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Western water and climate change

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Abstract. The western United States is a region long defined by water challenges. Climate change adds to those historical challenges, but does not, for the most part, introduce entirely new challenges; rather climate change is likely to stress water supplies and resources already in many cases stretched to, or beyond, natural limits. Projections are for continued and, likely, increased warming trends across the region, with a near certainty of continuing changes in seasonality of snowmelt and streamflows, and a strong potential for attendant increases in evaporative demands. Projections of future precipitation are less conclusive, although likely the northernmost West will see precipitation increases while the southernmost West sees declines. However, most of the region lies in a broad area where some climate models project precipitation increases while others project declines, so that only increases in precipitation uncertainties can be projected with any confidence. Changes in annual and seasonal hydrographs are likely to challenge water managers, users, and attempts to protect or restore environmental flows, even where annual volumes change little. Other impacts from climate change (e.g., floods and water-quality changes) are poorly understood and will likely be location dependent.

In this context, four iconic river basins offer glimpses into specific challenges that climate change may bring to the West. The Colorado River is a system in which overuse and growing demands are projected to be even more challenging than climate-change-induced flow reductions. The Rio Grande offers the best example of how climate-change-induced flow declines might sink a major system into permanent drought. The Klamath is currently projected to face the more benign precipitation future, but fisheries and irrigation management may face dire straits due to warming air temperatures, rising irrigation demands, and warming waters in a basin already hobbled by tensions between endangered fisheries and agricultural demands. Finally, California's Bay-Delta system is a remarkably localized and severe weakness at the heart of the region's trillion-dollar economy. It is threatened by the full range of potential climate-change impacts expected across the West, along with major vulnerabilities to increased flooding and rising sea levels.

Key words: Centennial Paper; climate change; Colorado River; Klamath River; Rio Grande; Sacramento–San Joaquin Bay Delta; water resources; western United States.

If climate change is the shark, then water is its teeth.
—Paul Dickinson, CEO of Carbon Disclosure Project

INTRODUCTION

The western United States has always been a nexus of great opportunity and great challenge for the Nation. The region is notable for burgeoning human settlements and its "wide open spaces"; for its anthropogenic land disturbances and native landscapes; for its complex terrains and diverse climates; and for its abundant resources and its scarce ones. Water has always played a pivotal role in its development, so that, to an extent unmatched elsewhere, water has been a limiting factor in where agriculture was undertaken, in where and how large its settlements have grown, and in the character and survival of many of its natural landscapes. And now, like so much of the Earth, social and natural conditions in the western United States are changing rapidly due to a variety of influences, including its long history of recurrent and severe droughts, floods, water-quality contamination, environmental degradation and endangered species, strong competition for the often limited water supplies that exist among a diverse set of

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water users, and growing changing populations and economies.

The western United States includes hundreds of rivers and catchments but, at the largest scale, a half dozen major basins drain about 66% of the area and constitute important touchstones for thinking about the future of water in the West. These drainages include the Colorado River basin, the Sacramento-San Joaquin drainages in California, the Klamath River basin, and the Rio Grande basin, which will be discussed as examples of the challenges facing western water managers later in this review. The remaining areas comprise large numbers of drainages, some interconnected but mostly not. The region and its drainages are remarkable for their diversity, ranging from the moist and abundantly flowing Columbia River system to the much drier and more tenuous hydrology of the Lower Colorado and Rio Grande catchments, with the fragmented and lonely Great Basin drainages standing in stark contrast to the well-connected and generally more populous and developed larger rivers. Given this diversity, it is difficult to provide a single vision of the future of western water, especially in its details, but on the whole, the region and its waters are notable for the challenges they will face. Western water, whether it is in rivers, soils, or aquifers, is essentially everywhere faced with a continuation of its long history of high demands even as its supplies are negatively impacted by hydroclimatic changes and fluctuations.

All told, climate change threatens water resources in the western United States to a degree that is probably unmatched anywhere else in the country. A "water supply stress index" for the United States, based on current conditions, is mapped in Fig. 1, showing widespread stress in much of the Southwest, western Great Plains, and parts of the Northwest relative to the rest of the country. In this figure, the stress indices are ratios of annual water demands to annual surface- and groundwater water supplies for each watershed, and watersheds are considered stressed (higher index values) when water demands for agriculture, power plants, and municipalities exceed 40% of available supplies. These stresses often cause conflict for water resources among sectors. In other contexts, basins can experience critical stresses even when demands are far below this threshold (Averyt et al. 2013).

Since the onset of American settlement of the West, when John Wesley Powell wrote his *Report on the Arid Regions of the United States* (Stegner 1953) 140 years ago, it has been understood that the West is a region where water will be a crucial, limiting determinant of where, when, and how humans can survive and prosper. Thus much of the history of the West has been about dividing the waters there, managing them, and building some of the most ambitious infrastructures around to store and move waters long and short distances across the landscape to ensure that water is available when and where needed, to the extents practicable.

Now, almost a century and a half later, we are in a time of adjustment in the West and some of the established methods and arrangements for water management are in states of flux. Looking forward, the western states will be confronted with many water-management challenges and tradeoffs including many from climate change, but the good news is that few of them are likely to be totally new: The West has already grappled with most of the problems that will face it in the future, however inadequately in some cases and however transformed some will be by larger trends in the future. The task confronting the West now is to resolve problems that it has long acknowledged but left partly or completely unresolved and to prepare for changes that will surely come. Drought, contamination, floods, environmental degradation, and difficult resource competitions are all part of the history of the region and lie at the core of most of its most pressing future challenges. Unfortunately, in recent decades, society within the region and globally has initiated changes aggravating these perennial issues, while adding a few more, with climate change being an increasingly pressing and threatening source of such "aggravations."

This paper is a distillation of findings regarding western water and climate change, from the Water Resources chapter in the 2014 National Climate Assessment (Georgakakos et al. 2014), coupled with several vignettes of issues developing in iconic western rivers to add specificity to those findings and to illustrate the diversity of conditions facing the region.

Climate-Change Impacts on the Western Water

In this section, observed changes and projections of future changes in the western water cycle are summarized. However, notably, natural climate variations occur on essentially all time scales from days to millennia, and the water cycle reflects these variations. Observations of recent changes in the water cycle in the West thus inevitably include natural hydroclimatic variations as well as local human influences (like dam building or land-use changes) in combination with whatever global climate changes are underway. Recent studies have begun to rigorously attribute a limited number of specific long-term and temperature-driven changes in the western water cycle to human-induced climate change (for example, Barnett et al. 2008). Although observed changes for many of the other water-cycle variables addressed in this section are consistent with projected human-induced climate changes, research to formally attribute these responses to global causes is still needed.

Warming

Much of the western United States has warmed in recent decades by about 1.5°C compared to the historical norms from 1901–1960 (e.g., Walsh et al. 2014), with greatest warming in summers and springs, and in nighttime temperatures (Hoerling et al. 2013).

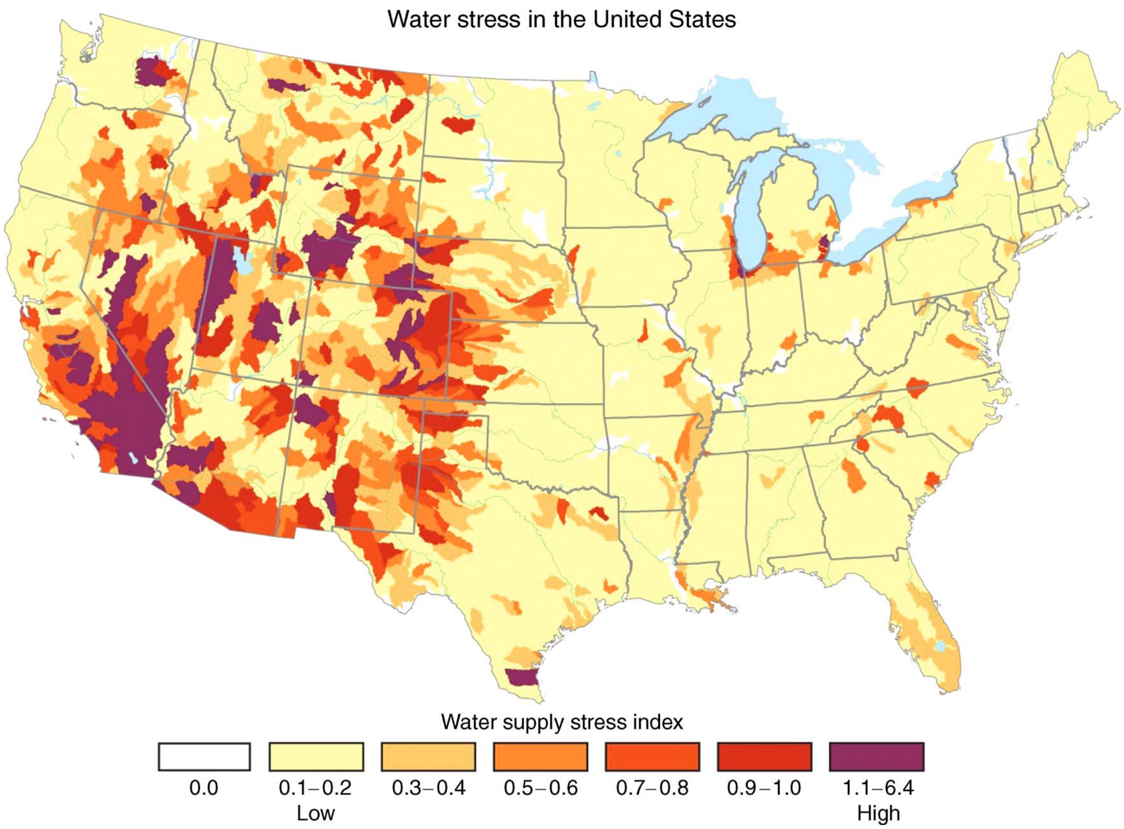

FIG. 1. Current surface-water-supply stress index of Averyt et al. (2013); see *Introduction* for definition of index.

The warming of minimum temperatures in the region has been confidently attributed to the influences of increasing greenhouse gases in the global atmosphere (Bonfils et al. 2008). Averages of many recent projections of future temperatures have the western United States warming by between about 2.5°C and 5°C by end of century (although some projections yield even warmer outcomes), depending most strongly on future rates of greenhouse-gas emissions (Walsh et al. 2014). Observed frost-free seasons have increased in length by between about 15% and 20%, a trend that is projected to continue well into the future, increasing by as much as 60–70% in many mountainous areas of the west (Walsh et al. 2014). On the whole, warming is projected to be largest in the continental interior and somewhat ameliorated as the Pacific coast is approached.

These warming trends reflect increasing greenhouse-gas concentrations in the atmosphere (Bonfils et al. 2008), and affect water in the West through a variety of processes. Warming is already directly affecting snow and ice processes (Pierce et al. 2008, Hidalgo et al. 2009), is lengthening growing seasons (Cayan et al. 2001), and thus potentially may be affecting evapotranspiration totals, and is increasing water temperatures and reducing mixing in some lakes. Warming, and its effects in the west, will continue in any event but at rates that will directly reflect future rates of greenhouse-gas emissions.

