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Groundwater dynamics mediate low-flow response to global warming in snow-dominated alpine regions

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[1] In mountain environments, spatial and temporal patterns of snow accumulation and melt are dominant controls on hydrologic responses to climate change. In this paper, we develop a simple conceptual model that links the timing of peak snowmelt with geologically mediated differences in rate of streamflow recession. This model demonstrates that within the western United States, spatial differences in subsurface drainage rates can exacerbate summer streamflow losses associated with diminishing snowpacks. Application of a process-based hydrologic model to four watersheds in the Western Cordillera further reveals that contingent on timing of snowmelt, slower draining watersheds are likely to have more water in summer but paradoxically are subject to the greatest summer water losses under a 1.5°C warming scenario. A slow draining watershed located in the young volcanic arc of the High Cascades in Oregon shows 4 times the summer streamflow reduction when compared with faster draining watersheds with similar timing of peak snowmelt. On the other hand, watersheds where snowmelt occurs late in the season but have little groundwater influence show high relative sensitivities to snowpack changes due to warming, as shown by a high-elevation granitic Sierran watershed. Our results highlight the importance of geological factors in interpreting hydrologic response to climate change and argue for a geoclimatic framework to guide the design of monitoring networks that will become the basis for assessing climate change impacts in mountain regions throughout the globe.

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1. Introduction

[2] Change in the timing and magnitude of streamflow under a warmer global climate can occur through direct changes in precipitation, and temperature-driven changes in evapotranspiration and snow (or glacier) accumulation, melt rates, and timing [*Barnett et al.*, 2005; *Bales et al.*, 2006]. The ultimate impact of these changes on seasonal streamflow patterns, however, may also depend on subsurface drainage processes that influence the translation of water inputs into streamflow. Such processes are primarily related to soils, geology, and topography, factors that determine the rate at which water is stored within and moves through the subsurface.

[3] Characterizing these subsurface factors that shape streamflow regimes continues to be a core research area in hydrologic sciences. Despite this emphasis, the connection between watershed drainage characteristics and streamflow sensitivity to climate drivers has received limited attention in most recent studies of projected climate change impacts on water resources. Particularly in mountain environments, spatial patterns of snow accumulation and melt have been emphasized as the dominant control on hydrologic responses to climate change [*Hayhoe et al.*, 2004; *Barnett et al.*, 2005; *Bales et al.*, 2006; *Intergovernmental Panel on Climate Change* (*IPCC*), 2007]. But how important, relative to other factors, are spatial differences in drainage rates? Moreover, if such differences are important, how accurately can these be measured and modeled for the purposes of projecting future water resource vulnerability to climate change?

[4] The western United States is characterized by a Mediterranean climate, with warm dry summers and cool wet winters. In mountain regions of the western United States much of the winter precipitation falls as snow. Streamflow follows this strongly seasonal pattern of winter precipitation and spring snowmelt. Streamflow is highest during winter precipitation and spring snowmelt periods, and lowest during the prolonged summer drought, when there is little recharge. While summer precipitation does occur, it is typically a small fraction (<5%) of annual totals. Agricultural irrigation, urban water supply, water-based recreational activities, and a broad spectrum of aquatic and riparian ecosystems all rely on summer streamflow. In the western United States, many hydroelectric projects rely on summer streamflow for power generation because they have little storage capacity. Historically, low flows during the summer have led to competing demands for limited water resources [*National Research Council* (*NRC*), 2002; *Poff et al.*, 2003]. Recent studies of climate change impacts in this region have shown that with a warming climate,

