Chapter 3: Climate Change Effects on Hydrologic Processes and Water Resources in the Sierra Nevada

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Introduction

The Sierra Nevada contains 24 major river basins that provide water to downstream ecosystems and human communities. Water resources and ecosystem services are derived from snowpacks accumulated at high elevations, replenishing soil moisture through snowmelt and generating streamflow during the spring and early summer. Streamflows produced from Sierra Nevada snowpack account for about 30 percent of California's total water supply, provide about 60 percent of water consumed by the state's population, and generate nearly half of the state's hydroelectric power (Bales et al. 2011a, Dettinger et al. 2018). Transportation infrastructure, hydroelectric networks, and recreational resources across the Sierra Nevada are tightly coupled with hydrological processes and fluctuations. As climate change leads to warming temperatures and shifting precipitation regimes, understanding the vulnerability of hydrologic functions of the Sierra Nevada will help to anticipate effects on water resources.

Streamflows produced from Sierra Nevada snowpack account for about 30 percent of California's total water supply, provide about 60 percent of water consumed by the state's population, and generate nearly half of the state's hydroelectric power.

Future shifts in hydrologic processes and water resources will span management boundaries. The majority of lands in the Sierra Nevada are federally owned and managed, with about 40 percent of the region (11.5 million ac) falling within 10 national forest units managed by the U.S. Department of Agriculture, Forest Service (USFS) (Britting et al. 2012) (chapter 1) (fig. 1.1). Given that the Sierra Nevada generates so much of the water used in the state, it is not surprising that USFS lands are a primary source of water for many cities, some quite distant from the Sierra. Thus management of these lands affects water supply, timing of when water will be available, and water quality. Given the complexity of climate change and the challenges of making decisions under increasing uncertainty, locally relevant climate information is needed to understand and manage future hydrological shifts that can affect natural resources and ecosystem services provided by national forests.

Scientists frequently describe hydrologic processes and the movement of water in terms of the water cycle and ecosystem water balance. These are concepts that describe the interconnected series of storage pools and transport fluxes that extend from the Earth's subsurface to the upper atmosphere. In this chapter, we use these

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concepts to provide a brief overview of the current hydrologic context for climate change in the Sierra Nevada. We also discuss how altered precipitation, water from snowmelt, subsurface moisture, streamflow, and evapotranspiration are interconnected.

Changes in Precipitation and Snow Water Resources

The Sierra Nevada experiences a Mediterranean climate with about 80 percent of precipitation falling during the winter months (Belmecheri et al. 2015, Dettinger et al. 2018) (chapter 2). Total incoming precipitation exhibits high interannual variability across the region, largely driven by atmospheric river events, in which currents of moisture-laden air are carried inland by jetstreams throughout the winter (Dettinger et al. 2011). Precipitation is orographically enhanced by the mountains as moisture held in air condenses when pushed upward into higher and colder elevations. Orographic effects result in the majority of precipitation falling on the west side of the Sierra Nevada, with precipitation rates sometimes exceeding those of low elevations by as much as 30 times (Dettinger et al. 2004b, Lundquist et al. 2010). On the wetter, west side of the Sierra Nevada, total incoming precipitation is strongly controlled by elevation; middle and higher elevations (greater than 6,500 ft) typically receive the highest annual precipitation (Dettinger et al. 2018). In addition to variation by elevation and terrain, total annual precipitation also varies by latitude, with the northern region of the Sierra Nevada typically receiving more precipitation than the southern region (chapter 2) (fig. 2.1).

Because precipitation regimes of this region are strongly winter dominated, precipitation predominantly falls as snow at higher elevations where temperatures are cooler. The southern Sierra Nevada, which is at a higher elevation than the northern Sierra Nevada, tends to be more snow dominated (Harrison and Bales 2016). Compared to other mountainous regions in the Western United States, the typical Sierra Nevada snow accumulation season is relatively short, and the majority of total annual snowfall is often delivered by a relatively small number of large precipitation events (Huning and Margulis 2017).

Shifts in precipitation type or phase (rain vs. snow) are one of the most direct effects of warming temperatures (Fritze et al. 2011). Over the past 50 years, snowpacks across the Western United States have been declining as a result of warmer winter conditions and shifts in precipitation regimes from snow to rain dominated (Fritze et al. 2011, Mote et al. 2018). Snowpack decline has also resulted from precipitation declines affecting higher and colder mountains in the Northwest (Luce et al. 2013). Unlike mountain ranges in the interior Western United States that typically experience colder climates, winter temperatures across much of the