Rain, snow, evapotranspiration, and runoff

In recent decades, annual average precipitation has increased across the Great Plains, California, the Pacific Northwest, and Alaska, while decreases have been observed in Hawaii and parts of the Southwest (Walsh et al. 2014). Annual average precipitation totals are projected to increase across the northern states, and decrease to the south, especially in the Southwest (Orlowsky and Seneviratne 2012, Cayan et al. 2013, Walsh et al. 2014: Figs. 2.12 and 2.13). Thus far, the correspondences between observed and projected precipitation changes are weak, suggesting that natural fluctuations are contributing significantly to the observed "changes." Furthermore, the most recent generation of climate-change projections (for the IPCC Fifth Assessments; IPCC 2013) have shown approximately the same pattern of precipitation change across the western states (growing wetter along the northern tier of states and drying along the southern tier) as previous projections, albeit with a southward shift of the transition zone between those two broad realms such that in the most recent projections, taken as an ensemble, increasing precipitation reaches farther south than in previous projections. The result is that newer

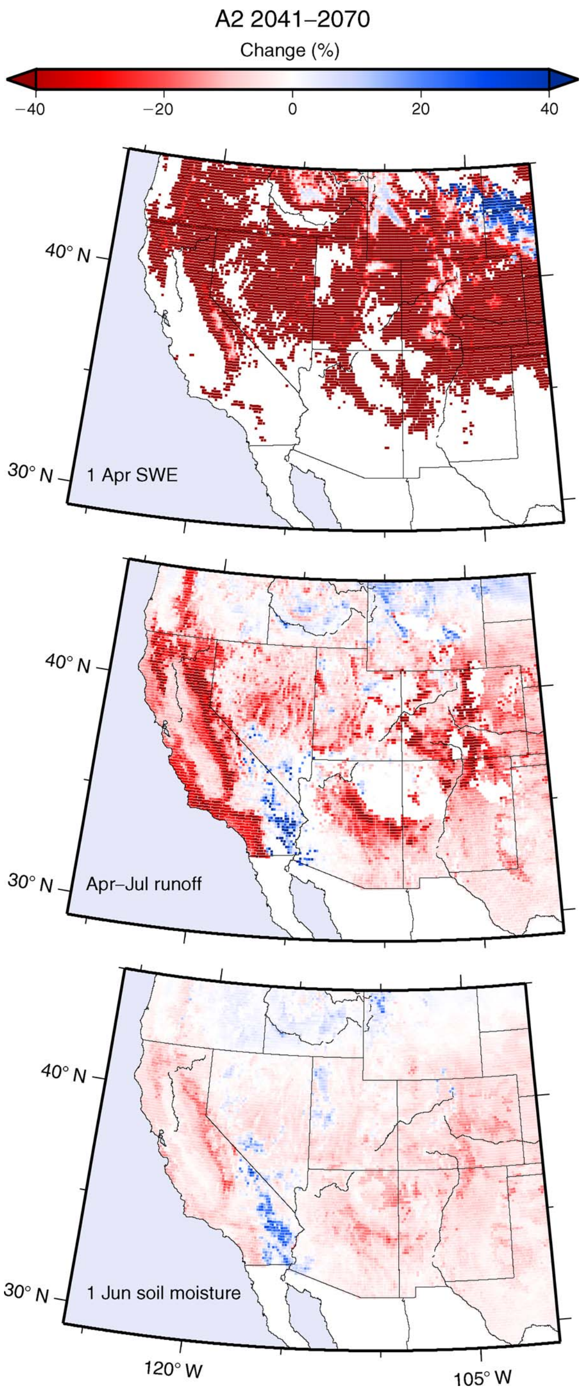

FIG. 2. Projected changes in snow (snow water equivalent, SWE), runoff, and soil moisture, as percent change in 2041–2070 from 1971–2000 conditions, under continued increases in greenhouse-gas emissions (A2 scenario; Cayan et al. 2013).

projections yield precipitation increases that extend into parts of the Upper Colorado River Basin and northern California that, in previous projections, received little change or even decreases in overall precipitation. The extent to which these differences between this generation of climate-change projections and the previous one should be interpreted as improved estimates of future precipitation remains to be determined, because the shift is rather subtle at the resolution of the climate models making the projections.

On the other hand, changes in precipitation extremes have been, and are projected to be, greater than changes in means. The number and intensity of very heavy precipitation events (defined as the heaviest 1% of all daily events from 1901 to 2012) have been increasing significantly across most of the United States. The amount of precipitation accumulated from those heaviest daily events has also increased in most areas of the United States (Georgakakos et al. 2014). Very heavy precipitation events are projected to increase everywhere in the western United States (Kharin et al. 2013, Polade et al. 2014, Walsh et al. 2014). Heavy precipitation events that historically occurred once in 20 years are projected to occur as frequently as every 12 years by late this century in the Southwest and every 15 years in the Northwest (Wang and Zhang 2008). Dry spells are also projected to lengthen in most regions, especially across the southern and northwestern parts of the contiguous United States (Walsh et al. 2014), with the most consistently projected increases being for the numbers of dry days in the southwest and up the west coast (Polade et al. 2014). Thus, although projected changes in total average annual precipitation are generally small in many areas, both wet and dry extremes are projected to increase substantially almost everywhere.

Snowpacks and snowmelt-fed rivers in much of the western United States have trended toward earlier melts and flows since the middle of the last century, including the past decade (Hamlet et al. 2005, Fritze et al. 2011, Hoerling et al. 2013, Walsh et al. 2014). These trends are related to declines in spring snowpack, earlier snowmelt, and larger percentages of precipitation falling as rain instead of snow. These changes have taken place in the midst of considerable year-to-year variability and long-term natural fluctuations of the western U.S. climate, as well as other influences, such as the effects of tree deaths from warming-liberated pest infestations (Pugh and Small 2012) and from dust and soot on snowpacks, as well as differences between the trends in the colder interior mountain catchments and the warmer maritime mountains of the Pacific Coast states (Hamlet et al. 2005, Stewart et al. 2005, Hodgkins 2009, Painter et al. 2010, Stoelinga et al. 2010, Fritze et al. 2011, Creamean et al. 2013). There are thus both natural and human influences on the observed trends (Barnett et al. 2008, Bonfils et al. 2008, Pierce et al. 2008, Das et al. 2009, Hidalgo et al. 2009), but studies specifically designed to differentiate between natural and human-induced causes have shown that up to 60% of these changes are attributable to human-induced climate warming (Barnett et al. 2008). Notably, not all snowpack variables have changed detectably, or should be expected to have changed yet (Pierce and Cayan 2013).

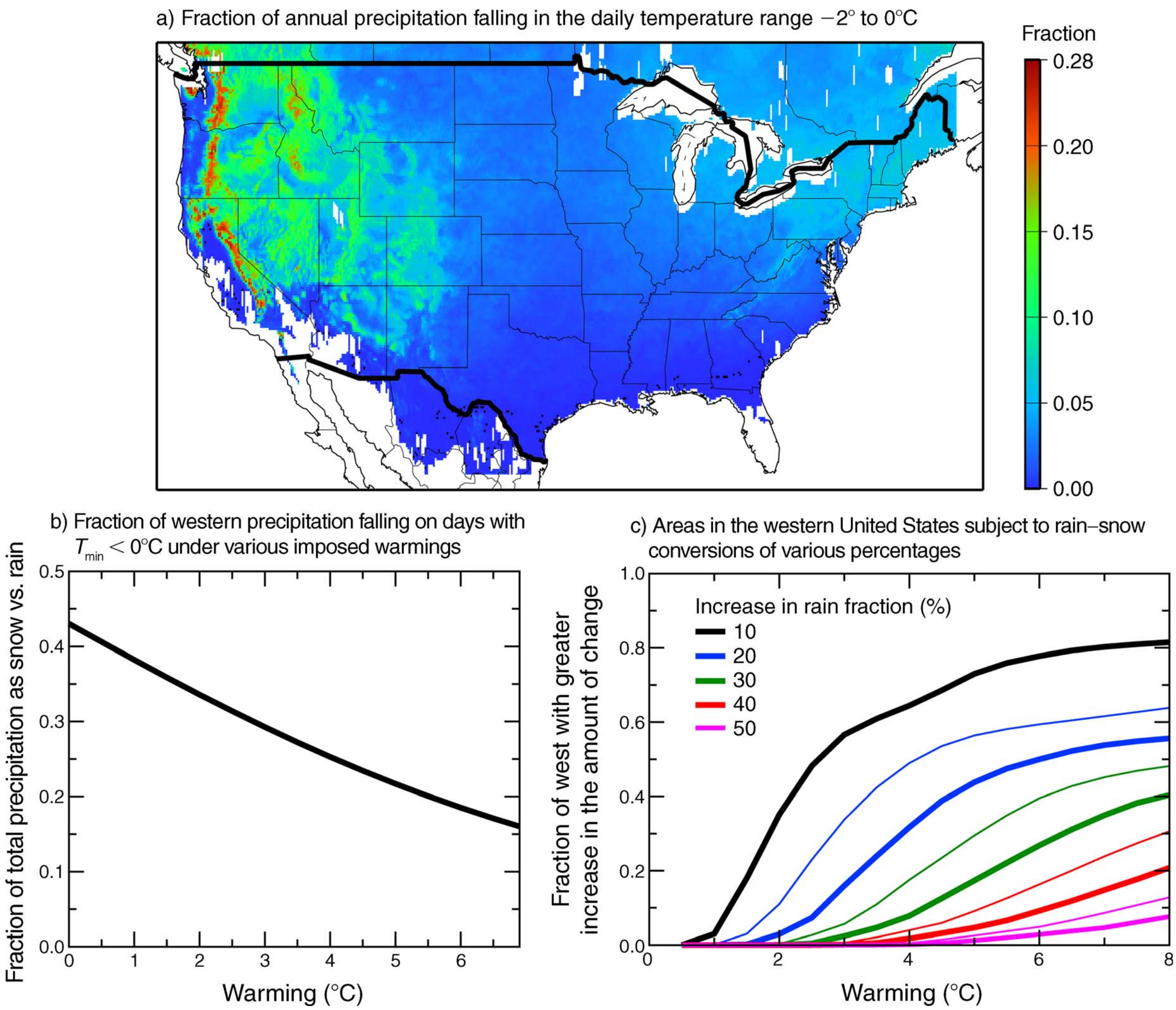

FIG. 3. (a) Influences of hypothetical +2°C warming (imposed uniformly on gridded daily temperature and precipitation, 1950–1999 (Maurer et al. 2002) on snow vs. rain fractions of total precipitation, as the historical fraction of precipitation that fell on days in the temperature range −2°C to 0°C; (b) fractions of overall precipitation, west of 100° W, falling historically on days with minimum temperature (T_{min}) less than freezing under various imposed warmings; and (c) fractions of the area of the western United States that would experience various degrees of snow–rain transition under various degrees of warming.

Snowpack and snow fed hydrologic conditions in the West are projected to continue to change, with major losses in the 1 April water content of the snowpack that feeds western rivers (snow water equivalent, or SWE; Fig. 2a); significant reductions in April to July runoff in California, Arizona, and the central Rocky Mountains (Fig. 2b); and reductions in warm-season soil moisture (Fig. 2c). A simple analysis of the historical record of daily precipitation and temperatures since 1948 helps to put the projected snow-system changes in the West into a national context: Fig. 3a illustrates the percentages of precipitation that have historically fallen on days in the temperature range between −2°C and freezing (Dettinger and Culberson 2008), as a proxy for the fraction of precipitation that might change from snowfall to rainfall under a modest +2°C warming. This simple consideration suggests that snowpacks are most vulnerable in the western United States (Klos et al. 2014), and indeed the western United States is where the largest changes have already been witnessed (Knowles et al. 2006, Feng and Hu 2007).

The possible rain–snow changes suggested in Fig. 2a are summarized for the western United States as a whole across a wider range of temperature changes in Fig. 3b and c. Fig. 3b shows a steady decline in the fraction of the regional-total precipitation that might transition from subzero to above-zero temperatures, indicating that about 4% more of the total precipitation would convert from snow to rain per °C warming, all other things being equal. This way of aggregating the snow-to-rain fractions gives, at the regional scale, a sense of the vulnerability of the overall water supply. However, only a fraction of the western land area is actually directly contact with water in lakes and streams, with about 10%

of the area of Colorado River Basin (as a proxy for western conditions more generally) lying within 60 m of open water, lakes, or streams (Batker et al. 2014). Across the broader dry-land areas of the West, changes from snow-dominated conditions to rain-dominated conditions are likely to impact winter and spring snow cover, length of snow seasons, soil freezing, and ultimately a variety of vegetation and ecosystem functions and services (such as potable water, flood risk reduction, water filtration, wildlife habitat, soil-erosion reduction, soil formation, raw materials, food, recreation, air quality, and aesthetic value; Batker et al. 2014). Ultimately these impacts may also result in changes in water supply yields (e.g., Goulden and Bales 2014, Painter et al. 2010) and carbon sequestration (e.g., Arnold et al. 2014). Fig. 3c, in contrast to Fig. 3b, summarizes areas (rather than precipitation totals) that might be making various levels of snow–rain transition as a function of warming. This metric has a somewhat less linear response to warming than that in Fig. 3b. Thus, for landscape managers, the snow–rain transition may entail an even more nuanced evaluation of impacts than for water managers.