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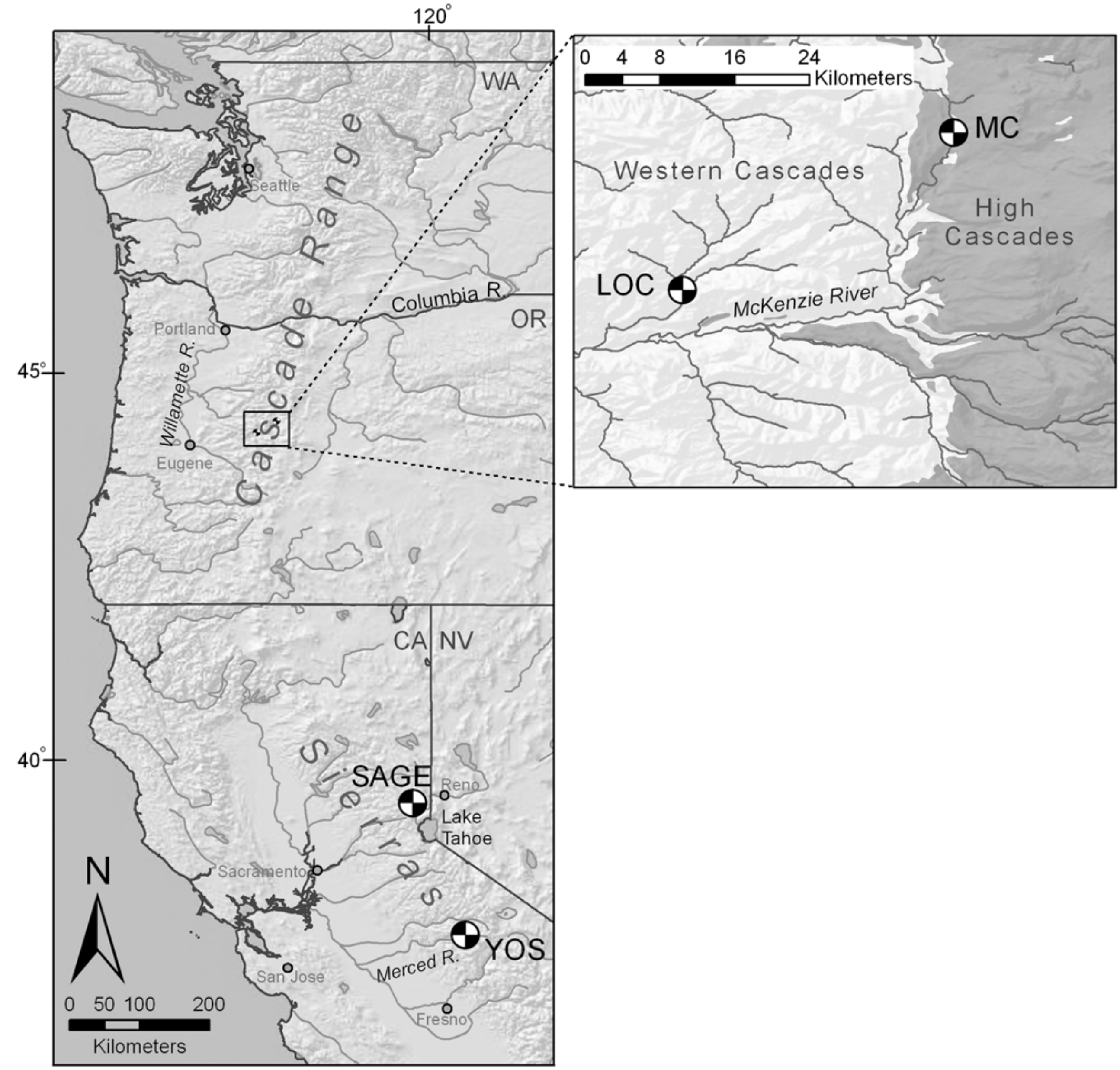

Figure 1. Western United States topography and study site locations.

timing of peak streamflow has shifted, and proportion of streamflow occurring during late summer has decreased for sites across the western United States [*Cayan et al.*, 2001; *Knowles and Cayan*, 2002; *Stewart et al.*, 2004; *Knowles et al.*, 2006]. Using both simulation models and empirical data, numerous studies also argue that there are strong spatial gradients in this response due to elevational and latitudinal differences in controls on snowpack dynamics. Lower elevations in the northern Sierra Nevada and Cascades Ranges, for example, have been identified as having large areas of "snow at risk" [*Hayhoe et al.*, 2004; *Payne et al.*, 2004; *Nolin and Daly*, 2006].

[5] Subsurface properties of soil and underlying geology clearly influence streamflow regimes. One of the key challenges in hydrologic science is to estimate these often cryptic properties of watersheds, either through calibration of hydrologic models against observed streamflow measurements, or through inferences based on catchment similarity, including geology and topography [*Beven*, 2006; *Schaake et al.*, 2006; *Wagener and Wheater*, 2006]. Conceptually, subsurface soil and geologic properties that control the rate of water flux (i.e., porosity, permeability, transmissivity) affect the response time of a watershed: the time delay between inputs as rainfall or snowmelt, and output as streamflow. In the western United States, complex geology and topography result in significant spatial differences in this time delay. For example, the Oregon Cascades comprise two distinct geologic units: the High and Western Cascades (Figure 1). Hydrologic differences between these regions reflect the dominance of a well-developed and steep drainage network with shallow subsurface flow paths in the older (Miocene to Pliocene) volcanic rocks of the Western Cascades, versus the gentler topography and much deeper groundwater and spring-dominated drainage system in the