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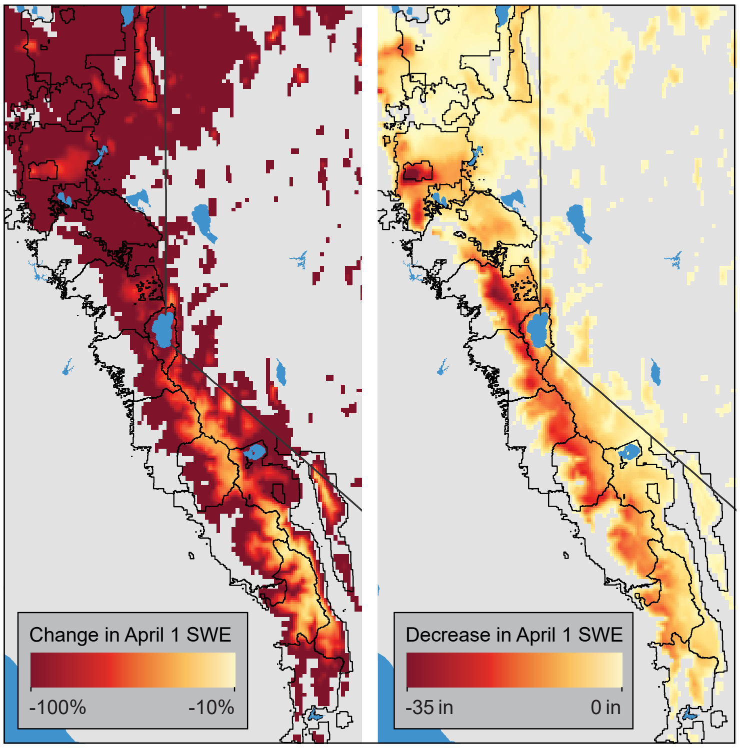

Figure 3.1—Projected changes in April 1st snow-water equivalent (SWE) across the Sierra Nevada from historical conditions (1975–2005) to the 2080s (2071–2090) based on temperature increases projected from a 20 global climate model ensemble mean under Representative Concentration Pathway 8.5.

Sierra Nevada are relatively mild, and temperatures frequently hover near freezing levels at low and middle elevations. These conditions make a large extent of the Sierra Nevada vulnerable to shifts from snow-dominated to rain-dominated precipitation regimes and reduced snow accumulation (fig. 3.1).

With climate change, projected shifts in precipitation type are largest for mid elevations (6,000 to 9,500 ft), although high-elevation sites (greater than 9,500 ft) will remain above the rain-snow transition zone where precipitation remains largely snow dominated even under warmer conditions (Ficklin et al. 2012, 2013; Sun et al. 2019). Under continued high greenhouse gas emissions, the total snow-dominated area of the Sierra Nevada could be reduced by 19 percent, and the total rain-dominated area could increase 26 percent by the middle of the 21st century (Klos et al. 2014). Shifts in precipitation regimes from snow dominated to rain dominated will likely reduce snowpack storage (Rhoades et al. 2018), alter the timing and magnitude of streamflow (Schwartz et al. 2017), and reduce soil moisture availability in the summer (Ficklin et al. 2012, Klos et al. 2018).

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With warming temperatures and increasing proportions of winter precipitation falling as rain, historically snow-dominated middle elevations will likely experience the largest reductions in snow-water equivalent (SWE) relative to historical conditions (Dettinger et al. 2018, Lute and Luce 2017, Sun et al. 2019). Peak SWE, typically related to SWE on April 1 of a given year, is projected to decrease by