Evapotranspiration (ET) is the second largest component of the western water cycle after precipitation and marks the divide between "green water" (that nourishes plants and landscapes and is quantified by ET) vs. "blue water" (that runs off or recharges groundwater, and is thus more often the subject of diversion and management for water supplies; Falkenmark and Rockstrom 2004). In snowy settings, sublimation of snow and ice can increase these returns of water to the atmosphere, sometimes in significant amounts (Strasser et al. 2008, Reba et al. 2012). Globally, land ET rates increased between 1982 and 1997 but then stopped increasing, or have decreased, since about 1998 (Jung et al. 2010), reflecting the so-called "hiatus" in atmospheric warming in this latter period (e.g., Trenberth and Fasullo 2013). The same ET decline has been witnessed in many areas of the western United States. Factors contributing to the land ET rate changes may include declining winds (Vautard et al. 2010, McVicar et al. 2012), declining solar insolation (Roderick and Farquhar 2002), increasing humidity (McVicar et al. 2012), and declining soil moisture (Jung et al. 2010).

Projections of actual ET rates vary by region (Hay et al. 2011, Wehner et al. 2011, Dai 2012, Hoerling 2012, Sheffield et al. 2012), but the atmospheric potential for ET is expected to increase globally and across the entire western United States region with warming. In the West, actual ET rates and totals will likely be affected by local soil moisture changes and by changing lengths of snow-covered and growing seasons. Changing vegetation and land uses in response to land developments and climate change also are likely to affect ET totals (Pugh and Gordon 2012, Goulden and Bales 2014). Much more research is needed to confidently understand the historical trends and to make confident projections of future ET rates and totals (Milly and Dunne 2011).

Runoff and streamflow at regional scales declined during the last half-century in the Northwest (Luce and Holden 2009), with no clear trends in much of the rest of the western United States (McCabe and Wolock 2011), although a declining trend may be emerging in annual runoff in the Colorado River Basin (USBR 2011). Historical fluctuations of streamflow have been dominated more by fluctuations in precipitation than by temperature (Karl and Riebsame 1989). Nevertheless, as warming proceeds and impacts ET and soil moisture, the amount of runoff generated by a given amount of precipitation is generally expected to decline (McCabe and Wolock 2011). Broadly speaking, in response to the combination of projected precipitation and temperature changes, annual streamflow is projected to decline in the Southwest (Milly et al. 2008, USBR 2011), and to increase in Alaska and the Northwest (Solomon et al. 2007, Milly et al. 2008, Elsner et al. 2010, USBR 2011, Markstrom et al. 2012), mirroring projected precipitation patterns (Strzepek et al. 2010). Annual and seasonal projected changes in runoff for eight basins in the Northwest, northern Great Plains, and Southwest are illustrated in Fig. 4 (USBR 2011, Georgakakos et al. 2014). Basins in the southwestern United States and southern Rockies are projected to experience gradual annual runoff declines, with basins in the Northwest to northcentral United States projected to experience little annual change through the midcentury, and increases by late century. Even though annual changes may be minimal, projected seasonal changes are greater in many areas, with cool season runoff increasing over the west coast basins from California to Washington and over the north-central United States. Basins in the southwestern United States and southern Rockies are projected to see little change to slight decreases in the winter months (USBR 2011). Warm season runoff is projected to decline substantially over a region spanning southern Oregon, the southwestern United States, and southern Rockies, and change little or increase slightly north of this region (USBR 2011).

Changes in annual hydrographs are likely to challenge water managers and users, even where annual volumes do not change. Higher flows in early spring will favor what have been junior and infrequently used storage rights, and senior rights may find less flow on the descending limb of the hydrograph through the summer and fall. In fact, the changing hydrograph will mean that some diversions thought in the 20th century to have reliable senior water rights may be without water during the hottest and driest periods of summer. The economic value of these once-prized rights would be vastly reduced (Stratus Consulting 2009). Environmental water will also be in short supply in this season, adding to overall stress.

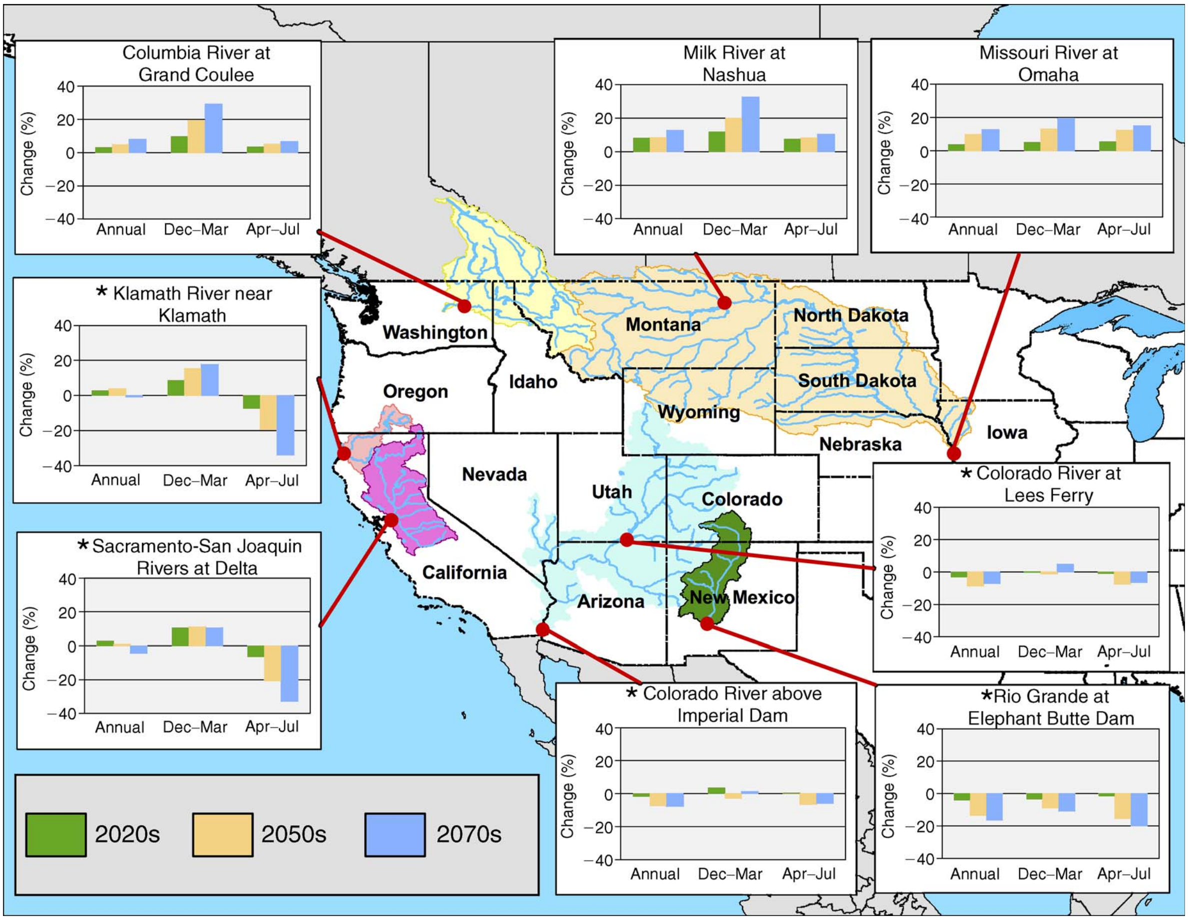

FIG. 4. Streamflow projections based on combinations of scenarios with substantial global-emissions reductions, some reductions from current emission trends toward the end of this century, and continuations of current rising emissions trends, for eight river basins in the western United States (USBR 2011), as percent change in average runoff for three future decades (2020s, 2050s, and 2070s) relative to the 1990s. Stars indicate four major river basins that are discussed in detail in this paper (the Colorado River basin is shown as Upper and Lower Colorado).

Drought

Droughts occur on time scales ranging from season-to-season to multiple years and even multiple decades. There has been no universal trend in the overall extent of drought across the continental United States since 1900. However, in the Southwest, widespread drought in the past decade has reflected both precipitation deficits and higher temperatures (Hoerling et al. 2013), in ways that resemble projected changes (Cayan et al. 2010). Except in the few areas where increases in summer precipitation compensate, summer droughts (Walsh et al. 2014) are expected to intensify almost everywhere in the continental U.S. (Trenberth et al. 2004) due to longer periods of dry weather and more extreme heat, leading to more moisture loss from plants and earlier soil moisture depletion in basins where snowmelt shifts to earlier in the year (Scibek et al. 2007, Huntington and Niswonger 2012). Basins watered by glacial melt in the Sierra Nevada, Rockies, and Alaska may experience increased summer river flow in the short term, until the amounts of glacial ice become too small to contribute significant river flow (Hall and Fagre 2003, Basagic and Fountain 2011), at which time flows may decline precipitously.

Flood

Fig. 5 shows statistically significant historical trends in flood magnitudes at only about 27% nationally of long-term gauges analyzed, and that floods have been decreasing in parts of the Southwest (see also Karl and Knight 1998, Gutowski et al. 2008, Villarini et al. 2009). With heavy rainfall events projected to increase, though, the potential for flash flooding is expected to increase in many settings. Land cover, flow and water-supply management, soil moisture, and channel conditions are also important influences on flood generation (Poff et al. 2006) and must be included in projections of future flood risks. Region-specific storm mechanisms and seasonality also affect flood peaks (Villarini et al. 2009). Because of this, and our limited ability to project future very heavy

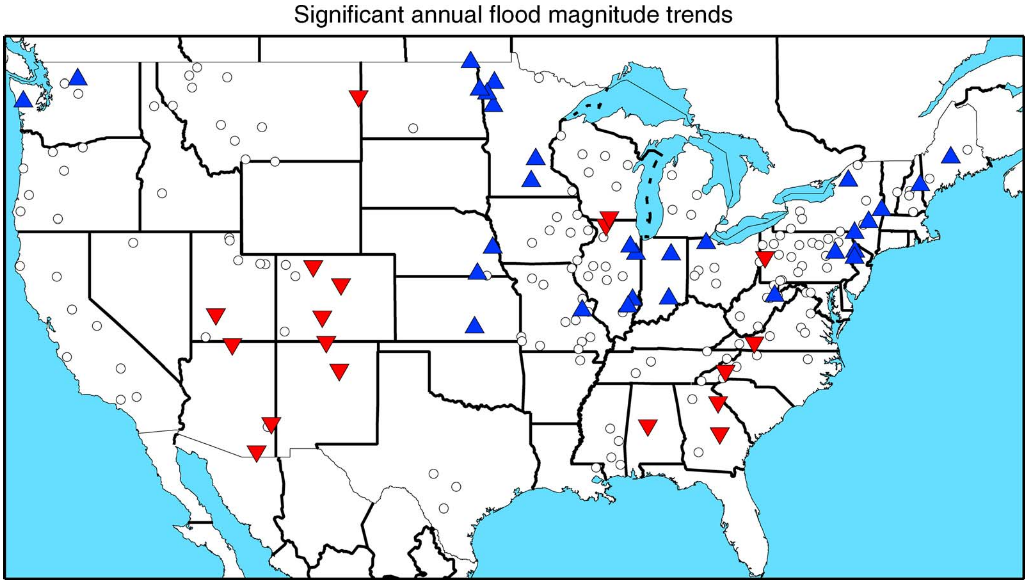

FIG. 5. Streamflow-gage locations (with >85 years of record) where the relationship between historical annual flood magnitudes and global atmospheric carbon dioxide concentrations has been statistically significant ($P < 0.05$; modified from Hirsch and Ryberg [2012]). Blue triangles indicate increasing annual flood magnitude trends, red triangles indicate decreasing trends, and white circles indicate trends that have not been statistically significant ($P > 0.05$).

events with precision, evaluations of the relative changes in various storm mechanisms may be useful (Villarini et al. 2009, Dettinger 2011). Warming is likely to directly affect flooding in mountain settings, as catchment areas receive increasingly more precipitation as rain rather than snow, and more rain on remaining snowpacks (Mote 2003, 2006, Knowles et al. 2006, McCabe et al. 2007, Nayak et al. 2012) In some such settings, flooding may increase as a result, even where precipitation and overall river flows decline (Raff et al. 2009, Das et al. 2013, Georgakakos et al. 2014).