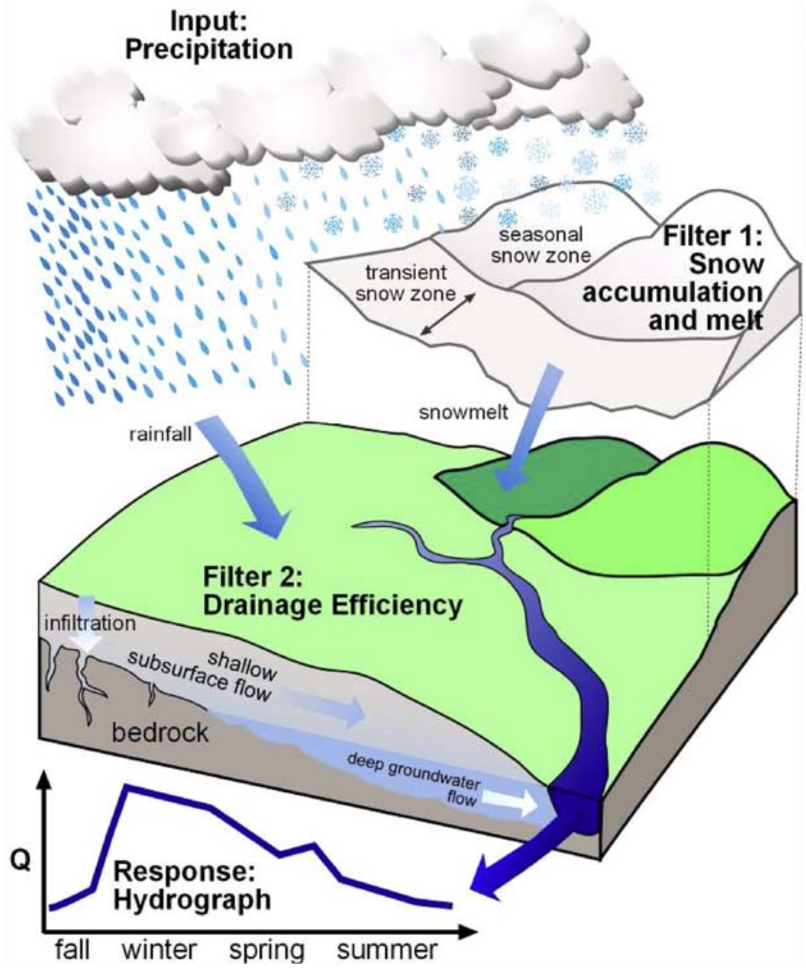

Figure 2. Filters controlling streamflow response to precipitation inputs.

younger (Pliocene to Recent) High Cascades [*Sherrod and Smith*, 2000]. Western Cascade streams are therefore typically flashier, with higher winter peaks and lower summer base flows than the High Cascades [*Tague and Grant*, 2004; *Jefferson et al.*, 2006]. Similar contrasts in hydrograph response can be found in the Sierra Nevada, where the dominantly granitic landscapes give rise to steep, shallow subsurface flow paths and rapid responses [*Harden*, 1988; *Norris and Webb*, 1990]. In some parts of the Sierras, however, younger Miocene to Pliocene volcanic rocks overlie granite [*Bovis*, 1987], and promote groundwater storage, leading to slower response times. Precipitation and snow accumulation and melt regimes also differ between and within the Sierra Nevada and Cascade regions along altitudinal and latitudinal gradients. Throughout both regions, a substantial portion of the landscape has a seasonal snowpack and snowmelt is the dominant mechanism of water input, at least at higher elevations.

[6] If subsurface properties were spatially homogeneous, understanding spatial patterns of summer streamflow sensitivity to climate change would depend primarily on analyzing geographic and elevational patterns of snow accumulation and melt. We suggest, however, that spatial differences in subsurface drainage characteristics are of commensurate importance with snowpack dynamics and play a key role in determining vulnerability of summer water resources to climate change. We address this issue by examining streamflow patterns in the western United States where both snowmelt and differences in underlying geology and subsurface drainage properties covary across the landscapes. Here we present a simple analytical model for characterizing landscapes with respect to their underlying sensitivities to snowmelt versus subsurface drainage processes as first-order controls on streamflow responses to recent and projected future climate warming. We then buttress this analysis by applying a spatially distributed hydrologic model to four western case-study watersheds in order to elaborate on and support more general conclusions derived from the simpler conceptual approach. We present methods and results for each section separately.