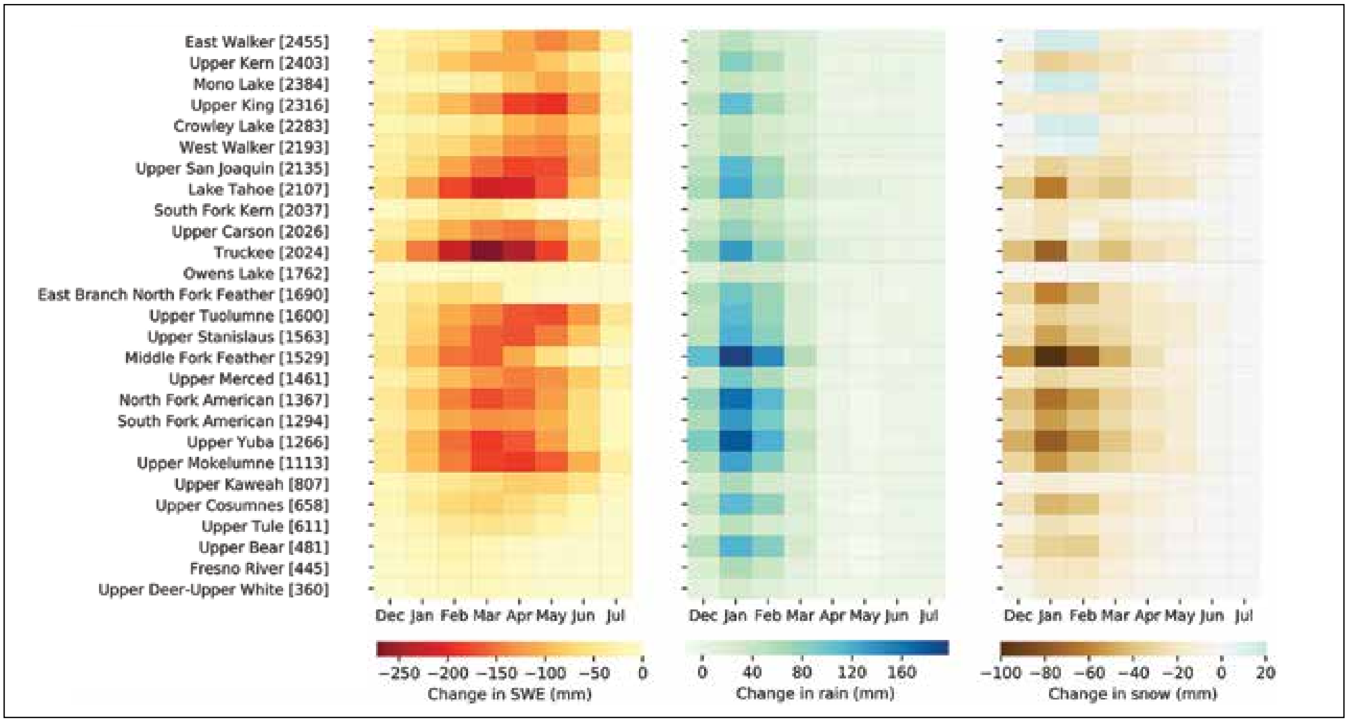

Figure 3.2—Monthly climatological changes (2091–2100 minus 1991–2000) of (left) snow-water equivalent (SWE), (middle) rain, and (right) snow according to the average of the five dynamically downscaled global climate models for Sierra Nevada watersheds. Unit in each panel is inches. Watersheds are ordered from highest to lowest elevation, with the watershed-averaged elevation noted in square brackets (unit: feet). (Figure from Sun et al. 2019)

over 75 percent across many elevations and by as much as 35 inches in portions of the central and northern Sierra Nevada by the end of the 21st century (fig. 3.1). Across these subregions, middle elevations (6,000 to 9,500 ft) currently retain a disproportionate amount of snow-water storage that will likely be reduced by decreased precipitation falling as snow and accelerated melt rates during the late winter and spring (Sun et al. 2019) (fig. 3.2). Overall, snowpacks in the Sierra Nevada are projected to decrease by about 60 percent by the end of the 21st century depending on future greenhouse gas emissions (Dettinger et al. 2018), with some estimates projecting declines as high as 80 percent where snowpacks are most temperature sensitive (Berg and Hall 2017, Ficklin et al. 2013, Rhoades et al. 2018).

Reductions in SWE are also coupled with snow-season length and snow residence time (SRT, how long snow lasts once it has fallen), both measures of the number of days when snow is present on the ground. With warming temperatures, reduced precipitation falling as snow, and accelerated melt rates, snow season is projected to be 39 days less (Rhoades et al. 2018) and SRT 75 days less across much of the Sierra Nevada by the end of the 21st century (fig. 3.3). Future reductions in SRT can be accelerated by feedbacks that further increase snow melt rates (i.e., the snow albedo feedback loop) (Walton et al. 2017). Reduced SRT can have significant

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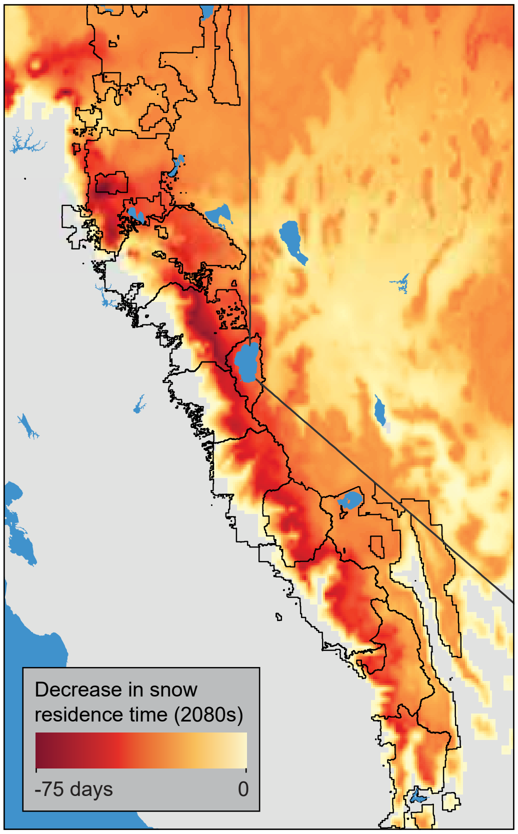

Figure 3.3—Projected changes in snow residence time across the Sierra Nevada from historical conditions (1975–2005) to the 2080s (2071–2090) based on temperature increases predicted from a 20 global climate model ensemble mean under Representative Concentration Pathway 8.5.

ecological effects by shifting the timing of vegetation growth and soil moisture uptake earlier in the spring.

The capacity of Sierra Nevada snowpack to store large amounts of water is important to the function of hydroelectric operations, flood control programs, transportation infrastructure networks, and recreational opportunities (chapter 5). Warming temperatures and highly variable annual precipitation increase the vulnerability of water-limited communities and ecosystems to climate change effects on water resources. The direct impacts of warming temperatures on precipitation type and patterns of snow accumulation will likely affect other hydrologic processes and water resources throughout the year.

