Contrasting warming and drought in snowmelt-dominated agricultural basins: revealing the role of elevation gradients in regional response to temperature change

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Abstract

For snow-dominated basins like the San Joaquin in California, warmer temperatures affect hydrologic processes and stress water resources that support valuable irrigated agriculture and urban populations. Large inter-annual swings in precipitation, seen recently in California, highlight the need to better understand the effects of potential future warming combined with such extreme multi-year precipitation variability. In this study we use an integrated hydrologic model (ParFlow-CLM) to examine the effects of mean annual warming of 2°C and 4°C on hydrologic response over a recent wet-dry cycle (2009–2013). Simulations are performed at a 1 km resolution over the San Joaquin basin to assess the hydrologic response that bridges the local and basin scales common to many previous studies of the region. At the basin scale, warmer temperatures reduce San Joaquin River runoff by an amount consistent with the contemporary dry years: for all but the wettest year, an increase in temperature of 4°C reduces simulated runoff to the baseline value of the next driest year simulated. This runoff loss can be attributed to offsetting warming-induced increases in annual evapotranspiration, subsidized in dry years by subsurface storage. Locally, hydrologic response to warming manifests as variation along an elevation gradient. The basin-wide reduction in runoff is the net balance of local increases and reductions that follow a complex function of elevation: negative mean runoff sensitivity can occur at all elevations, yet a positive runoff sensitivity exists for select locations between 2000 m and 3500 m elevation. In contrast, warming increases mean ET at all elevations in the Sierra Nevada, with the highest increase between 1000 m and 3000 m. The average increase in local runoff and ET combine to reduce percolation below the root zone in locations across the Sierra Nevada while shifting event-scale increases in recharge to Central Valley river channels.

1. Introduction

California’s San Joaquin River is one of many basins worldwide in which the key source of water supporting extensive urban and agricultural uses—i.e. a seasonal snowpack and mountain runoff—is at significant risk in a warming climate (Mankin et al 2015). The central role of the San Joaquin River basin’s water supply, and its sensitivity to climate, has motivated a host of studies over the past several decades that have sought to illuminate the connections between warming temperatures and changing hydrology in the basin. In the wake of the significant system-wide stresses induced by the historic drought of 2012–2015 (Dettinger and Anderson 2015, He et al 2017, Swain et al 2014) and the extreme wet year that followed in 2017 (Wang et al 2017), the importance of understanding these connections has received renewed urgency.
Climate change analysis in California—with a traditional focus on the Sierra Nevada as a critical source region—has evolved over the last three decades to quantify hydrologic impacts using a mix of approaches. Coarsely-resolved regional models have been useful in translating projections of future warming into long-term first-order terrestrial impacts like reduced snowpack and earlier melt-out (Gleick and Chalecki 1999, Hayhoe et al. 2004, Kapnick and Hall 2011, Lettenmaier and Gan 1990) that leads to earlier and reduced streamflow (Cayan et al. 2001, Dettinger et al. 2004, Knowles and Cayan 2002, Null et al. 2010, Stewart et al. 2005, Vicuna et al. 2007, Vicuna and Dracup 2007). Yet the response to warming temperatures is not uniform: empirical observational approaches (Goulden and Bales 2014) and models targeted at more detailed hydrology (Godsey et al. 2014, Huntington and Niswonger 2012, Jepsen et al. 2016, Markovich et al. 2016, Tague and Grant 2009) indicate that local-scale storage and transmission of water in the subsurface, via impacts to evapotranspiration and baselows, are key mechanisms controlling hydrologic response to climate across Sierra Nevada landscapes. Further evidence suggests a spatial sensitivity of runoff to temperature that depends on elevation—with co-varying subsurface properties (Jepsen et al. 2016) or vegetation (Goulden and Bales 2014) implicated to explain this variability. Altogether, these factors suggest that a fully-rendered assessment of basin-scale climate change impacts to hydrology should incorporate local scale processes and interaction (distributed lateral connectivity, spatially-explicit land cover distributions, and subsurface processes) combined with sufficient spatial scope to capture dominant topographic patterns and water supply source areas. This approach, however, has not previously been utilized in the San Joaquin basin nor in basins of similar scales.