2. A Simple Conceptual Model

[7] In snowmelt-dominated watersheds, streamflow can be viewed as the convolution of two filters: snowpack dynamics and the subsurface drainage network (Figure 2). These filters combine to yield a temporal smoothing of the time series of precipitation inputs. We define the drainage efficiency of a watershed as the rate at which recharge, either as rain or snowmelt, is translated into streamflow. We develop a relatively simple assessment of how differences in this efficiency might affect spatial patterns of summer streamflow and its sensitivity to climate change. Note that efficiency here is not necessarily equivalent to classical

concepts of soil hydraulic conductivity, but refers to the net effect of all geologic and soil characteristics that shape the response time of the watershed to inputs.

[8] We use a simple conceptual model as a framework to illustrate how drainage efficiency combines with changes in the timing and magnitude of input (recharge as snowmelt or rainfall) to control summer streamflow. We consider a linear reservoir that receives a single pulse of recharge. Following *Tallaksen* [1995], flow from a linear reservoir is given as

$$Q(t) = Q_0 e^{(-kt)}, \tag{1}$$

where Q_t is streamflow at time, t (in days), Q_o is streamflow at the beginning of the recession period, and k is a base flow recession constant.

[9] For watersheds where spring snowmelt and/or winter rainfall are the primary sources of recharge, Q_o reflects the magnitude of this recharge. For our conceptual model, we simplify the time dimension of the recharge signal by considering a simple system where recharge (snowmelt) occurs in a single time step. Clearly this is an oversimplification, since recharge, both as precipitation and snowmelt, is distributed over the winter and spring and, to a much lesser degree, summer periods. We use this simple model, however, as a heuristic tool to demonstrate interactions between the timing and magnitude of recharge and drainage rates. While snowmelt inputs occur over days to months, examining the behavior of a single pulse provides a foundation for understanding how changes in the timing and magnitude of inputs translate into streamflow throughout the summer. As a proxy for Q_o, we consider the maximum daily snowmelt. We estimate snowmelt as the maximum daily loss in a 15-day running average of snowpack depth ($pk_{15\text{-day},}$ in mm of water), averaged over a watershed. Thus $pk_{15\text{-day}}$ reflects a pulse of water into the system and its magnitude varies with the magnitudes of seasonal snowpacks. In equation (1), expected flow at a particular time point during the recession trajectory depends on

$$t_r = t_{\text{summer}} - t_{pk} \tag{2}$$

or the number of days between the day of the recharge event (or snowmelt) (t_{pk}) and day of interest (t_{summer}). In the western United States, the time series in (1) is truncated each fall when recharge occurs, typically as fall rainfall. In this region, low summer streamflows usually occur in late August and early September. Earlier snowmelt thus increases t_r, the number of days of recession, and produces lower flows during August–September.

[10] We combine these temporal indices with k, the geologically mediated recession coefficient, which provides a proxy for drainage efficiency, to give the following model of summer streamflow (Q_r):

$$Q_r = pk_{15\text{-day}} e^{-k(t_r)}. \tag{3}$$

Values for k can be derived using standard base flow recession analysis of observed or modeled hydrographs during postsnowmelt periods [*Tallaksen*, 1995]. Larger values of k imply a steeper rate of recession and faster drainage.

[11] Insight into spatial and temporal sensitivity of summer flow to changes in the controlling variables can be gained by looking at the first derivatives of (1). Climate warming alters both $pk_{15\text{-day}}$ and t_r but does not change k, so conceptually we can describe sensitivities of summer streamflow to climate as

$$\frac{\partial Q_r}{\partial \left(pk_{15\text{-day}} \right)} = e^{-k(t_r)} \tag{4}$$

$$\frac{\partial Q_r}{\partial (t_r)} = pk_{15-\text{day}} * ke^{-k(t_r)}. \tag{5}$$

We do not expect that (4) or (5) will yield precise predictions of summer flow sensitivity to climate change, given that $pk_{15\text{-day}}$ and t_r are proxies for recharge characteristics. We propose this analysis as a conceptual rather than physical model and as a heuristic guide to demonstrate interactions between timing and magnitude of snowmelt and drainage efficiency. This model suggests that climate driven sensitivity of summer streamflow to $pk_{15\text{-day}}$ will be a function of k, such that systems with higher k, or greater subsurface drainage efficiency, will be less sensitive to changes in the magnitude of peak recharge. At the same time, this effect is mediated by the timing of snowmelt, t_r, such that regions where snowmelts later in the season (smaller t_r) will be more sensitive to a change in peak recharge. The model also suggests that streamflow sensitivity to changes in the timing of melt (t_r) will depend on a combination of the initial melt volume, subsurface drainage efficiency, and a priori timing of melt (t_r itself).