Groundwater

Groundwater is the only perennial source of fresh water in many western regions and is commonly used as a buffer against climate extremes. As such, it is essential to water supplies, food security, and ecosystems. In regions of Nevada, Utah, and the southern Great Plains, groundwater is a primary water supply. Groundwater aquifers in these areas, and even in the rest of the western United States where surface water provides large fractions of overall supplies (Fig. 6), are susceptible to the combined stresses of climate and water-use changes. For example, during the 2006–2009 California drought, when groundwater was drawn upon to augment for flagging surface-water supplies for much irrigation in California's Central Valley, groundwater storage declined dramatically (Famiglietti et al. 2011). The current California drought has sparked enough groundwater development and pumpage so that the State has undertaken significant changes in how groundwater will be managed. Even in the Colorado River basin, where surface water provides large fractions of most water supplies (Fig. 6), sustained dry conditions during the past decade have resulted in massive groundwater depletions (Castle et al. 2014).

Climate change impacts on groundwater storage are expected to vary from place to place and aquifer to aquifer. Although precise responses of groundwater storage and flow to climate change are not yet well understood nor readily generalizable, recent and ongoing studies (Earman and Dettinger 2011, Taylor et al. 2012, Crosbie et al. 2013) identify key risk factors: (1) precipitation is the key driver of aquifer recharge in the widespread water-limited environments of the West (Hidalgo et al. 2008) while ET is the key driver in energy-limited environments (like swamps or marshlands) and (2) climate change impacts on recharge depend on several factors, including basin geology, frequency and intensity of high-rainfall periods that drive recharge, seasonal timing of precipitation, and strength of groundwater–surface water interactions. In many mountainous areas of the United States, groundwater recharge is disproportionately generated from snowmelt infiltration, suggesting that the loss of snowpack to warming may affect recharge rates and patterns (Earman et al. 2006, Scibek et al. 2007, Earman and Dettinger 2011, Huntington and Niswonger 2012).

Generally, though, impacts of changing demands on groundwater systems, whether due directly to climate changes or indirectly through changes in land use or surface-water availability and management, are likely to cause more immediate changes in groundwater availability (Taylor et al. 2012, Sheng 2013). Changes in

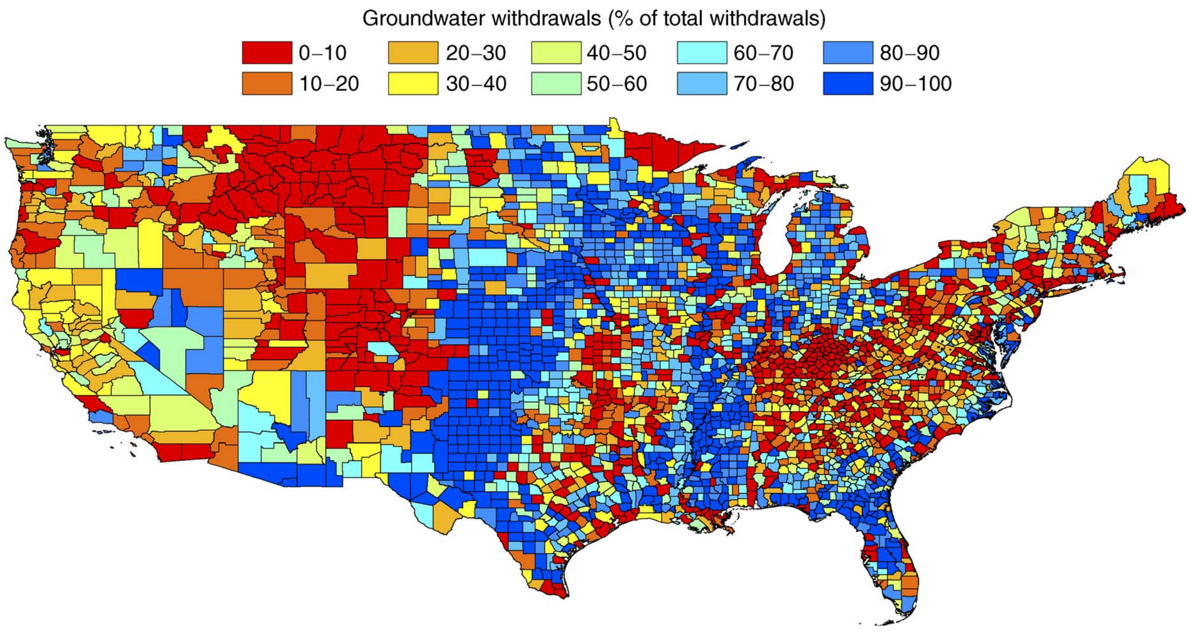

FIG. 6. Groundwater withdrawals as a percentage of total withdrawals (from all surface and groundwater sources) by county (Kenny et al. 2009, Georgakakos et al. 2014).

recharge and resulting changes in storage may be more subtle and take longer to emerge.

Water quality

Projected changes in air and water temperatures, precipitation intensity, and droughts will likely affect water quality in the West's rivers and lakes. Increasing water temperatures and intensifying droughts can inhibit lake mixing, reduce oxygen in bottom waters, and increase the time pollutants remain in water bodies. More intense runoff and precipitation can increase river sediment, nitrogen, and pollutant loads. Lower flows can concentrate pollutants, increase stream temperatures, and reduce dissolved oxygen. Unfortunately, our understanding of the specific of how quality will change remains limited.

Water temperature has been increasing in many rivers globally (Kaushal et al. 2010). Changes in streamflow temperature and flow regimes can affect aquatic ecosystem structure and function (Groffman et al. 2014). Water temperature directly regulates the physiology, metabolism, and energy of individual aquatic organisms, as well as entire ecosystems. Streamflow quantity influences the extent of available aquatic habitats, and streamflow variability regulates species abundance and persistence. Flow also influences water temperature, sediment, and nutrient concentrations (Maurer et al. 2010).

Other factors being equal, the length of the season that lakes and reservoirs are thermally stratified is increasing with increased air and water temperatures (Schneider and Hook 2010, Sahoo et al. 2012) and mixing may be inhibited or even eliminated in many lakes. For example, in Lake Tahoe—one of the deepest lakes in the world—the length of the season in which differences in lake temperatures with depth cause stratification (separate density layers) has been increasing since the 1960s (Fig. 7) in response to increasing air and surface water temperatures (Coats et al. 2006). Because of its large size (relative to inflow) and long water-residence times, other influences on stratification have been largely overwhelmed and warming air and water temperatures have caused progressive declines in near-surface density, leading to longer stratification seasons (by an average of 20 days), decreasing the opportunities for deep lake mixing, reducing oxygen levels, and potentially impacting many species and numerous aspects of aquatic ecosytems (UC Davis Tahoe Environmental Research Center 2012). Increasing stratification reduces deep mixing in the lake, which in turn is projected to lead to decreasing dissolved oxygen in the deep water and bottom sediments (Sahoo et al. 2012). These conditions are expected to encourage the release of nutrients (nitrogen and phosphorous; Baron et al. 2013), heavy metals (such as mercury), and other toxins into lake waters (Schneider and Hook 2010, Sahoo et al. 2012).

Water withdrawals and demands

Total U.S. freshwater withdrawals (including water that is withdrawn and consumed as well as water that returns to a source) and consumptive uses have leveled off and even declined nationally since 1980 (Maupin et al. 2014). Western water withdrawals have followed suit despite more than a 50% increase in the region's population (Fig. 8; Brown et al. 2013*b*). This leveling

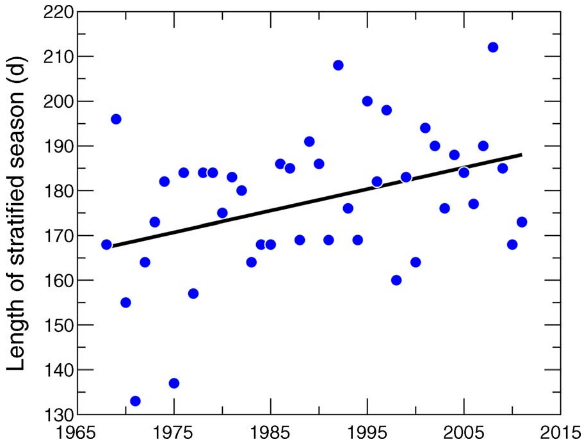

FIG. 7. Observed changes in lake-stratification season length for Lake Tahoe. The black line is a linear trend fitted to the season lengths, by linear regression ($r = 0.39$, $P < 0.01$), indicating increases in season length of about 5 days per decade since 1968.

reflects demand management, including switching from flood irrigation to more efficient methods in many parts of the western United States (Brown 2000, Foti et al. 2012), enhanced water use efficiencies in response to environmental pollution legislation (in the industrial and commercial sector); new plumbing codes, water efficient appliances, efficiency improvement programs, and pricing strategies (Groves et al. 2008, Jeffcoat et al. 2009, Rockaway et al. 2011) in the municipal sector; changes from water-intensive manufacturing and other heavy industrial activities to service-oriented businesses (David 1990); and replacement of older once-through-cooling electric power plants by plants that recycle their cooling water (in the thermoelectric sector). At the national level, irrigation and all electric power plant cooling withdrawals account for ~77% of total withdrawals but most of the power-plant usage is in the eastern states. In most of the West, though, irrigation is the dominant water use (Fig. 9d). Comparatively few of the farms thereby serviced are the small family farms of yesteryear (Fig. 9b). In the West, about 81% of the irrigation waters are consumed by evapotranspiration and plant growth.

Water demand is projected to increase as population grows, but is projected to increase substantially more as a result of climate change. In the absence of climate change but in response to a projected population increase of 80% and a 245% increase in total personal income from 2005 to 2060, simulations indicate that total water demand in the United States could increase by 3% (Brown et al. 2013*b*). Under these conditions, approximately one-half of the western United States would experience an overall decrease in water demand, while the other half would experience an increase (Fig. 10a). Recent projections of western water consumption between 2010 and 2030 suggest that, while irrigation uses may not increase much (neglecting, for the moment, climate change), increased uses for municipal and industrial sectors are expected (Tidwell et al. 2014). If, however, climate change is also factored in, the total water demand is projected to rise by an average of 26% over the same period (Fig. 10b; Brown et al. 2013*b*). When climate change is included, 90% of the country and 100% of the West is projected to experience a total demand increase, although—using a different methodology—Averyt et al. (2013) found some areas in the far Northwest and deepest Southwest escaping the increases. By 2090, total water demand is projected to increase by 42% under the A1B scenario and 82% under a higher-emissions A2 scenario. Crop irrigation and landscape watering needs are directly affected by climate change, especially by projected changes in temperature, potential ET, and soil moisture. Consequently, the projected increases in water demand are larger in the western states, where irrigation dominates total water withdrawals. Thus the impacts of projected population, socioeconomic, and climate changes may combine to amplify water demand in the West.

Instream water uses

Hydropower contributes 7% of electricity generation nationwide, but provides up to 70% in the Northwest and 20% in California, and Alaska (USEIA 2013). Climate change is expected to affect hydropower directly through changes in runoff (average, extremes, and seasonality), and indirectly through increased competition with other water demands. Based on runoff projections, hydropower production is expected to decline in the Southwest (EPRI 2011), unless offset by new hydropower operations and technologies.