Changes in Soil Moisture Inputs and Subsurface Water Storage

Soil moisture and deeper subsurface water storage are critical sources of water to forests and streams in the Sierra Nevada during the extended periods of summer drought that typically occur months after winter snowpacks have disappeared (Bales et al. 2011b, 2018; Holbrook et al. 2014; Klos et al. 2018). Warming temperatures and increasing proportions of winter precipitation falling as rain shift the timing of soil moisture inputs and initiation of drying earlier, affecting dry-season groundwater recharge, soil moisture, and outflow to rivers and streams. (Dettinger et al. 2004a, Ficklin et al. 2013, Luce et al. 2016). In water-limited ecosystems, multiyear subsurface storage could help maintain resilient forests in the proximity of groundwater discharge zones as snow-water storage is reduced and summer drought severity increases (Bales et al. 2018).

Many parts of the Sierra Nevada are particularly vulnerable to larger summer soil moisture deficits driven by earlier snowmelt (Harpold et al. 2015). The combined effects of decreasing snow-water storage, shorter snow residence time, and increased soil drying and plant water use during the spring are projected to reduce summer soil moisture over the course of the 21st century. These shifts will increase the importance of deeper subsurface moisture that can supplement vegetation demand and streamflow later into the dry season. Although critical to hydrologic functions across the landscape, subsurface storage capacities are heterogeneous and difficult to measure directly (Klos et al. 2018).

The effects of changing soil and subsurface moisture availability may also affect recreation and tourism resources. For example, giant sequoia (*Sequoiadendron giganteum* (Lindl.) J. Buchholz) groves in the southern Sierra Nevada provide numerous ecological, aesthetic, and tourism-based benefits. Drought stress experienced by these trees is influenced by topography, snow cover, and subsurface moisture (Stephenson et al. 2018). Future snowpack declines, hotter droughts, and larger summer soil moisture deficits may lead to more severe drought stress and increased sequoia mortality in lower elevation stands (Ray 2016).

Shifts in Streamflow

Streamflow processes in the Sierra Nevada play a critical role in the timing and delivery of water resources to downstream ecosystems and human communities and have been extensively studied in recent decades. In addition to total incoming precipitation, the amount and timing of streamflow are further determined by temperature and precipitation across a watershed, soil and geologic characteristics, and local vegetation that takes up subsurface moisture during the growing season. Because streamflow is coupled with numerous climatic and environmental factors, the effects of climate change on streamflow are less direct than effects on precipitation type and snowpack. However, the effects of increasing temperatures and decreasing snowpacks will likely affect seasonal streamflow in many regions of the Sierra Nevada.

Annual precipitation exhibits high interannual variability in the Sierra Nevada, and spring snowmelt has historically provided a relatively consistent and controlled release of stored precipitation to streams and rivers. Large advances in the timing of snowmelt-derived streamflow are projected to follow earlier snowmelt, with spring flows occurring 30 to 80 days earlier in streams across the Sierra Nevada by the end of the 21st century, depending on greenhouse gas emissions and watershed characteristics (Schwartz et al. 2017, Stewart et al. 2004). This means that storage in the snowpack buffering water supply timing downstream will be reduced, and water managers will be more challenged to supply water through the full growing season.

Shifts from snow-dominated to rain-dominated precipitation regimes can lead to more frequent high streamflow events in the winter and earlier peak flows in the spring (Regonda et al. 2005, Wenger et al. 2010). Future high streamflow events may be further exacerbated by increasingly intense winter rainfall events (Musselman et al. 2018, Pierce et al. 2013, Polade et al. 2017). Over the 21st century, the magnitude and intensity of floods are projected to increase relative to historical conditions, with flood frequencies also increasing under a majority of emission scenarios and remaining stable or slightly decreasing under scenarios that project significant drying trends (Das et al. 2011). Future shifts in flood frequency will likely be driven by the increasing size and frequency of extreme storms, as well as increases in the fraction of total precipitation falling as rain instead of snow (Das et al. 2011). By the end of the century, discharges from 50-year floods may increase 30 to 90 percent in the northern Sierra Nevada and 50 to 100 percent in the southern Sierra Nevada, depending on future temperature increases (Das et al. 2013).

Altered precipitation reduces the skill of statistical runoff forecasting tools used to manage water for flood control and allocation to downstream users, limiting the capacity of water managers to respond to extreme events such as flooding and low flows (Harrison and Bales 2016, Stewart et al. 2015). Under these conditions, water will be managed increasingly as a risk as opposed to a resource to be stored for future use. Higher precipitation intensity and more winter precipitation falling as rain can increase soil saturation, leading to an increased risk of landslides and debris flows (Ren et al. 2014). Increasing frequency of these natural hazards would have serious implications for water quality, human safety, and transportation infrastructure. Risks from extreme wet periods would be exacerbated by increasing occurrence of fire events (Goode et al. 2013).

In this assessment, the Variable Infiltration Capacity (VIC) model was used to simulate streamflow processes for streams across the entire Sierra Nevada. VIC is a physically based and spatially distributed hydrologic model that simulates hydrological processes including snow accumulation and melt, streamflow, and evaporation while accounting for differences in vegetation and elevation (Liang et al. 1994). The climate change projections and modeling approach to simulate stream hydrology follow the methods of Wenger et al. (2010) in which VIC simulations were run for streams at 1/16th degree resolution under historical conditions (1975–2005) and projected into the mid (2040s) and late 21st century (2080s) under the A1B emission scenario.