Consistent with the coarse spatial and process resolution historically employed, much of the previous work to assess potential future climate impacts to hydrology has been framed in the context of long-term, multi-decadal change. Hydrologic impacts of climate warming are often quantified as a difference in average response compared between a reference and a future period of interest (e.g. Maurer et al. 2010, Null et al. 2010, VanRheenen et al. 2004). Such an approach provides a measure of how long-term average conditions may change under a projected future climate but does little to put the variability of specific contemporary hydroclimatic conditions into the context of a warmer future. Given the range of stresses to California’s water supply system caused by recent drought-flood cycles, an assessment of how such inter-annual precipitation variability translates to hydrologic response in a warmer climate represents an additional path to better understand potential futures in the region.

We present a simulation study assessing the impacts of future warming on San Joaquin River basin hydrology. We contrast results of simulations driven by recent historical and uniformly warmed climate forcings while addressing the issues of spatial and process resolution using a high-resolution regional integrated hydrologic model. We show that the effect of projected 4°C warming reduces basin runoff incrementally toward drought conditions; using a common basin index for categorizing water year type (SWRCB 1995), current ‘above normal’ and ‘below normal’ water years become equivalent to ‘below normal’ and ‘dry’ under warmer temperatures. While runoff decreases basin-wide, we show a distribution of local runoff increases at higher elevations due to snow to rain transitions that are offset by increases in ET at lower elevations. Elevation is a key variable controlling the sensitivity of local hydrologic change that, in turn, makes up basin-wide response to a warmer climate.

2. Methods

We study the impact of a uniform temperature shift on the hydrology of the San Joaquin River basin using the fully integrated hydrologic modeling framework ParFlow-CLM (PF.CLM) (Ashby and Falgout 1996, Jones and Woodward 2001, Kollet and Maxwell 2006, Maxwell 2013, Maxwell and Miller 2005). The PF.CLM framework provides a globally implicit solution to the three-dimensional form of Richards’ Equation (variably-saturated flow) in the subsurface and the kinematic wave approximation to overland flow at the land surface. The coupled CLM component simulates land surface processes (interception, snowpack, evapotranspiration) and exchanges fluxes with the PF component over a user-defined range of top PF model layers.

The San Joaquin Basin Model (SJBM) used in this study is developed on a 1 km lateral resolution grid with five variable-thickness layers spanning a total terrain-following vertical thickness of 500 m. The model domain covers the entire San Joaquin River drainage above the confluence with the Stanislaus River, including the major tributary watersheds of the Tuolumne and Merced Rivers. Hydraulic and land surface property inputs are defined based on previous studies and datasets. Details on model construction and development and validation are provided in Gilbert and Maxwell (2017). In this study the SJBM is forced with hourly meteorology derived from the 1/16 degree National Land Data Assimilation System, phase-2 product (NLDAS-2) (Xia et al. 2012) and a 4 km resolution dataset developed at Princeton University (Ming Pan, pers comm), mapped to the 1 km model grid for the time period spanning water years 2009–2013. This period was chosen because it spans a range of water supply conditions in the basin. Based on San Joaquin Basin Index, a record summarizing annual precipitation and basin water supply (SWRCB 1995), these years effectively sample historic variability: 2011
and 2013 are in the top and bottom deciles, respectively, of water supply conditions while the other years are distributed between these extremes (table S1 available at stacks.iop.org/ERL/13/074023/mmedia).