Changing climate is also projected to affect water and wastewater treatment and disposal in ways that depend on system-specific and interacting attributes. For example, elevated stream temperatures, combined with lower flows, may require wastewater facilities to increase treatment to meet stream water quality standards (USEPA 2011). More intense precipitation and floods, combined with escalating urbanization and associated increasing impermeable surfaces, may increase contaminated overland flows or combined sewer overflows (USEPA 2008). Moderate precipitation increases, however, could result in increased stream flows, improving capacity to absorb wastewater in some regions. Sea level rise and more frequent coastal flooding could damage wastewater utility infrastructure and reduce treatment efficiency (Flood and Cahoon 2011, Moser et al. 2014).

The projected increases in water withdrawals and uses (Fig. 10) threaten to deepen and widen ecosystem impairments, especially in the Southwest where drier conditions are projected (Groffman et al. 2014). These impairments include too much and too little sediment, hydrographs out of alignment with fish and habitat needs, water temperatures below dams too cold in summer and too warm in winter, and dams that impair

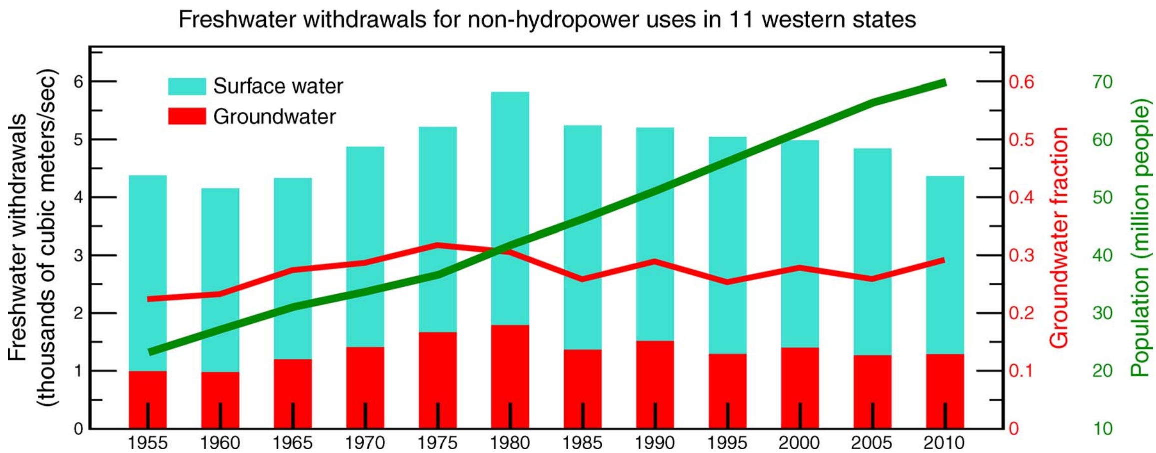

FIG. 8. Western U.S. freshwater withdrawals from groundwater and surface water sources (bars; left-hand *y*-axis), with fractions of withdrawals from groundwater (red curve; inner right-hand *y*-axis) and population trend (green curve; outer right-hand *y*-axis) overlain. States included in data are Arizona, California, Colorado, Idaho, Montana, Nevada, Oregon, Utah, Washington, and Wyoming. Primary data are available at http://water.usgs.gov/watuse.

upstream and downstream fish movements (Poff and Mathews 2013).

WESTERN WATER AND CLIMATE CHANGE: FOUR ICONIC RIVERS

Water strategies and solutions to meet western population growth have spanned a broad range from increasing supplies to decreasing demands. Many of these could also be used to adapt or prepare for climate change adaptation. Examples of these strategies include new dams (being considered in California and Colorado), desalination (San Diego), basin imports via pipeline (St. George, Utah and the Front Range of Colorado), municipal conservation, permanent transfers from agriculture (Colorado Springs), water markets, land fallowing (Los Angeles), canal lining (San Diego), retirement of grass lawns by purchase (Las Vegas), groundwater banking (Arizona), reuse (Orange County and Aurora, Colorado), new rate structures, consumer education, municipal conservation, indoor fixture rebates (Denver), new landscape design, water loss management from leaky mains, and aquifer storage and recovery (Arizona) (Western Resource Advocates 2005). On the whole, given the uncertainties about the precise forms that climate-change will take, it may be that solutions that engage whole portfolios of differing supply and demand options, with differing climate vulnerabilities, may be the most robust in the future. However, detailed analyses of future water-supply reliabilities in the Inland Empire area of southern California under a wide range of highly uncertain future climates (Groves et al. 2008) showed that (1) strategies in which adaptions and plans are continually revisited and rethought, as additional information emerges, are the least expensive options that agencies can pursue and (2) the next most effective and cost-efficient strategies are demand reductions. In this context, the good news is that per capita demand has declined in recent years in many Southwestern cities through active demand management programs (Gleick 2010, Cohen 2011).

Both tools and barriers confront those who intend to prepare and adapt western water systems for climate change. A quick overview of the situations in four iconic western river basins (Fig. 4) provides a sense of the challenges that confront the region.

The Colorado River basin

The Colorado River drains parts of seven states and two nations in the American Southwest (Fig. 4). Its waters irrigate over 20 000 km^2 of land inside and outside of the basin, and serve 40 million Americans in every major southwestern city (USBR 2011). The river's waters were originally allocated under the 1922 Compact that split the river into a Lower Basin (California, Nevada, and Arizona) and an Upper Basin (Colorado, Utah, New Mexico, Wyoming). A 1944 international treaty set aside 1.85 km^3 annually for Mexico. Agriculture consumes over 80% of the total water use in the basin (USBR 2011, Cohen et al. 2013). Additional laws, agreements under NEPA, international treaties, and Supreme Court Decrees have added to the original agreements (Meyers 1966, Getches 1984, Verburg 2011), and constitute what is called "The Law of the River." Upper Basin agriculture is mainly alfalfa production and pasture for cattle. The Upper Basin climate, with few exceptions, does not support other crops due to the relatively short growing season. Notably, alfalfa is highly consumptive of water (Glennon 2012, Robbins 2014). Lower Basin agriculture is extremely varied and includes cotton, wheat, and many winter vegetables, in addition to large amounts of alfalfa (Cohen et al. 2013). Reflecting the aridity of the region, most of the cities served are either beyond the basin's boundaries (Los Angeles, San Diego, Denver, Salt Lake, Albuquerque)

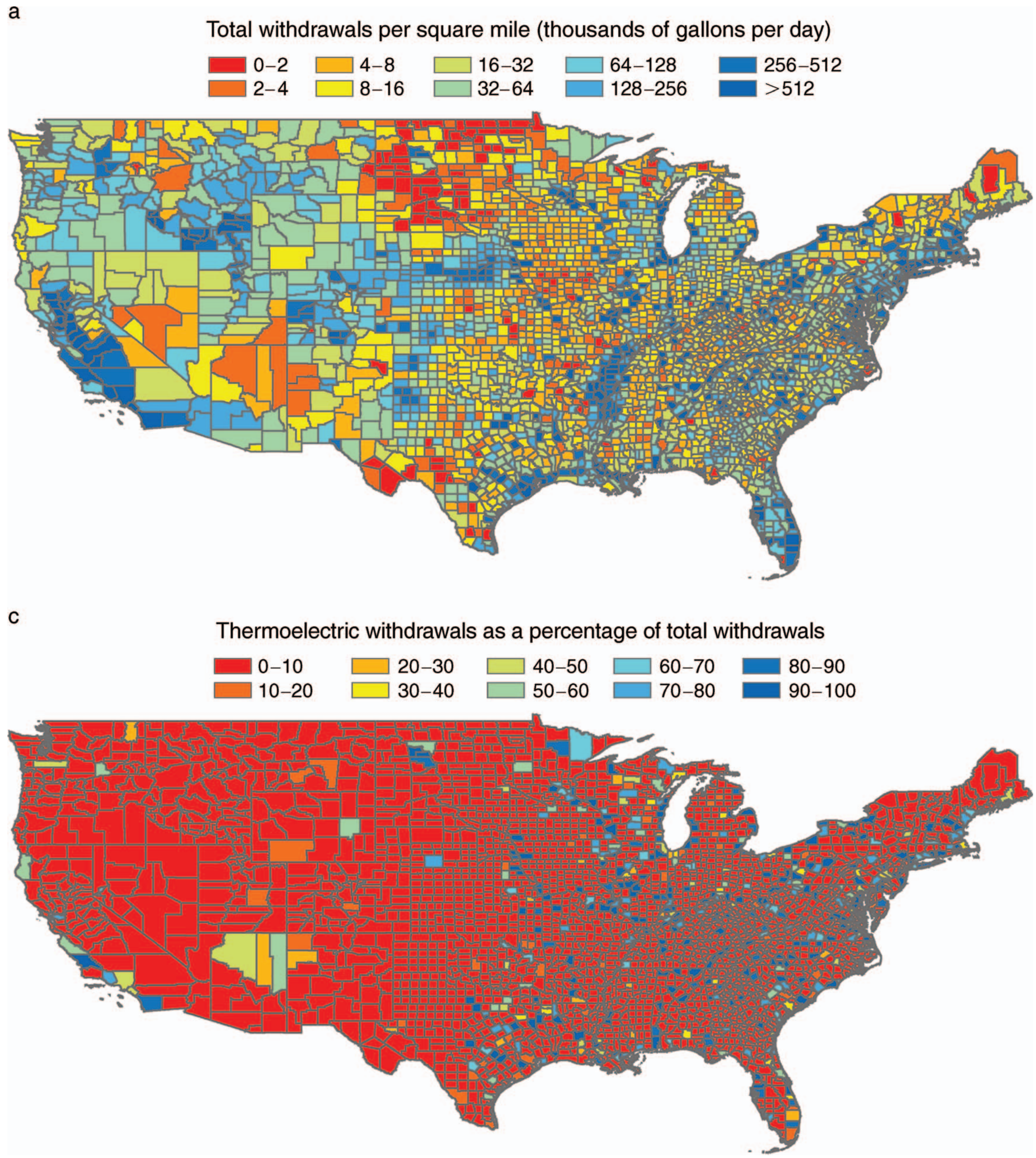

FIG. 9. Geographical distribution of 2005 U.S. water withdrawals by sector and source (Kenny et al. 2009, Georgakakos et al. 2014): (a) total withdrawals (surface and groundwater) in thousands of gallons per day per square mile (about 10 $m^3 \cdot d^{-1} \cdot km^{-2}$); (b) fraction of farms operated by family or individual, by county as a percentage of total (U.S. Department of Agriculture 2012); (c) thermoelectric plant cooling withdrawals as percentage of total withdrawals; and (d) irrigation, livestock, and aquaculture withdrawal, as percentage of total withdrawals. Ranges are inclusive at the upper end (i.e., 0–10, 10.01–20, etc.).

or significantly uphill from their supply points (Las Vegas, Phoenix, Tucson).