Our discussion of climate change effects on streamflow focuses on three widely used metrics: (1) change in the number of days when winter flows exceed the 95th percentile (W95, days), (2) change in timing of center of mass flow (CT, days) (Stewart et al. 2005), and (3) change in mean daily summer flows (in both ft^3 s^{-1} and percent), where summer flows for a given year are defined as the period starting from the first day after June 1 when flows fall below mean annual flow rates through September 30. Although these metrics provide only partial quantification of all changes to streamflow, they are ecologically and socially relevant, often tightly coupled with changes in precipitation and snowpack, and provide additional context for the effects of climate change on seasonal water availability.

The frequency of large winter streamflow events will likely increase across much of the Sierra Nevada as winter precipitation becomes increasingly rain dominated (Das et al. 2011, Fritze et al. 2011). Frequent rain-on-snow events at higher elevations where snowpacks were historically stable may lead to rapid snowmelt, which can increase event volumes by as much as 200 percent in the central and southern Sierra Nevada (Musselman et al. 2018). A projected increase in W95 for a stream indicates an increase in the frequency and magnitude of winter flood events under warmer and more rain-dominated precipitation regimes. By the end of the 21st century, VIC-simulated W95 is exceeded as many as 15 days more frequently than historical conditions throughout middle and high elevations in the central Sierra Nevada, with slightly smaller increases projected for streams in the southern Sierra Nevada (fig. 3.4).

Increased W95 frequency occurs in regions where elevations are vulnerable to precipitation switching from snow to rain, and streamflows are less buffered by high groundwater storage capacities. For example, streams in the northern Sierra Nevada experience less variability in winter flows and W95 relative to the central and southern Sierra Nevada, largely because of increased groundwater storage capacities in the north that buffer flashier winter water inputs. This is mainly due to geologic characteristics that result in high infiltration, large groundwater storage capacities, and long water-residence times.

Accurately projecting shifts in streamflow timing is important for water managers. The extensive network of dams and water-delivery infrastructure in the Sierra Nevada stores and allocates water resources to downstream users through managed reservoir discharges throughout the year. Shifts in the timing of peak streamflows can make it difficult to manage reservoir levels for the timing of controlled releases

