                  | Increase environmental flow      |                             |                  | CVPIA Refuge Water Supply Program | Expand protected areas |
different WES over space and time must be taken into account for sustainable water resource management in a changing climate.

Conclusions and Suggestions for Future Research

We investigated the potential impacts of climate change on WES in California. Drawing from the recent literature, we identified that climate change will have substantial effects on provisioning, regulating, and cultural WES, but the specific effects of climate change on specific WES will be different depending on the degree of spatial and temporal changes in the water cycle and the adaptive capacity of the region’s social and biophysical system. The 2015 California drought revealed the cascading effects of climate change on multiple WES. Declining streamflow and the concomitant rising stream temperatures have immediately threatened not only provision of water to humans but also to ecosystems that rely on water. The secondary effects of drought on WES are widespread across different water-dependent industries, including water-based recreation. The findings of our study also suggest that climate change impacts on WES will differ by location, suggesting that place-based climate adaptation strategies are necessary.

To come up with effective place-based climate adaptation strategies, a hybrid approach is needed that combines top-down with bottom-up approaches, with an active consultation of regional stakeholders at multiple stages (Armstrong et al. 2015). The top-down approach, which is a dominant paradigm of most scientific research, starts from regional climate downscaling of global climate models under different greenhouse gas emission scenarios and then feed in the downscaled scenarios into impact assessment models. While scenario-led top-down adaptation frameworks offer a range of possible future impacts, potential uncertainties associated with modeling may prevent relevant stakeholders from devising proactive climate adaptation plans. In contrast, the bottom-up approaches look at local specific vulnerability to past and present climate variability and seek to identify ways to reduce vulnerability at a local scale. As such, they are very site-specific and focus on communities’ complex socio-ecological systems to cope with climate-induced risks (Van Aalst et al. 2008). However, this approach often neglects the non-stationarity of changing climate in future. A compromised approach between the two is a decision-centric adaptation framework (Brown et al. 2012). With this approach, multiple stakeholders and experts co-identify critical thresholds that require additional investment or policy changes to make the system resilient in a changing climate. The engagement process is thus largely collaborative in nature, and involving parties can update the framework easily as socio-ecological conditions that affect climate-related risk changes (Armstrong et al. 2015). Fig. 9 illustrates the potential synergistic relationship among the three aforementioned climate adaptation frameworks for WES. The collaborative decision-centric framework makes an essential linkage between the other two frameworks. As ecosystem management can play a central role in climate adaptation (Munang et al. 2013), the explicit engagement of science and stakeholders in a decision-relevant manner is likely to reduce climate-induced risks in future. Table 2 describes some specific climate adaptation strategies to sustain WES and their direct and indirect impacts on multiple WES, showing potential WES synergies and tradeoffs with different strategies.

There are a few areas that warrant further investigations. First, more thorough studies are needed to examine the multiple cascading effects of climate change on potential synergies and tradeoffs among different WES. As enhancing one WES may inadvertently reduce the other WES, the complex feedbacks and linkages among different WES in a changing climate need to be further studied. Second, the specific effects of changing climate and hydrology and WES connectivity over space (e.g., service provision vs. service beneficiary areas) need to be studied more carefully in a spatially explicit way. Because downstream water users rely on upstream water supply, understanding WES connectivity is equally important as well as changes in WES in specific places (Yeakley et al. 2016). Third, the changing value of WES over space and time will require careful examination. By identifying the high value location, society would be able to sustain and even maximize WES in a changing climate. Finally, further investigation is needed to evaluate the effectiveness of various climate adaptation measures including land management practices on the whole suite of WES. Land use decisions and water infrastructure (dams, reservoirs) could either enhance or reduce specific WES in a changing climate. Therefore, future studies are needed to investigate the specific and combined effects of different infrastructure investment and management on WES. By aligning climate adaptation measures across multiple WES, future climate challenges can turn into opportunities (Kundzewicz and Gerten 2015).

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