We tested the sensitivity of basin hydrology to warming mean temperatures by applying uniform temperature increases of 2 °C and 4 °C (Plus2 and Plus4, respectively) to the baseline (BL) hourly meteorological forcing for the period spanning water years 2009–2013. The 2 °C and 4 °C increments of warming were chosen based on the range of temperature projections reported for California for the 21st century (Cayan et al 2008, Hayhoe et al 2004, Maloney et al 2013, Pierce et al 2013) and their use in previous hydrologic studies (Jepsen et al 2016). We assess the hydrologic impacts of warming as the difference between the Plus2 and Plus4 scenarios and the BL scenario. Precipitation inputs are left unchanged in all scenarios in order to isolate the effects of temperature alone. For this study, unperturbed precipitation is justified given uncertainties and comparatively small mean projected precipitation change over the San Joaquin basin (Allen and Luptowitz 2017, Cayan et al 2008, Pierce et al 2013). We do not expect that a bulk perturbation of project precipitation change would substantially affect the outcome of this study, as year-to-year precipitation variability is a dominant factor driving hydrologic response. While we might expect changes in precipitation event characteristics (frequency, intensity, location, and elevation) to affect the results we present, such information was not readily available to inform this study. We develop climate-consistent initial hydrologic conditions by performing iterative one-year simulations for each scenario using the corresponding forcing for water year (WY) 2009 until the beginning-of-year to end-of-year change in root zone moisture falls below 1%, based on guidance from previous studies (Ajami et al 2014, 2015, Kollet and Maxwell 2008).

The SJBM simulates land surface energy and water fluxes, overland flow, streamflow, and subsurface (soil and groundwater) flow and storage change for every 1 km² cell in the model domain. These simulated hydrologic components are consistent with the available observed hydrology for the 2009–2013 period. Comparisons of simulated results to naturalized streamflow (figure S1), remote sensing-derived ET (figure S2), estimated snowpack (figure S3), and terrestrial water storage (figure S4) show that the model captures both seasonal patterns and inter-annual variability well as conditions transition from average and wet (2009–2011) into the first years of the drought (2012–2013). We note that the system simulated in this study does not include the effects of water management activities, instead depicting a naturalized or unimpacted hydrology. While this complicates comparison to observations affected by water management, the simulation of unimpacted hydrology is directly relevant to water management policies that rely on unimpaired benchmarks (e.g. State Water Resources Control Board 2016).

A comparison of the BL scenario with the Plus2 and Plus4 scenarios reveals a range of basin-wide hydrologic responses that are, in general, consistent with previous studies in the region. Impacts of warming, relative to the BL scenario, are apparent in reduced peak basin snow water equivalent volume and earlier melt-out (figures S5(a) and (b)), a redistribution of basin runoff that includes consistently reduced spring flows and occasional increased late fall and winter event flows (figures S5(c) and (d)), and a change in basin total ET weighted heavily towards winter and spring increases with minor late summer and fall decreases (figures S5(e) and (f)).

3. Results and analysis
3.1. Annual and basin scale
The magnitude of basin response to warming depends broadly on the amount of precipitation received, as illustrated in figure S5. Annual total basin precipitation for the simulation period is shown in figure 1(a), with the PRISM 30 year climatologic mean shown for reference (Daly et al 2008, PRISM Climate Group and Oregon State University 2015). The dependence of annual basin runoff, ET, and subsurface storage on precipitation and temperature perturbation is summarized in plots B–D in figure 1. While precipitation is a primary control on basin-wide runoff, ET, and storage change, the mean temperature acts as an important secondary control on hydrologic partitioning. Warming by 2 °C and 4 °C reduces runoff in each year (figure 1(b)), although the incremental reduction in flow is greater for the BL to Plus2 case (compared to differences between the Plus2 to the Plus4 cases) as well as in wetter years. Importantly, a comparison between years and temperature perturbations shows that, for all but the wettest year, an increase in temperature of 4 °C reduces streamflow sufficiently to be equivalent to the next driest year simulated. For example, the annual runoff simulated for the Plus4 scenario for water year 2010 is 14 cm, approximately equal to the runoff for water year 2009 in the BL scenario (13 cm), a year which received 15 cm less precipitation.