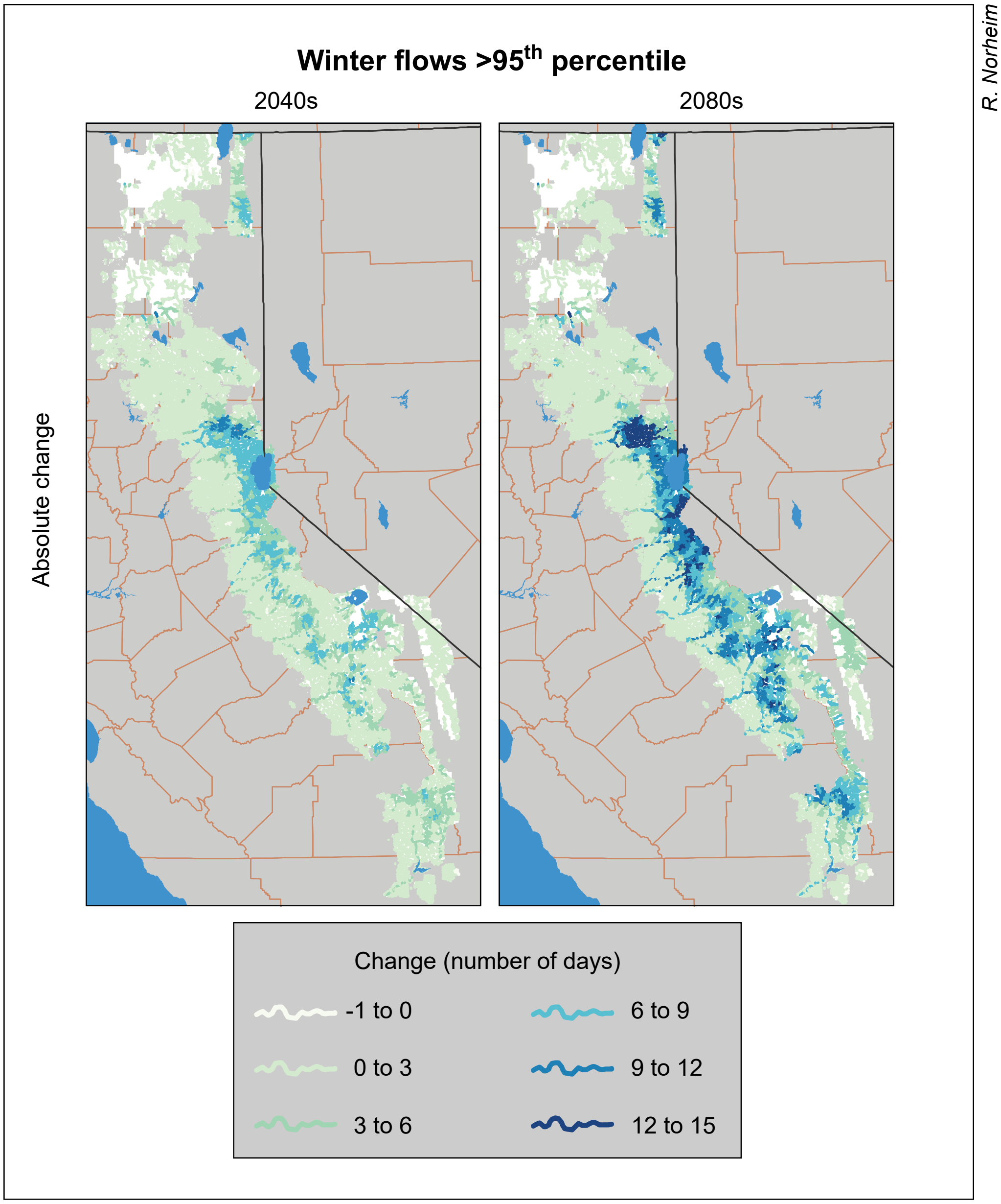

Figure 3.4—Absolute change in the number of days from historical conditions (1975–2005) to the 2080s (2071–2090) when winter flows exceed the historical 95^{th} percentile. An increase in the number of days indicates a higher likelihood of larger and more frequent winter streamflow events and potential flooding. Climate change projections assume temperature increases following the A1B emission scenario.

to create extra storage in reservoirs in advance of large streamflow events, as well as maintain stored water reserves to support power generation and irrigation later in the summer.

Streamflow timing is often described in terms of the timing of CT flow, or the date on which half the total annual streamflow is exceeded (Regonda et al. 2005, Stewart et al. 2005). Because water inputs (snowmelt) are occurring earlier, runoff is occurring earlier. VIC simulations project a shift toward earlier CT across most of the central and southern Sierra Nevada. Advances in CT are largest in the central Sierra Nevada, with spring peak flows occurring nearly 2 months earlier in many streams by the late 21st century (fig. 3.5). Less change in CT occurs farther north because there is less snowpack being affected, and less occurs farther south because high-elevation snowpacks are insensitive to temperature until substantial warming occurs (Lute and Luce 2017). Similar to projections of W95, future shifts in CT are

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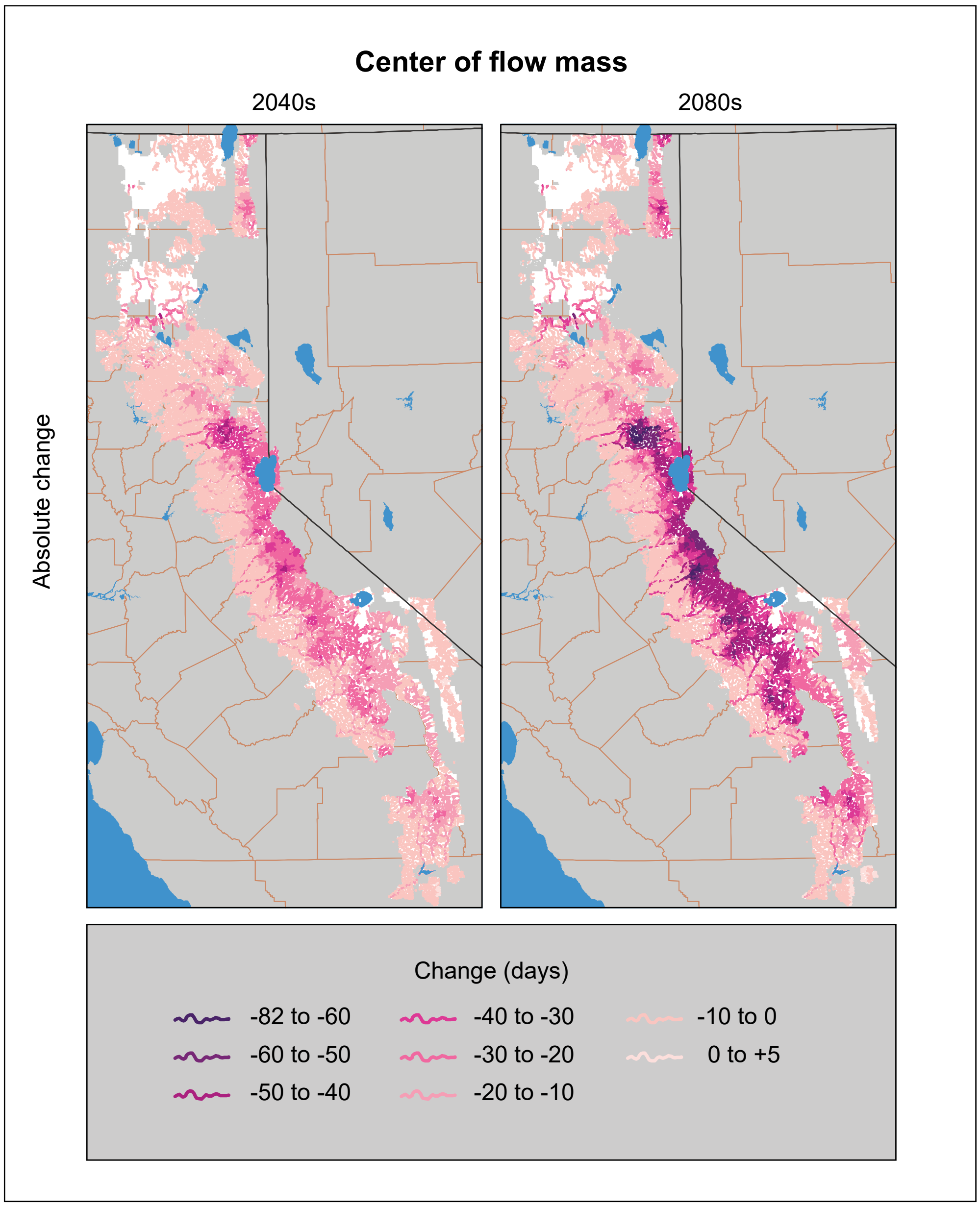

