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Hydrogeologic influence on changes in snowmelt runoff with climate warming: Numerical experiments on a mid-elevation catchment in the Sierra Nevada, USA

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SUMMARY

The role of hydrogeology in mediating long-term changes in mountain streamflow, resulting from reduced snowfall in a potentially warmer climate, is currently not well understood. We explore this by simulating changes in stream discharge and evapotranspiration from a mid-elevation, 1-km^2 catchment in the southern Sierra Nevada of California (USA) in response to reduced snowfall under warmer conditions, for a plausible range in subsurface hydrologic properties. Simulations are performed using a numerical watershed model, the Penn State Integrated Hydrologic Model (PIHM), constrained by observations from a meteorological station, stream gauge, and eddy covariance tower. We predict that the fraction of precipitation occurring as snowfall would decrease from approximately 47% at current conditions to 25%, 12%, and 5% for air temperature changes of +2, +4, and +6 °C. For each of these warming scenarios, changes in mean annual discharge and evapotranspiration simulated by the different plausible soil models show large ranges relative to averages, with coefficients of variation ranging from −3 to 3 depending on warming scenario. With warming and reduced snowfall, substrates with greater storage capacity show less soil moisture limitation on evapotranspiration during the late spring and summer, resulting in greater reductions in annual stream discharge. These findings indicate that the hydrologic response of mountain catchments to atmospheric warming and reduced snowfall may substantially vary across elevations with differing soil and regolith properties, a relationship not typically accounted for in approaches relying on space-for-time substitution. An additional implication of our results is that model simulations of annual stream discharge in response to snowfall-to-rainfall transitions may be relatively uncertain for study areas where subsurface properties are not well constrained.

1. Introduction

The timing and quantity of stream discharge from snow-influenced mountain regions, occupied by over one-sixth of the world's population, is vulnerable to the effects of projected climate warming (Barnett et al., 2005; Nogués-Bravo et al., 2007). In California, USA, where approximately two-thirds of developed water is supplied by streamflow from the Sierra Nevada (CA DWR, 2009, pp. 3–10), climate could warm by 1.5–4.5 °C during this century (Cayan et al., 2008). Such warming in California would substantially decrease the volume of a snowpack – by anywhere from 37% to 80% (Cayan et al., 2008) – that has seasonally stored approximately two-thirds of annual precipitation (Serreze et al., 1999). This scenario now has particular relevance given the record setting drought conditions in California that began in water year 2012 (http://water.ca.gov/waterconditions/). Previous studies assessing the effect of possible atmospheric warming on changes in annual stream discharge from the Sierra Nevada have produced variable outcomes (Table 1)—with changes ranging from +3% to less than −20%. The reasons for these different predictions are unclear because of the large number of factors that vary between studies, including climate scenarios, elevations, and prediction methodologies.

Two approaches used to assess possible changes in stream discharge (hereafter "runoff") with projected climate warming are: (i) empirical, which employ statistical relationships between

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Table 1
Summary of predicted changes in annual runoff (ΔR) and evapotranspiration (ΔET) with climate warming of snow-influenced areas of the Sierra Nevada [U.S. coverage in Berghuijs et al. (2014)]. Values shown are best approximations of the published results. Ref = reference (listed below table), ΔT_{air} = change in air temperature (°C), ΔP = change in precipitation, – = not available. Braces ({}) denote approximate baseline values.

Ref	Study area	ΔT_{air}	ΔP	ΔR	ΔET
Studies using empirical approach (Refs. 1–4)					
1	E Fork Carson R	+4	None	+22% {44 cm}	–
	N Fork American R	+4	None	−46% {81 cm}	–
2	Sacramento R Basin	Varying	–	Virtually no change	–
3	Ninety-seven catchments in U.S.	+4	None	−33% {52 cm} (note 1)	–
4	Upper Kings R	+4.1	None	−26% {52 cm}	+28% {48 cm}
Studies using watershed models (Refs. 5–14)					
5	N Fork American, Merced R, two other rivers	+2 to +4.5	"Appears small"	–	"Little change" (except for Merced R)
6	E Fork Carson R	+4.4	None	+3.4% {49 cm}	−6.3% {53 cm}
	N Fork American R	+4.4	None	−12% {88 cm}	+3.8% {51 cm}
7	E Fork Carson R, N Fork American R, Upper Merced R	+2.5	"Small" (∼ −10%)	"No significant trend"	−4 to +1% {54 cm}
8	Upper Merced R, basinwide	+4	None	−6 to 0% {52 cm}	0 to +5% {59 cm}
	Upper Merced R, 1500 m elev.	+4	None	–	−15% {100 cm}
	Upper Merced R, 3400 m elev.	+4	None	–	+22% {51 cm}
9	Northern catchments	+4	None	−10 to −4% {69 cm, average}	–
	Southern catchments	+4	None	−10 to −2% {36 cm, average}	–
10	Eight watersheds on E and W slopes	+4.1	−15 to −6%, decreasing N to S	−18% (W slopes), −13% (E slopes)	Approximately no change
11	Watersheds of Owens and Mono Lakes	+2 to +5	−24 to +56%	"Insensitive to warming"	"Insensitive to warming"
12	Upper San Joaquin R	+4.5	None	−24% {77 cm}	–
13	Mono Lake Basin	+4.1	−2% (mean, large range)	−15% {42 cm}	+8% {13 cm}
14	Sagehen Creek	+3	None	−16% {37 cm} (note 2)	+10% {60 cm}