As the complementary outflow to runoff, annual basin ET increases with both precipitation (due to the higher wet-season ET response) and increasing temperature, with greatest sensitivity to the first 2 °C incremental warming (figure 1(c)). Consequently, a between-year comparison of annual ET values reveals that a 4 °C increase in temperature increases ET towards equivalence with the next wettest year simulated, with the exception of WY 2013. The apparent outlier ET response for WY2012 demonstrates the carryover impact of subsurface storage (figure 1(d)) in supporting dry year ET, and to a lesser extent, runoff: combined basin ET and runoff outflows are
Figure 1. Warming shifts runoff response similar to drought in the San Joaquin. A below-average year (i.e. 60% of historical record is wetter than this year) under warming behaves like a severe drought year. Groundwater recharge (subsurface storage change) is much less sensitive to warming than to drought. Annual total San Joaquin Basin precipitation for 5 year simulation period (a). Relationship between annual precipitation amount and runoff (b), evapotranspiration (ET) (c), and subsurface storage change (d) for each temperature scenario. Relative partitioning of precipitation into ET and runoff for each temperature scenario, without storage change correction (e) and with storage change correction (f). All units are in basin area-averaged depth as meters.

more than 125% of precipitation in WY2012 and more than 105% in WY2013. Notably, these impacts are relatively constant across each temperature scenario as temperature perturbations have only minor effects on annual storage changes across the San Joaquin River basin. While absolute soil and subsurface storage amounts differ among the scenarios, the consistency in inter-annual storage change suggests that the impact of warming is largely isolated to surface processes: at the basin scale, increases in ET are supported by water that would otherwise have contributed to runoff, rather than impacting the net aggregate infiltration.

The plots in figures 1(e) and (f) show the relative partitioning of precipitation into basin total runoff and ET. Points for each year fall on a line of constant precipitation and the slope of the line reflects the proportion of precipitation that goes to ET compared to runoff. We include the effect of storage change in figure 1(f), which aligns the points for WY2012 more consistently with the known precipitation gradient and
ensures the lines passing through the points for each year have x and y intercepts at that year’s precipitation value. We note that the nonlinear relationship between runoff and ET varies as a function of temperature (figure 1(e)) but conforms to a more consistent shape when storage change is considered in the partitioning.

The results shown in figure 1 summarize a comparison of how warming and drought impact hydrology. While runoff response is more strongly driven by precipitation, warming has an influence that can approach that of drought: a 4 °C warming reduces runoff by an amount ranging from 2.2 cm to 7.8 cm over the basin while the baseline reduction in runoff in the driest year (2013) relative to an average year (2010) is 10.2 cm.

3.2. Local scale variability and elevation control

These aggregate changes can be considered the net effect of a range of local impacts distributed across the basin. The SJBM simulations suggest that local variations in runoff, ET, and recharge are key explanatory component processes. First, consider that the shift toward more frequent rain-on-snow or rain-on-bare ground events that accompanies rising temperatures may change when and where runoff is generated. As rain becomes the dominant precipitation phase, runoff may be generated more frequently in time but exist for shorter periods that more closely mimics the precipitation time. It follows that runoff variability in space and time would tend to increase because, without the slow-release store of snowpack, sustaining runoff depends more directly on precipitation event duration and upstream contributing area. This effect is enhanced by the fact that much of the conversion from snow to rain happens at the upper reaches of watersheds like the San Joaquin, reducing the support of runoff from upstream contributions.