Figure 3.5—Absolute change in the timing of the center flow of mass from historical conditions (1975–2005) to the 2080s (2071–2090). Climate change projections assume temperature increases following the A1B emission scenario.

smaller in the northern Sierra Nevada where streamflow timing remains more consistent as a result of higher groundwater inputs and storage.

Following spring snowmelt and runoff, Sierra Nevada summers are characterized by low precipitation and long periods with warm, dry atmospheric conditions. Summer streamflows are important to the function of aquatic and riparian ecosystems, occurring during periods of greatest demand for energy generation, irrigation, and other forms of downstream water use. Although streamflows are typically at their lowest point during summer and early fall, they can be sensitive to changes in snowpack that occur during the preceding winter and spring. For example, in several Sierra Nevada watersheds, a 10 percent reduction in SWE has historically led to reduced minimum flows of 9 to 22 percent and earlier low flows (Godsey et al. 2013).

VIC simulations indicate that many small streams in the Sierra Nevada are not projected to experience large absolute changes in mean daily summer flows. However, percentage of flow is expected to decrease by as much as 90 percent in the central and southern Sierra Nevada by the end of the 21st century (fig. 3.6). The high percentage of changes occur because flows during this period are generally low, so even a small change in absolute terms can be large in relative terms. In the northern Sierra Nevada, where groundwater inputs buffer streamflows, projected fractional declines in mean daily summer flows are typically smaller. However, recent and continued declines in the frequency of summer precipitation events could potentially prolong the duration and intensity of summer low flows for many streams (Ficklin et al. 2012, Holden et al. 2018).

Streamflow timing, peak flows, and summer flows are influenced by regional climate, snowpack characteristics, local geology and geomorphology, and evaporative demand during spring and summer (Ficklin et al. 2013). Increasing temperatures and changing streamflows will widen the gap between timing of water availability and timing of greatest water demand for ecological, agricultural, hydroelectric, and municipal uses. Shifts in seasonal streamflows can also affect water quality by increasing stream temperatures, decreasing dissolved oxygen concentrations, and increasing sediment loads and transport rates (Ficklin et al. 2013). At local scales, forest and water managers will experience increasing uncertainty in a warmer and more variable climate, with competing demands for water supplies.

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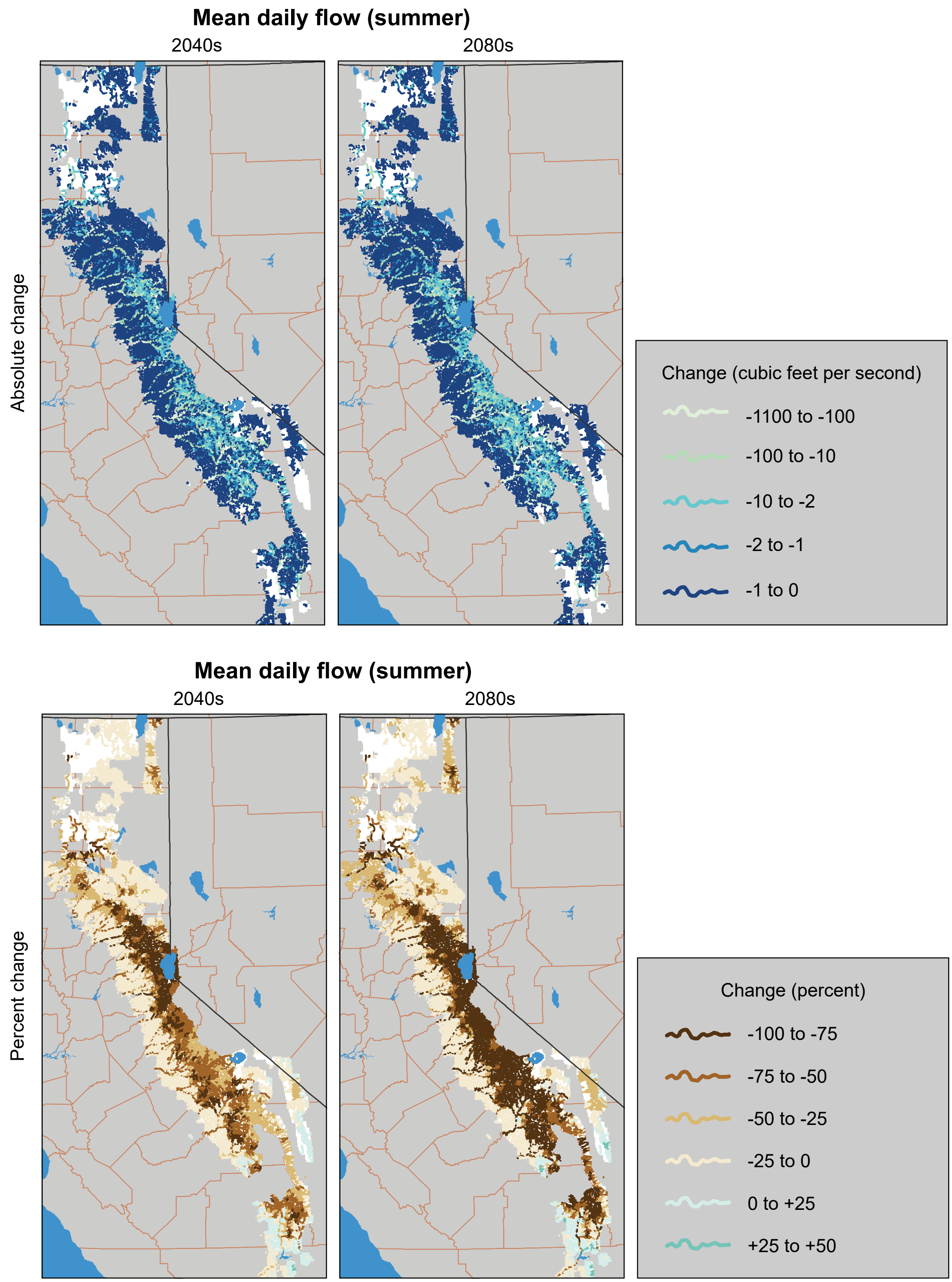