The river is fed primarily by winter snowpack from the Rocky Mountains, with roughly 15% of the total basin area (mostly in the Upper Basin) generating 85% of the flow. The 20th-century mean annual flow at Lees Ferry, the dividing line between Upper and Lower Basins, was approximately 18.5 km^3. Half of this volume was allocated to the Lower Basin and half to the Upper Basin in the original Compact. (A small but important part of the basin's runoff (1.1 km^3) enters the river below Lees Ferry in the Grand Canyon.) Unfortunately, the 20th century is now known to have been anomalously wet, especially at the time of the compact negotiations, and megadroughts substantially more severe than those in the 20th century have occurred many times during the

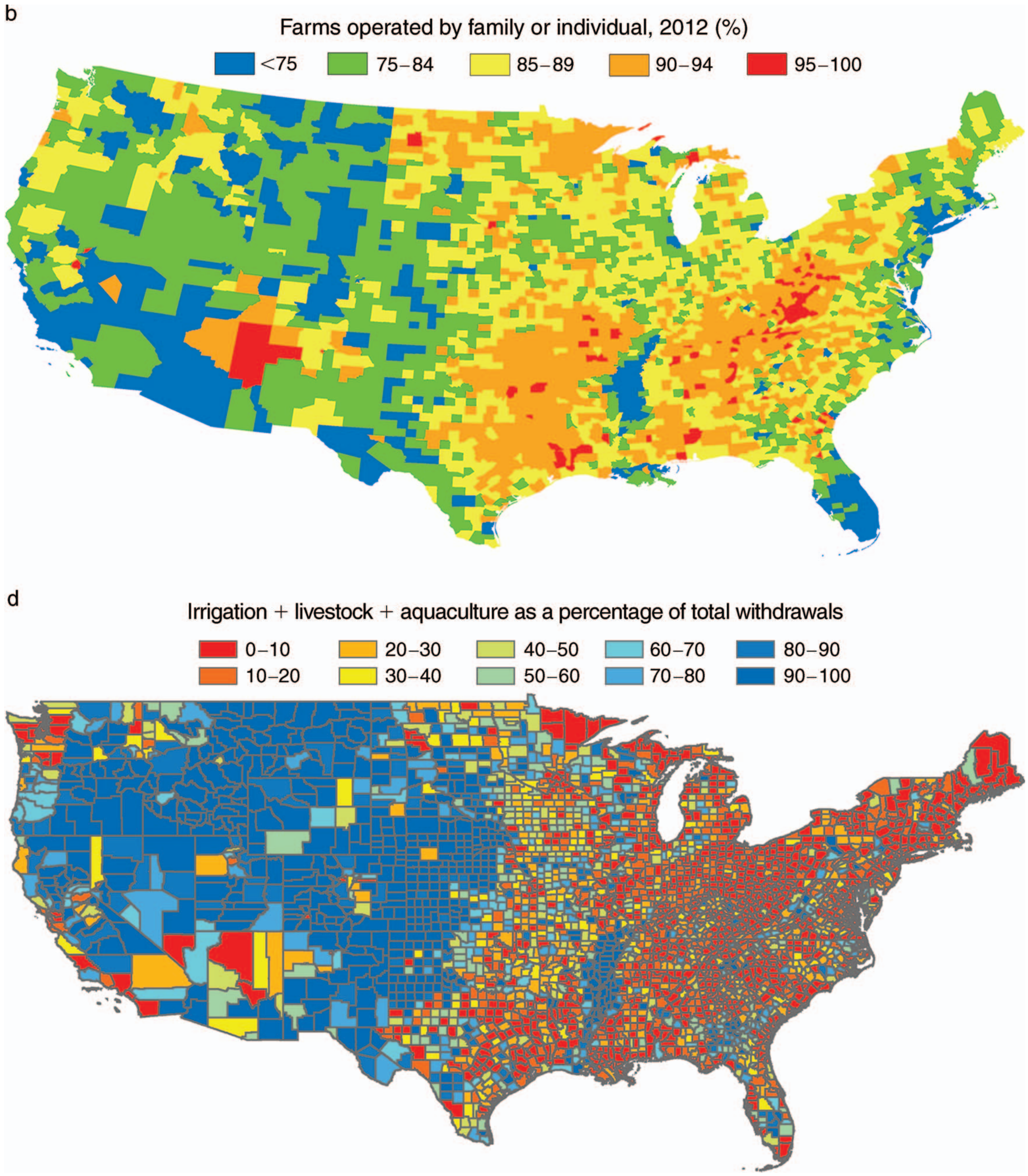

FIG. 9. Continued.

past several thousand years (Woodhouse et al. 2006, Meko et al. 2007). Climate change is now expected to exacerbate droughts and likely lower the mean flow (Ault et al. 2014).

Recent climate-change projections over the basin have consistently indicated that the southern parts of the basin are likely to face precipitation declines and enhanced droughts, in contrast to the northernmost parts of the basin that may experience smaller precipitation declines or even increases (Gao et al. 2011, Cayan et al. 2013, Polade et al. 2014, Walsh et al. 2014). Most of the basin lies in the area between these two trends, so that projected future precipitation amounts are quite climate-model dependent and uncertain. Temperatures are of course projected to warm throughout the basin, and evaporative (and transpiration) demands are thus generally expected to increase. Thus less runoff and recharge may result from any given amount of precipitation, however much precipitation does or does not change in the basin. Nonetheless, precipitation projections remain quite uncertain and variable (from place to place and model to model), so that the precise effects of climate change on water supply in the basin as a whole remain uncertain.

Furthermore, dust on snow from the southwestern deserts has been shown to advance runoff timing by three weeks and decrease water quantity by 5% by darkening snowpack and thus absorbing more solar energy. Much of this blowing dust results from land use disturbances such as construction, grazing, and off road vehicles in the region. Under climate change, another loss of as much as 1% and a significant additional three-week timing advance might occur (Painter et al. 2010, Deems et al. 2013).

Despite this supply-side uncertainty, the Colorado River basin almost certainly faces major future water-resource shortages because it is already overallocated and demands upon the river continue to grow (see Plate 1). Under the continuous onslaught of built-in deficits and (likely) reductions in its flows relative to the allocations of its waters and, especially, continued growth of water demands on the system, even the basins abundant storage options provide only short-term respites. The river system is restricted and managed by over 100 reservoirs. Bureau of Reclamation reservoirs provide the majority of storage in the system. Hoover Dam, completed in 1935, and Glen Canyon Dam, completed in 1963, provides over 62 km^3 of storage in the nation's two largest reservoirs, Lakes Mead and Powell. An additional 12 km^3 is stored in Upper Basin reservoirs (USBR 1981). Total reservoir storage is four times the annual flow, a very large amount of storage relative to most other comparable rivers in the world. Recent studies have explored the chances that the major reservoirs will dry out under the combined influences of climate change and heavy demands; all reach the conclusion that this is a very likely outcome under current management practices sometime before 2050 and perhaps as soon as 2020 (Barnett and Pierce 2008, 2009, Rajagopalan et al. 2009).

There are two distinct but related water quantity problems in the Colorado River Basin, one in the Upper Basin, and one in the Lower Basin. In the Lower Basin, the passage of the 1968 Colorado River Basin Project Act created a long-term built-in deficit, defined as an imbalance between the water legally available to the Lower Basin and the amount used by its three states. This act authorized the construction of the Central Arizona Project (CAP), an annual 2-km^3 diversion from the Colorado River to Phoenix, Tucson, and agricultural areas in Arizona. Of this amount, availability of 1.5 km^3 per year is dependent on the Upper Basin not using their full allocation. It was known that over time this "extra" Upper Basin water would decline due to increasing population and use in the Upper Basin (Tipton and Kalmbach 1965, Johnson 1977). The only unknown was when the Upper Basin would use their full allocation, thereby depriving CAP of its supply. Also, the 1968 Act did not account for the growth of Las Vegas from approximately 275 000 residents to the current 2 million people with 90% of their supply coming from Lake Mead. Climate-change reductions in flow will only speed the day of reckoning due to these gaps and could make the built-in deficit worse, especially if flow declines were to occur to the limited but critical aforementioned inflows below Lees Ferry.

The drought of the past 15 years in the Southwest has made the built-in deficit obvious, and by 2007 the Basin states agreed to new operational rules for reservoirs and Lower Basin deliveries in times of shortage (U.S. Department of Interior 2007). Only one-half of the 1.5-km^3 built-in deficit was covered by the agreement, however. With continuing drought conditions, in 2010 and again in 2014, Lake Mead dropped to within 3 m of the first trigger point established in the 2007 rules. The Lower Basin states are reportedly in negotiations to solve this difficult problem, which will likely require that California share in shortages (Wines 2014*a*, *b*).

The Upper Basin faces a different, but related, problem. Under the terms of the 1922 compact, they agreed to not deplete the flows at Lees Ferry below 93 km^3 in any given 10-year period. This arrangement was reached as an imperfect way to limit Upper Basin consumptive use (Colorado River Commission 1922). When the compact was negotiated, it was never anticipated that this limit would be reached, because the supply was thought to greatly exceed the amount allocated. The flows, however, have proven to be less than originally thought, thus providing the Upper Basin with an allocation to an uncertain, continually varying amount of water, which makes planning for future Upper Basin development difficult. The most immediate examples of this difficulty and uncertainty is provided by the current drought, which has yielded flows that have been approximately 20% below the long-term mean and has reduced reservoir storage by 60%. If the drought continues apace for even a few more years, the Compact could require the Upper Basin to curtail its uses to meet its 93-km^3 obligation.

In the midst of these large-scale built-in and developing challenges, significant tribal rights need to be addressed. A number of Indian tribes inhabit the basin on federally created reservations. Under the Winters Doctrine, these tribes are entitled to reserved water rights (Royster 1994, Shurts 2000). Only some of these tribal rights have been fully quantified, with most other tribes who are still seeking to finalize rights residing in Arizona. One of the more uncomfortable aspects of this situation is that supplies for tribal rights come from the states in which they live, despite the federal nature of the obligation (Royster 1994). Arizona has by now allocated all of its most senior CAP water right for tribes, and remaining settlements will have to come from its lower priority CAP supplies, supplies that are most likely to be curtailed by the 1968 agreement (Weldon and McKnight 2007).

A number of environmental concerns also challenge the basin (Pitt et al. 2000, Pitt 2001, Adler 2007). Dams

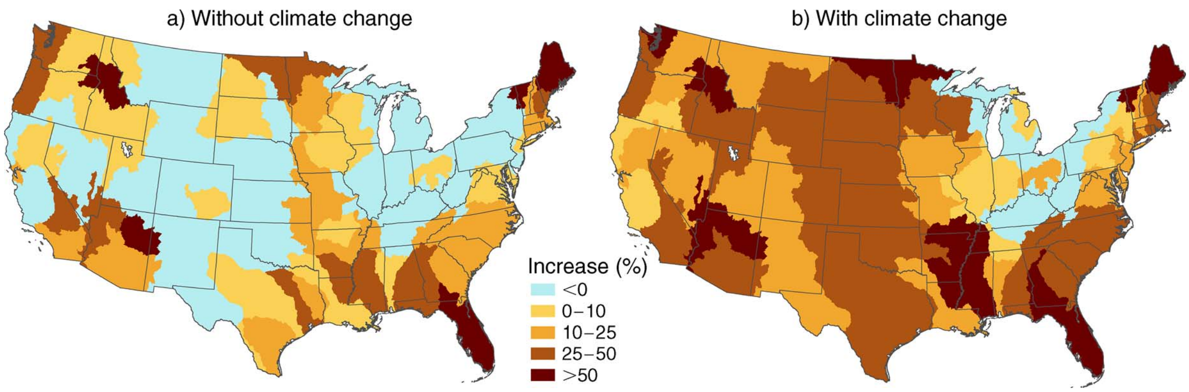

FIG. 10. Projected 2005–2060 changes in water withdrawals (Brown et al. 2013*b*) (a) incorporating projections of economic and population growth and (b) also including climate change projected by three climate models under a middle-of-the-road A1B greenhouse-gas emissions scenario (increasing emissions through the end of this century, with reductions in the rate of increase after 2070). Ranges are inclusive at the upper end (i.e., 0–10, 10.01–25, etc.).

and other infrastructure on the river have blocked fish movements, restricted sediment transport, and changed the timing and temperature of flows. In addition, introduced nonnative fishes threaten endemic fishes. In the Upper Basin, there are federally listed endangered fish in multiple tributaries including the San Juan, Gunnison, Colorado main stem and Green. There are Recovery Programs under the Endangered Species Act (ESA) in place (Adler 2007), but these programs are funded from hydropower sales that have been reduced during the drought. In the Lower Basin in 2005 a basin-wide Habitat Conservation Program was finalized, the Multi-Species Habitat Conservation Program. It provides for over US$650 million over 50 years to conserve 26 species; 6 threatened and/or endangered and 20 non-federally listed species (Adler 2007). The river also has not reliably reached its terminus in the Sea of Cortez for almost 50 years. New international agreements are in place to provide environmental flows in the lowest river reaches and, in 2014, the first of these flows was released.