We examine spatial runoff response for each temperature scenario using simulated surface pressure as a measure of distributed runoff production. Pressures above zero in the top layer of the model indicate formation of overland flow subject to subsequent routing across the land surface. The dominant response to warming is a reduction in mean runoff generation, but areas of increased runoff production are distributed throughout the Sierra Nevada portion of the model domain. Figure 2(a) summarizes this distribution of differential runoff generation as a function of elevation through the use of a two-dimensional histogram of mean surface pressure sensitivity, defined as the difference in simulation mean surface pressure between the warming (Plus2, Plus4) and baseline (BL) scenarios divided by the BL values calculated at each model cell (lighter colors reflect higher frequency and the color scale is logarithmic for clarity). The histogram shows that runoff sensitivity to warming depends on elevation in two distinct ways. First, reductions in runoff occur at all elevations but with decreasing sensitivity as elevation increases. Second, there is a superimposed pattern of runoff generation that increases with warming that occurs within the 1000–3500 m elevation band, with the highest positive sensitivities concentrated in the 2000–2500 m range for both the Plus2 and Plus4 scenarios. We conceptualize the region above approximately 2000 m as one where warming induces the biggest transition in snow-rain dynamics yielding more frequent local runoff generation. Below this 2000 m elevation, warming-driven increases in ET and less frequent snow cover reduce the potential for increased runoff.

The spatial plot in figure 2(b) shows the temporarily averaged surface pressure across the five-year simulation period for the BL scenario. Darker shading (deeper mean surface ponding) delineates the channel network of the main drainages in the San Joaquin basin while the lighter shading (note the logarithmic color scale) indicates much of the catchment generates comparatively less mean runoff, either in amount or frequency. A 2 °C warming over the five-year simulation shifts the intensity of runoff generation and transmission across the catchment: figure 2(b) shows that mean surface pressures in scattered areas across the Sierras increase by as much as 50% under the Plus2 scenario relative to the baseline condition, while tending to decrease by similar proportions in channels and lower elevation zones in the foothills and the Central Valley. Spatial patterns of surface pressure increases and decreases are similar in the Plus4 scenario (not shown) but include more intense losses in the foothills and portions of the Central Valley.

The plot in figure 2(c) places the simulated runoff changes in the context of the historical runoff record. The plot compares the temperature-sensitivity of simulated runoff (black triangles and line) against observational equivalents derived from streamflow data as select gage locations (red circles and line) within the headwaters of the San Joaquin and its tributaries. The gage stations were selected for unmanaged or minimally-managed watersheds within the model domain that had at least 20 years of measurement record. The annual (by water year) measured streamflow was normalized against the sum of the annual PRISM precipitation (Daly et al. 2008, PRISM Climate Group and Oregon State University 2015) for the upstream contributing area to yield a time series of runoff ratios at each gage location. We then calculated an annual fraction change in runoff ratio at a station (red circles in figure 2(c)) as the difference in runoff ratio for a given year from the long-term mean divided by that mean. Data for each station are plotted as a function of the mean elevation of the contributing area above the gage location. The corresponding simulated comparison values were calculated in the same way, but using the NLDAS-2 meteorologic forcing in place of the PRISM data. For consistency with the observation calculations, we concatenated the simulated BL and Plus2 annual runoff ratio time series (creating a 10 year series), then subtracted from and subsequently divided.
Figure 2. Elevation governs a balance of impacts on streamflow from increased ET and decreased snowpack under warming scenarios. At lower elevations, streamflow decreases are driven by increased ET while at higher elevations runoff increases are due to rain-snow transition. This is illustrated in the two-dimensional histogram of sensitivity of average surface pressure (a measure of overland flow generation) as a function of elevation (a) for the Plus2 and Plus4 scenarios and spatially across the domain for the Plus2 scenario only (b). In histogram plot, blue colors denote sensitivity for the Plus2-baseline (BL) comparison and red colors the Plus4-BL comparison. The simulated sensitivity of precipitation-normalized runoff to temperature as a function of elevation compares well with available observational records (c).