Figure 3.6—Change in the timing and magnitude of mean daily summer flows from historical conditions (1975–2005) to the 2080s (2071–2090). Climate change projections assume temperature increases following the A1B emission scenario.

Changes in Evaporative Demand and Evapotranspiration

The transport of surface and subsurface water back into the atmosphere is a key component of the hydrologic cycle and overall water balance. The transport of water to the atmosphere, or evapotranspiration (ET), is the combined amount of water that is both evaporated from water and soil surfaces and transpired by vegetation. In mountainous regions like the Sierra Nevada, fluxes of water to the atmosphere are largely mediated by climate, with temperature, water availability, and energy availability being the dominant controls on the timing and amount of seasonal ET.

The evaporative demand driving ET is generally characterized by how dry the atmosphere is compared to saturated conditions and is one component of the capacity of the atmosphere to evaporate water. Under warming temperatures, evaporative demand is expected to increase, and given adequate moisture and radiant energy supply, would be expected to increase evaporation. Vapor pressure deficit (VPD), the difference in moisture held in the air under actual conditions compared to saturated conditions, is projected to increase across the Western United States during the 21st century (Ficklin and Novick 2017). Increased VPD indicates increasingly dry atmospheric conditions which can lead to increased ET in areas where there is a sufficient supply soil moisture and continued transpiration by vegetation. Evapotranspiration is also limited to the increase in net radiation (Luce et al. 2016, Milly and Dunne 2017, Roderick et al. 2014).

In the Sierra Nevada, steep elevation and climatic gradients result in both water and energy limitations on ET. At lower elevations, where water availability is often the dominant factor limiting ET, increasing VPD (as a function of warming temperature) may slightly increase soil moisture use, and warming temperature may increase the drought stress experienced by water-limited and middle-elevation forests (Adams et al. 2009, Lutz et al. 2010, Trujillo et al. 2012, van Mantgem and Stephenson 2007). At higher elevations, lower VPD and shorter growing seasons have historically resulted in lower seasonal ET compared to warmer mid-elevations where adequate soil moisture and higher VPD are conducive to higher ET across longer growing seasons. With climate change, the total area where ET has historically been limited by cold temperatures is expected to increase in elevation as temperatures warm. These shifts may subsequently reduce subsurface moisture and streamflow inputs (Goulden and Bales 2014, Trujillo et al. 2012).

Chapter Summary

The Sierra Nevada is already experiencing effects of climate change, and as temperatures rise, shifts in hydrologic processes and water resources will be complex and interconnected across all aspects of the regional water cycle. Subsequent changes in ecosystem services and the availability of water resources will likely have major downstream effects on ecosystems, communities, and economies. The severity of climate change effects will vary both spatially and temporally and be further influenced by interactions with socioeconomic factors such as water rights, population growth, and future decisions regarding water policy.

Large-scale efforts to assess climate change vulnerabilities and adapt current land management practices, infrastructure networks, and human uses of water and forest resources are needed to better prepare for future climate change effects (chapter 6). Much of this responsibility begins with public land managers because a large proportion of Sierra Nevada water resources originates from forested lands managed by the USFS and other agencies. The effects of altered climatic and hydrologic regimes will span management boundaries. Collaborating with adjoining landowners and local communities will be a critical part of adapting to climate change and its effects on water resources. However, limited time and resources can constrain the ability of managers to rapidly respond to uncertain conditions. Integrating management priorities across resource areas (e.g., recreation and infrastructure) will be important for improving the capacity of managers to coordinate management strategies and increase the extent of adaptation actions.

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