References
1. Duell (1994); 2. Risbey and Entekhabi (1996); 3. Berghuijs et al. (2014); 4. Goulden and Bales (2014); 5. Lettenmaier and Gan (1990); 6. Jeton et al. (1996); 7. Dettinger et al. (2004); 8. Tague et al. (2009); 9. Null et al. (2010); 10. Ficklin et al. (2012); 11. Costa-Cabral et al. (2013); 12. He et al. (2013); 13. Ficklin et al. (2013); 14. Tague and Peng (2013).
Notes:
1. Precipitation and runoff assumed equal to 100 cm yr^{-1} and 52 cm yr^{-1} based on Goulden and Bales (2014).
2. Determined from modeled ET values assuming no long-term change in water storage.

runoff and climate, and (ii) watershed modeling, which simulate the physical processes governing water and energy flows across the landscape. Predicted changes in runoff from these two approaches tend to differ in magnitude. For a 4 °C increase in air temperature and no change in precipitation, decreases in annual runoff exceeding 25% are predicted using empirical approaches, while lesser changes are generally predicted using watershed models (Table 1). Such decreases in runoff under conditions of constant precipitation would be caused by increases in evapotranspiration, which in turn would be influenced by any changes in soil and/or land cover. Some of the empirically based predictions in Table 1 (i.e., Berghuijs et al., 2014; Goulden and Bales, 2014) used the space-for-time substitution approach (see Lester et al., 2014), which implicitly assumes that all influential factors in the system, such as soil and land cover, vary in phase with air temperature. However, this assumption would not likely hold true for soil development, which has time-scales on the order of thousands of years (Holbrook et al., 2014). Subsurface hydrologic properties are known to have an important effect on magnitudes of evapotranspiration and runoff, and the response of these fluxes to climate variability (Milly, 1994; Tague et al., 2008, 2014; Lundquist and Loheide, 2011; Sanadhya et al., 2014). Subsurface hydrologic properties also play an important role in the response of vegetation to climate (Kammer et al., 2013; Moyes et al., 2013; Osborn et al., 2014); for example, vegetation may be sustained through dry periods using water supplies in weathered bedrock (Witty et al., 2003; Bales et al., 2011; Kitajima et al., 2013). However, subsurface properties must not always be limiting, as demonstrated by fast and flexible shifting of vegetation across mountain landscapes in response to climate (Cannone et al., 2007; Kullman, 2008; Lenoir et al., 2008). Previous studies have contributed to the mechanistic understanding of how shifts in timing of snowmelt and/or rainfall affect changes in subsurface storage and water fluxes to streams (e.g., Milly, 1994; Risbey and Entekhabi, 1996; Tague et al., 2008; Null et al., 2010; Huntington and Niswonger, 2012). However, the extent to which subsurface hydrologic properties will mediate the effect of climate warming on long-term evapotranspiration and runoff from snow-influenced mountain regions remains unclear.

Our goal is to better understand the spatially varying effects of climate change on the hydrology and ecology of snow-influenced mountain regions. In particular, we are interested in how ecohydrologic responses to climate change may differ with hydrogeology and the partitioning of precipitation between rainfall and snowfall. Our objective here is to quantify the coupled effects of reduced snowfall (with warming) and subsurface hydrologic properties on long-term changes in runoff and evapotranspiration. Our hypothesis is that in areas where increased air temperature leads to a substantial reduction in snowfall, and advance in timing of snowmelt (earlier in the year), subsurface hydrologic properties can play a key role in long-term changes in runoff and evapotranspiration. We test this hypothesis using physically based numerical models that simulate interactions between flow-paths of water at the hillslope scale, and changes in timing and rates of surface water inputs and potential evapotranspiration. We apply our models to a small (1 km^2), mid-elevation catchment in the southern Sierra Nevada (USA), Providence Creek, using catchment-averaged characteristics and meteorological forcings. Such simplifications are reasonable considering the substantial uncertainty in spatial averages of important characteristics, such as subsurface storage capacity (Bales et al., 2011; Holbrook et al., 2014) and evapotranspiration (Goulden et al., 1996), relative to their likely spatial variability at this scale. We also discuss the implications of our findings for possible large-scale differences in ecohydrologic responses across elevations with varying soil and regolith properties.