Despite the differences between the observations and simulated streamflow datasets—i.e. greater number of observational years sampled, different (and less controlled) hydrologic conditions in the observational record—the plot in figure 2(c) shows good agreement between simulated and measured runoff response in San Joaquin River headwaters. Because each gage location measures an integration of upstream processes, one would not expect to recreate the full distribution shown in figure 2(a). Yet, the correspondence between observed and simulated changes in runoff ratio as a function of annual temperature variability suggests the SJBM captures the sensitivity of runoff generation processes with reasonable fidelity.

The coexistence of increased runoff at locations within the 1000–3000 m elevation band and decreased runoff at lower elevations indicates that enhanced high-elevation runoff is lost as it concentrates from the landscape toward streams and rivers. Simulation results show that ET driven by warmer temperatures is the dominant mechanism for removing this additional runoff. The plots in figure 3 show the ET difference from the BL scenario, averaged by elevation (lines) with one standard deviation shown (shading), in the Sierra Nevada portion of the San Joaquin River basin for the Plus2 and Plus4 scenarios as a function of elevation and water year (color). Elevation-averaged ET increases across all elevations and for all water years, although the amount of increase tends to be highest in the 1000–3000 m elevation range, coincident with the elevation range of simulated runoff increases. The sensitivity of ET in this elevation range suggests a negative feedback mechanism: the warming that drives more frequent snowmelt or a snow-to-rain transition and subsequent increases in landscape runoff generation also facilitates a compensatory increase in potential ET that effectively limits propagation of runoff farther downstream.

A consequence of increased runoff and increased ET under warmer conditions is that less water is available to be partitioned to deep subsurface infiltration. One metric of recharge that can be extracted from the simulation results is the change in average vertical flux across the lowest two model layers under saturated conditions between the baseline and two temperature change scenarios. The change in the temporal average of this flux at each cell provides a measure of how
both soil column moisture (tendency toward saturation) and the direction of flow (downward being recharge below the root zone, upward being discharge to support runoff or ET) are affected by warming temperatures and the associated ET and runoff changes. The plots in figure 4 show that the shift in runoff and ET under the Plus2 and Plus4 scenarios is accompanied by a reduction in mean downward flux across much of the model domain—i.e. a reduction in saturated recharge or an increase in saturated discharge. Figures 4(a) and (b) show that saturated recharge is reduced extensively across the Sierra Nevada, with the intensity of the reduction greater in the Plus4 scenario. Local reductions (increases) in recharge (discharge) flux can exceed 15 cm over the simulation period (∼3 cm yr⁻¹), though these are interspersed with more modest average recharge reductions and even some local recharge increases. In the Central Valley, the balance of changes is dominated by an increase (decrease) in saturated recharge (discharge) along many segments of the San Joaquin River and its tributaries. This increase is driven by steeper vertical gradients in the stream and river channels that arise from a mix of lower near-channel water tables and deeper channel flow (higher pressure head) that accompanies increased fall and early winter event streamflow (figure S1) in the Plus2 and Plus4 scenarios.

The plot of San Joaquin River basin total net saturated recharge is shown in figure 4(c) for each of the temperature scenarios. Here positive values represent net recharge (vertical flow to the lowest model layer) and negative values represent net discharge (vertical flow out of the lowest model layer). The time series shows that the basin is characterized by a predominant net discharge of groundwater punctuated by focused recharge events. These net recharge events tend to occur in late spring and early summer under the baseline scenario (even then only occurring during the two wettest years simulated), with local snowmelt and elevated river flows driving the recharge in the mountains and Central Valley, respectively. In contrast, the higher fraction of precipitation falling as rain in the warmer Plus2 and Plus 4 scenarios leads to more immediate fall and early winter runoff at the expense of building the snowpack (figure S5). The increased fall runoff supports more intense focused recharge events in the valley streams while the lower snowpack water content reduces both late spring diffuse recharge across the Sierra Nevada as well as focused recharge through spring snowmelt flows in the Central Valley. Furthermore, the time series in figure 4(c) indicates that temperature increases change the timing of groundwater discharge: peak upward flow of groundwater is dampened and shifted earlier with successive increases in temperature, regardless of how much precipitation was received.