The Rio Grande

The Rio Grande drains a bi-national basin that flows through Colorado and New Mexico before reaching Texas at El Paso, from whence it continues south and east to form a 2000-km U.S.–Mexico international border (Hill 1974). The river's headwaters in Colorado's eastern San Juan Mountains drain a small area compared to the Colorado, and consequently those headwaters produce a comparatively small amount of flow, about 1.2 km^3 per year from snowpack. Flows are also highly variable from year to year (Gutzler 2011). Near these headwaters, the Rio Chama is the largest U.S. tributary to the Rio Grande, contributing another approximately 0.5 km^3 per year from a drainage that also drains part of Colorado's San Juan Mountains (Thomson 2011). The present discussion will only extend as far south as Fort Quitman, Texas, a bit south of El Paso and Cuidad Juarez, Mexico. (The river is often dry at Fort Quitman due to upstream extractions and only regains flow at its confluence with Mexico's Rio Conchos [Schmandt 2002].) The Rio Grande upstream from Fort Quitman (the Upper Rio Grande) comprises three distinct agricultural segments: Colorado's San Luis Valley; the Middle Rio Grande, in New Mexico, from near Cochiti Reservoir to Elephant Butte Reservoir; and the Paso del Norte region from Elephant Butte Reservoir to Fort Quitman, also mostly in New Mexico.

Water in the river is derived predominantly from snow, although New Mexico in some years has a pronounced summer monsoon that can provide significant if unpredictable water in the Middle and Paso del Norte reaches. At least two studies have investigated future flows of the Rio Grande under the influence of climate change (Hurd and Coonrod 2012, Llewellyn et al 2013). Lewellyn et al.'s 2013 study indicated that, by 2100, flows available for irrigation uses in Colorado's San Luis Valley could decline by 25%. Divertible flows in the Middle Rio Grande were projected to decline by 35%, in large part because the compact allows Colorado to use more flow at lower flow levels so that it could deliver less to New Mexico. Below Elephant Butte, flows could decline by 50%. These declines are Reclamation's worst modeled flow outcomes from climate change in the entire United States, and reflect the small size of the basin, the small size of its primary runoff-generating snow-covered areas, and its position far enough south so that it is projected (by nearly every climate model) to lie within the zone where climate change is most likely to entail significant precipitation declines.

The river is governed by a 1906 international treaty and a three-state compact signed in 1939. The compact was designed to protect senior agricultural water rights in both Colorado and near El Paso. Under the compact, the upper two sections have annual (and occasionally year-to-year) delivery requirements to river sections downstream that vary nonlinearly according to input flows The compact has been the source of much interstate litigation between the three signatory states (Paddock 2001), and the most recent ongoing litigation involves the consequences of groundwater pumping on a large scale, something not envisioned in the compact. The 1906 treaty requires a small 0.074-km^3 delivery to Mexico near El Paso.

Two aspects of water management of the Rio Grande are not present elsewhere in the West. Acequias are communal water systems that share in maintenance and shortages, unlike the predominate western legal doctrine of prior appropriation. These rights are typically tied to the land and cannot be transferred to new uses. New Mexico's 12 Pueblos were established before the United States existed, and hence have unquantified but "time immemorial" water rights that predate even the Spanish Law once utilized in the region. Pueblo rights have been the subject of some of the longest-running Supreme Court cases. Both of these rights complicate and add uncertainty to water management.

Three large cities, Albuquerque, population 555 000, El Paso, population 672 000, and Ciudad Juarez, population 1.3 million, rely on the river for large fractions of their supplies, along with heavy groundwater pumping (which involved significant aquifer overdrafts in the past, that in recent years have been stabilized). However, as with other regions around the West, agriculture is a dominant water use. The Bureau of Reclamation constructed four federal projects in the basin. The Rio Grande project was approved in 1905, and its primary reservoir, the 2.5-km^3 Elephant Butte, was completed in 1916 to service project lands (Littlefield 2008) in the Paso del Norte region and beyond. Water from this reservoir is delivered by Elephant Butte Irrigation District and El Paso County Water Improvement District #1 to farmers in New Mexico and Texas. The Rio Grande Project services 728 km^2 of U.S. land and another 100 km^2 in Mexico (USBR 1981). Major irrigated crops are cotton, alfalfa, pecans, vegetables, and grain. The Bureau of Reclamation's Middle Rio Grande Project was approved in 1950s and involved rehabilitation of an existing regional irrigation system, the Middle Rio Grande Conservancy District. Reclamation channelized the Rio Grande in this river section creating a number of environmental problems. Approximately 400 km^2 are irrigated by the project. Alfalfa, barley, wheat, oats, corn, fruits, and vegetables are the principal crops grown (USBR 1981). Still farther upstream, in the San Luis Valley, agriculture and irrigation developed prior to federal involvement (USBR 1981). The Closed Basin Project there was completed in the 1970s to provide agriculture with extra supplies not subject to the compact. The fourth Bureau of Reclamation project is the San Juan–Chama built in the 1970s to move Colorado River water into the Rio Grande, thereby providing an additional 0.1 km^3 per year for the Rio Grande. This project provides municipal supplies for Albuquerque and Santa Fe, irrigation supplies for the Middle Rio Grande Conservancy District, and is also used for a federal reserved rights settlement with the Jicaralla Apache Tribe. In recent drought years, this water has been critical for environmental, municipal and irrigation interests. This water, however, is subject to New Mexico's Colorado River Compact allocation and could be curtailed by drought and climate change.

The river has been heavily modified by human activities, including changes in sediment loading and capture, changes in the seasonal hydrograph, increases in salinity, channelization, and on-stream reservoir construction (Llewellyn et al 2013). In 1994, the Rio Grande Silvery minnow was listed as federally endangered. The fish was found only in the reach between Cochiti and Elephant Butte dams, 5% of its historic range from the mountains to the ocean. Severe habitat loss, channelization, blockage of fish movement, too much and too little sediment, and increased salinity have all contributed (Cowley et al. 2006). A severe drought began in 1996 and that same year the diversion of the entire river brought about a large minnow kill. The Bureau of Reclamation began using stored water from up its San Juan–Chama (SJC) Project near the headwaters of the river against the protests of the SJC contractors to benefit the minnow. Beginning in 1999, a number of complicated legal disputes ensued over a proposed recovery plan, critical habitat designation, biological opinions, and the legality of the using SJC water for the minnow (Katz 2007, Kelly and McKean 2011, DuMars 2012). Proposed solutions for minnow recovery include removal of Cochiti Dam, thus providing a riverine environment that never historically dried, more water in the river, sediment control in river uplands, "naturalize" irrigation drains to mimic habitat, set levees further back to allow ecosystem services to occur, and enactment of strict water conservation (Cowley 2006).

Thus, the Rio Grande is another western basin that is using its water to the maximum, and even more so than in the Colorado, current projections of climate change suggest that the flows that are currently being disputed and wrangled in the Rio Grande are likely to be less and less available for any use as the century wears on. On the whole, the Rio Grande is facing the largest climate-change water-supply deficits (relative to historical record) among the four basins considered here.

The Klamath

The Klamath River is volumetrically the third largest river on the West Coast, with approximately 480 m^3/s in average discharge. The basin is smaller than the others considered here, with the river traveling about 425 km from headwaters in southern Oregon to discharge in the Pacific Ocean in California. The Klamath is an "upside down" basin: it is relatively flat in its headwaters (the Upper Basin) and its 300-km lower canyon is relatively steep and narrow (the Lower Basin). Above its discharge point, the Klamath is joined by the Trinity River in

PLATE 1. Climate change is projected to exacerbate extreme climatic events, like drought and its impacts on western water supplies. This photo shows Lake Mead and Boulder Dam, on the Colorado River (USA) in February 2015, with a stark white "bathtub ring" of dry slopes exposed below normal water levels as a result of current drought conditions over much of the Southwest United States. Photo credit: Kelly Redmond.

California. Also unusual is that the Upper Basin generates a relatively small fraction of the total flow (12%) while lower tributaries, the Salmon, Shasta, Scott, and Trinity, generate the remainder (Powers et al. 2005). The Bureau of Reclamation's Klamath Project in the Upper Basin was authorized in 1905 and water deliveries from it began in 1907 (USBR 1981, Powers 1999). The Project includes seven dams and four major natural but enlarged lakes, and many irrigation canals and pumping facilities. Upper Basin lakes are large (0.6 km^3) but are very shallow. These reservoirs provide negligible carry-over storage from year to year. Approximately 900 km^2 are irrigated in the Upper Basin producing wheat, malt barley, alfalfa, onions, and potatoes. Cattle are grazed on irrigated pasture. About 250 000 people inhabit the basin. Four private hydroelectric dams were installed in the early 20th century just below the Upper Basin. These dams block coho, chinook, and steelhead migrations into the Upper Basin, where the fish were historically present (Hamilton and Curtis 2005). The Federal Energy Regulatory Commission (FERC) license for the dams expired in 2004 and long-term relicensing has been delayed pending resolution of the basin's problems.

Under natural conditions, the Klamath River was the third most productive salmon river on the West Coast, after the Columbia and Sacramento Rivers. Barriers to fish passage, eutrophication, and warmer water temperatures now impact migrating salmon, especially during droughts. Irrigation along the upper Klamath, along with the almost-total diversion of the Trinity River, have reduced flows, impacting migrations of salmon in both spring (outward migrations) and fall (upstream migrations; Hamilton and Curtis 2005, National Research Council 2008). The Upper Basin contains six national wildlife refuges encompassing almost 800 km^2 of freshwater marsh, open water, croplands, meadows, and some old growth forest. Two of the refuges utilize Klamath Project water, thus competing with farmers. The refuges provide habitat for waterfowl, water birds, wintering bald eagles, and other animals. The Lost River and shortnose suckers that inhabit the upper basin were listed as endangered in 1988. Water quality conditions in the (Upper) Klamath Basin lakes have been a concern with respect to sucker mortality, with the lakes subject to warming and eutrophication with concomitant loss of dissolved oxygen (Kann and Welch 2005). Low levels of dissolved oxygen have been associated with fish mortality (Martin and Saiki 1999).

The lower Klamath River is affected by Reclamation's Shasta/Trinity River Division project, a very large transbasin diversion of up to 90% of the Trinity's flows into the Upper Sacramento River for use by the Bureau of Reclamation's Central Valley Project (McBain and Trush 1997). Low flow levels and high water temperatures in the Lower Basin are also of concern to salmon species (once present throughout the basin and now restricted to the Lower Basin), such that, in 1997, coho salmon were listed as threatened.

All told, the Klamath fisheries and flows have been much impacted by agricultural development and heavy management of its waters (including those of the Trinity), and the basin is well known as a setting for some of the most contentious and near-violent confrontations between various water-use communities. In 2001, Reclamation issued a biological assessment of the endangered suckers. In response, biological opinions from the U.S. Fish and Wildlife Service (USFWS) for suckers and National Marine Fisheries Service (NMFS) for coho were released later that year. Both the USFWS and NMFS called for higher reservoir levels and higher mainstem flows to protect the fish. Also, in 2001, Reclamation announced that due to severe drought no water would be released to farms in order to minimize stress to the three fish species, the first time such a ruling had been made in the history of the project. Some water was ultimately released later in the year. The announcement was met with strong opposition by the community. In 2002 warm water temperatures and low flows led to a large Chinook salmon kill near the mouth of the Klamath (Levy 2003). In 2002, a National Research Council committee was convened to investigate the soundness of the governing biological opinions, and found that scientific support was lacking for requirements of higher water levels in Upper Klamath Lake and for higher minimum stream flows in the upper Klamath River proposed in the 2000 USFWS and NMFS biological opinions. The NRC Report was highly controversial (Cooperman and Markle 2003, Lewis 2003). The USFWS and NMFS subsequently released modified biological opinions in 2003, and over the next six years the NRC released two additional reports, one on the causes of the declines and strategies for recovery (National Research Council and Committee on Endangered and Threatened Fishes in the Klamath River Basin 2004), and one on hydrology, ecology, and fishes (National Research Council 2008). The USFWS and NMFS subsequently released revised opinions in 2008 and 2013, respectively. In 2011, some Klamath Basin tribes (including Klamath, Modoc, and Yahooskin tribes) finally received a quantified water right by Oregon, although not all have been federally recognized. Tribal interests are not always aligned, with lower basin tribes having different viewpoints than upper basin interests.