4. Summary and implications

Our simulations demonstrate the complex spatiotemporal response of a large mountainous watershed to climate warming in the context of a recent wet-dry cycle. From the perspective of basin-scale runoff, recent dry years in the San Joaquin basin can be viewed as a proxy for the effect of future warming—increasing temperatures during ‘average’ precipitation years reduces runoff towards levels historically categorized as drought (as defined by common water year indices (SWRCB 1995)). Over the five years simulated, this runoff effect was equivalent to the loss of approximately 15 cm of precipitation each year when the temperature was raised 4°C. Furthermore, the high spatiotemporal and process resolution of the SJBM reveals how smaller scale processes and their interactions contribute to these changes. Importantly, the response of different hydrologic processes to spatially uniform warming is itself not spatially uniform—the aggregate response depends on
Figure 4. Temperature increases shift surface-subsurface exchanges. Difference in mean simulation-period saturated recharge relative to the baseline simulation for the Plus2 (a) and Plus4 (b) simulations. Time series of net San Joaquin River basin saturated recharge (positive) and discharge (negative), in area-averaged rate of m d$^{-1}$ (c).

The connection of snowpack, runoff, ET, and subsurface storage changes that vary across the landscape. This finding is not exclusive to the Sierra Nevada—the local-scale and elevation-dependent warming effects illustrated in this study are relevant to understanding hydrologic change in similar regions around the world (e.g. Meng et al 2016, Vicuña et al 2011).

These results highlight two key considerations for land and water resource management in the San Joaquin River basin. First, assuming a warmer future climate yields precipitation comparable to historic levels, the frequency of basin runoff supply shortages appears likely to increase while surplus years will be fewer and less intense. Second, the spatially-distributed nature of hydrologic response to warming calls for more targeted local management and adaptation actions that coordinate with larger basin goals. This presents a challenge and opportunity for the numerous local, state, and federal agencies with jurisdictional boundaries spread and fragmented across the San Joaquin basin (Hanak et al 2011).

An important assumption underlying the simulations in this study is that vegetation distribution does not change in response to warming (i.e. between simulation scenarios). Such warming-induced vegetation shifts have been implicated in projected ET-driven reductions to runoff (Goulden and Bales 2014), but other evidence suggests climate warming may be a more dominant driver of hydrologic change in mountain systems (Pribulick et al 2016). Our results indicate that vegetation expansion or redistribution is not a prerequisite for enhanced high-elevation ET and reduced runoff under warming—but the extent to which dynamic vegetation amplifies or modifies the climate impact at the basin scale remains an important topic for continuing research.

The results of this study have implications for groundwater within and beyond the Sierra Nevada. Results of previous studies in the Sierra Nevada suggest that water that percolates past the surface soils and nominal ‘root zone’ is an important reservoir for maintaining summer baseflows in streams (Godsey et al 2014) and for supporting deeper-rooted vegetation (Bales et al 2011). Our simulations show that warming temperatures tend to reduce the saturated recharge below the root zone in the Sierra Nevada, preferentially partitioning water toward runoff and ET losses at the land surface compared to a scenario without warming. This in turn has the potential to reduce groundwater contributions that support
summer streamflow (with concomitant impacts to stream temperatures) and exacerbate temperature-driven tree mortality effects (van Mantgem and Stephenson 2007). These impacts propagate to the Central Valley—the simulations indicate that, absent water management activities, the increased and shorter-duration fall and early winter runoff events in the Sierra Nevada lead to event-scale increases in recharge, with much of this occurring in stream channels in the Central Valley. This suggests an increasingly important role for basin water managers and management infrastructure in mitigating the warming-driven reductions in runoff by capturing this water for future use in traditional surface reservoirs or through managed recharge on the valley floor.

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