In 2010, 45 separate federal, state, and local entities signed to two agreements for resolution of at least some of the problems facing the basin. The Klamath Basin Restoration Agreement (KBRA) attempts to restore native fish production, establish water and power supplies to support agriculture, communities, and the refuges, and contribute to the public welfare and sustainability for all Klamath Basin communities (Stern et al. 2013). The price tag for the KBRA has been estimated at US$1 billion. The Klamath Hydroelectric Settlement Agreement (KHSA) provides for the removal of the four private hydroelectric dams, primarily to improve fish habitat. It mandates a number of studies pertaining to dam removal feasibility and impacts (some of which have been concluded), limits costs to some participants, and contains a number of implementation details including a removal schedule. The KRBA and the KHSA are cross linked, each requiring Congressional approval of the other settlement (Stern et al. 2013). The agreements failed to pass Congress in 2014 and are set to expire in 2015 if no action is taken. Some parties, notably some of the Lower Basin Tribes, some environmental groups, and some local governments, actively oppose the agreements. The tribes oppose the agreements because they do not include the Trinity River, the environmental groups believe not enough water for environmental flows will be present during drought years, and local governments oppose the dam removal.

The Trinity now has its own restoration project that has increased Trinity flows and reduced the out-of-basin diversions to the Central Valley Project, with the Bureau of Reclamation electing to use some of this water to provide additional fish flows in the Lower Klamath rather than divert the water into the Sacramento basin. This action has been opposed in federal court by irrigators in California's Central Valley, who otherwise would benefit from this water.

The Klamath basin has a small enough area and population so that, in principle, a basin-wide perspective for solutions to these many challenges is still possible, especially if discussions are expanded to include interests on the Trinity River. The basin is far enough north so that the majority of climate models project gradual increases in precipitation this century (Cayan et al. 2013, Polade et al. 2014), which, combined with rising temperatures and evaporative demand, may yield modest flow declines overall (but significant declines in summer streamflow; Fig. 2; Cayan et al. 2013). The declining flows (from climate change and increased irrigation demands) coupled with warmer air temperatures threaten the basin most directly through rising water temperatures and further water quality declines, that may place many of the agricultural and ecological interests in this contentious basin at risk in coming decades.

The Sacramento–San Joaquin Bay Delta

The stabilization of the Sacramento–San Joaquin Bay-Delta is the most critical single water problem in California and arguably the most pressing water issue in the United States. The Bay-Delta is the largest estuary on the West Coast and is central to California's trillion-dollar water economy and many of its ecosystems. The 163 000-km^2 watershed that feeds freshwater to the Bay-Delta is bounded by the Sierra Nevada, southernmost Cascade Mountains, and California's Coastal Ranges, providing freshwater flows of the Sacramento and San Joaquin Rivers that merge in the Bay-Delta (California Department of Water Resources 1993). An average of 40% of annual runoff to the river network is produced from snowmelt (Knowles 2000) and flows into and through the Bay-Delta estuary. Pacific Ocean tides propagate through the Golden Gate to the Delta, and the extent of salinity intrusion into northern San Francisco Bay is determined by the highly variable standoff between sea-level height and river inflows. The Delta's contributing hydrology has followed the climate-driven trends already observed across the western United States and attributed to human-induced warming (Barnett et al. 2008), including trends of increasing winter and spring air temperatures and lengthened growing seasons (Cayan et al. 2001), declining contributions of snow to annual precipitation (Knowles et al. 2006), and hastening of spring snowmelt by 5 to 30 days (Stewart et al. 2005). Mean sea level at the entrance to San Francisco Bay has increased $\sim$2.2 cm per decade since the 1930s, and the frequency of extreme tides has increased 20-fold since 1915 (Cayan et al. 2008).

The Delta itself encompasses 3000 km^2 of tidal to freshwater wetlands, agricultural lands, and river/estuarine channels at the confluence of the Sacramento and San Joaquin rivers. The Bay-Delta is a critical element in the state-scale water-conveyance systems that contribute drinking water supplies for two-thirds of the state's population (22 million people) and irrigation supplies for at least US$27 billion in agricultural production (45% of the nation's produce), and are thus a primary water source for California's trillion-dollar economy (Healey et al. 2008). About 6 km^3 of freshwater are pumped from the Delta by the federal Central Valley Project and the State Water Project each year to supply municipal and agricultural water demands in southern and central California (Healey et al. 2008). Salinities fluctuate seasonally and from year to year within both the Bay and Delta (Peterson et al. 1996). These salinity variations are managed by upstream reservoir releases with the dual purposes of preserving uncontaminated freshwater supplies and ensuring healthy ecosystems in and around the estuary, ecosystems that historically have supported at least 750 known plant and animal species (Healey et al. 2008).

Mount et al. (2006) have identified five primary drivers of future risk and adverse change in the Delta: land subsidence, invasive species, population growth and urbanization, seismicity, and climate change with sea-level rise. Both the ecosystems and the freshwater supplies associated with the Delta are in jeopardy. Freshwater diversions have altered the water balance and water quality of the estuary in ways that threaten the ecosystems. In 1993, two fish species in the Delta were listed under the Endangered Species Act (ESA). Within the Delta, approximately 60 islands sit below or near sea level, protected by $>$1800 km of aging levees. The levees continually risk failure due to combined pressures from sea-level rise, island subsidence, freshwater flooding, poor levee maintenance, and earthquakes (Mount and Twiss 2005). Major failure among the Delta levees could draw a massive influx of sea water from the San Francisco Bay into the freshwater parts of the Delta, which could render it unusable as a central link in the State's major freshwater-conveyance systems. Disruption of these conveyances could cost upward of US$30 billion and require many years to fix (Benjamin and Assoc. 2005). Both the State Water Project and the federal Central Valley Project are at risk (California Department of Water Resources 2009, Lund et al. 2010). Besides its vulnerable water infrastructure, the Delta is traversed by other key infrastructure including major north-south and east-west highways, electrical power lines, gas lines, and rail lines, all of which are threatened by flooding from the two rivers and by sea-level rise (Lund et al. 2010, Suddeth et al. 2010).

The listing of two fish species in 1993 under the ESA precipitated a crisis that led to the development of the CALFED Bay-Delta Program (Morandi 1998), which has recently been replaced by the Delta Stewardship Council. The express goal of these programs has been improving both ecological health and water management in the San Francisco Bay-Delta and its watershed. The program was envisioned as a multi-decade attempt through inter-agency coordination and decision-making to improve deteriorating ecosystems (Luoma et al. 2008), stressed water supply reliability, threatened water quality, and precarious levee systems in the Bay and Delta (National Research Council 2010). Over the last 15 years, federal, state, municipal, agricultural, and environmental interests have engaged in a variety of occasionally contentious and always complex and expensive initiatives in an attempt to create solutions acceptable to all parties (Isenberg et al. 2007, 2008, Owen 2007, National Research Council 2011). Hanneman and Dyckman (2009) have argued using game theory that, with current lines of authority, all participants have little incentive to agree as long as they can await a better solution; issues in the Colorado River basin, by contrast, have been more readily resolved because of the strong authorities that the Secretary of the Interior and Water Master wield. Nonetheless, this fall, the voters of California approved a massive US$7.5 billion bond issue to, once again, try to put many different water-supply systems around California on firmer footing, including crucial elements in the Delta.

Climate change threatens the Bay-Delta in many ways (Cloern et al. 2011), but California is an exceptionally well "plumbed" state (Lund 2006) and has an economy that can support as large an array of investments to address the problems in the Delta as any other system on earth (even if one current estimate indicates that an additional 7.4 km^3 of storage could be used; Lund et al. 2010). The large variety of canals, diversions, markets, and reservoirs (including groundwater reservoirs) presumably offer many opportunities for responding to and ultimately reducing many of those climate-change challenges. Indeed, Harou et al. (2010) have applied a hydroeconomic model of the state's water supply systems to conclude that even a multidecade-long "megadrought" could be weathered, albeit with high costs and many losers. Water temperatures in the Delta are expected to rise, causing difficulties for fisheries there that are already in peril (Brown et al. 2013*a*). In this overall context, among the many climate-change challenges that the state faces, some of the most pressing for the Bay-Delta will be the combined influences of sea-level rise (Cayan et al. 2008) and projected increases in flood flows and frequencies (Das et al. 2013). California has somewhat more than one year's worth of reservoir storage space at its disposal to meet dry-year water demands, and only about one-third of that space is typically available for flood protection. Storage management is currently based on historical climate responses, but adaptive management would be a more effective alternative in the face of climate and demand changes (Georgakakos et al. 2012). As has been noted, floods and sea-level rise combine to threaten the aging levees at the heart of California's water system, and the consequences of widespread levee failures could be essentially crippling to the state's economy (e.g., Porter et al. 2011). The Delta is a localized and extreme weakness at the heart of California's water systems unlike any found in the other basins considered here, and unlike any others around the West. California is blessed with a forward looking population as regards climate-change matters and this will likely be a very important asset, perhaps the most important asset as it comes to terms with the challenges (not just floods and levees) to come.

Conclusions

The western United States is a region that is defined by the water challenges that it faces and that it has accommodated throughout its history. Climate change adds to those historical challenges, but does not, for the most part, introduce entirely new challenges; rather it is likely to stress water supplies and resources that are already in many cases stretched to, or beyond, their limits. Current projections are for continued and, likely, increased warming trends across the region, with a strong potential for attendant increases in evaporative demands. Projections of future precipitation in the region are less conclusive, but it seems likely that the northernmost West will see precipitation increases while the southernmost West will see precipitation declines. However, most of the region lies in a broad area where some climate models project precipitation increases and others project precipitation declines, so that only increased precipitation uncertainties can be projected with any confidence. Even with the precipitation uncertainties, the net effect of the projections of evaporative changes and the precipitation changes is an expectation that, nearly everywhere, the amount of runoff and recharge yielded by each increment of precipitation will fall, with increased likelihoods and persistence of droughts becoming the new norm. Changes in the annual hydrograph are likely to challenge water managers, users and attempts to protect or restore environmental flows, even with similar annual volumes. Other kinds of impacts from climate change (e.g., floods and water quality changes) are poorly understood and will likely be very location dependent.

In this context, the four iconic river basins surveyed here offer a glimpse into specific challenges that climate change may bring to the West. At risk of oversimplifying, the Colorado River is a system in which overuse and the growth of demands is projected (by the U.S. Bureau of Reclamation) to be even more challenging than climate-change induced flow reductions. With or without large climate-change flow reductions, in the next few decades, the region faces the prospect of reservoir drying with water and power supplies for 40 million people placed at risk. The Rio Grande offers the best example of how climate-change induced flow declines might sink an admittedly smaller, multistate, water system into permanent drought. The Klamath may be in best shape, if current precipitation-change projections hold, in terms of volumes of runoff, but the fisheries (and by extension, irrigation management) may be placed into dire straits by warming temperatures, rising irrigation demands, and especially warming waters in a basin that is hobbled by the tensions between endangered fisheries and agricultural demands. Unlike the other basins, some promising initial solutions are at hand, albeit with a very large price tag. Finally, the Bay-Delta system is the remarkably localized and severe weakness at the heart of California's trillion dollar economy. It is threatened by the full range of potential climate-change impacts seen elsewhere in the West, along with unique and major vulnerabilities to increased flooding and rising sea levels.

All told, western water and projected climate change is a precarious mix. Nineteenth-century water law, twentieth-century infrastructure, and twenty-first-century population growth and climate change are on a collision course throughout the West. The sooner and more comprehensively we can address the historical water difficulties that define the region, the more likely we will be able to meet and accommodate the new challenges that climate change will bring.

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