[12] Although this model is conceptual, it can be usefully solved using empirical data to provide insight into regional variation in streamflow response to climate warming. Given the simplicity of the conceptual model, we focus here on approximating differences in the magnitude and timing of snow and drainage rates for four sites that differ in terms of geology and snow accumulation and melt regimes (Figure 1 and Figure 3). Two Cascade watersheds (Lookout Creek (LOC) and McKenzie River at Clear Lake (MC)) represent Western and High Cascade geologies, respectively. Sagehen Creek (SAGE) is an example of a Sierra watershed where the primary lithology is granite capped by basalt, while the upper Merced River (YOS) represents the more common granitic lithology of the southern Sierras. As described above, the High Cascade geology is associated with slower drainage relative to both Western Cascade and Sierran geologies. Within the Sierra, the basaltic cap at SAGE results in slower drainage relative to the purely granitic YOS. Together, these four watersheds also represent a range of elevations and latitudes and thus reflect a range of snow regimes, with YOS representing the highest elevation watershed with latest annual snowmelt and LOC representing the watershed with lowest elevation and earliest snowmelt. Mean monthly precipitation values for each watershed are estimated from meteorologic stations within each watershed (Figure 3).

[13] By placing these four sites within the response surfaces described by equations (4) and (5) we show how between-site differences in the timing of snowmelt and drainage efficiency combine to influence August stream-

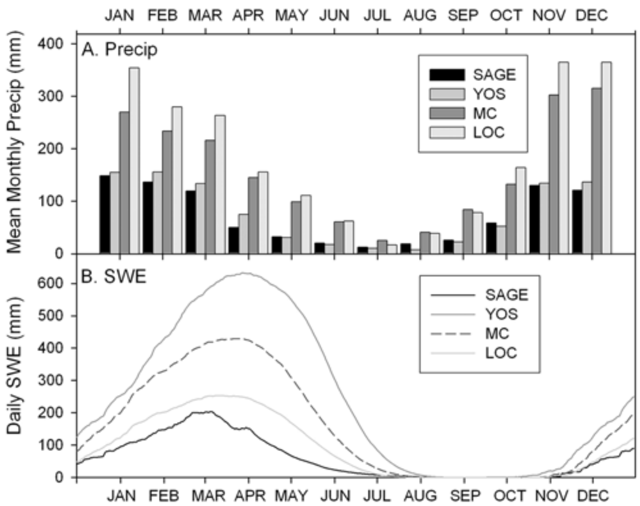

Figure 3. (a) Mean monthly precipitation for four study sites. (b) Mean daily snow water equivalent (SWE), estimated with the Regional Hydro-Ecologic Simulation System (RHESSys) and averaged over 1970–2000 water years for each of four study sites.

flow sensitivity. Snowmelt records at the watershed scale are difficult to obtain. Daily snowpack, averaged over watershed area, is estimated using the snow accumulation and melt component of a spatially distributed hydrologic model called Regional Hydro-Ecologic Simulation System (RHESSys; described in more detail in section 4) (Figure 3). Previous studies have shown good correspondence between RHESSys estimates of snow accumulation and melt and point snow water equivalent (SWE) estimates and remote sensing–derived estimates for the Cascades [*Tague et al.*, 2008] and Sierra [*Christensen et al.*, 2008] sites. From RHESSys snow trajectories, we estimate an average value of t_r for August streamflow (e.g., t_r = 214-day of peak melt where 214 is year day of 1 August) (Table 1). To estimate the value of k (equations (1)–(4)), we use recession analysis of stream gage data for the four sites [*Tallaksen*, 1995]. For each site, we computed mean daily streamflow over the historic gage record (1970–2000) and determined k from this daily average hydrograph. We use streamflow recession during the period between snowmelt (as estimated using RHESSys snow accumulation and melt trajectories) and the end of August. We emphasize that these values of k are rough approximations. In all of these basins, snowmelt inputs are distributed over space and time and influence hydrograph recession in complex ways. Further, watershed drainage is only approximated by a linear reservoir model. We include these values, however, to show how potential differences in drainage efficiency might influence sensitivity.

3. Results: Conceptual Model

[14] Figures 4a and 4b illustrate the response surfaces for (4) and (5), respectively, and show how August streamflow responds to a change in the magnitude and timing (in days) of snowmelt (in mm/area). Streamflow sensitivity is shown for the range of drainage efficiencies (k) and timing of peak melt (t_r) found within the Sierra Nevada and Oregon Cascade ranges. The response of August streamflow to a change in the amount of recharge (Figure 4a) shows a clear difference (more than double) across this range of geologically mediated variation in k. The impact of changes in the timing of recharge (e.g., earlier snowmelt) is also strongly controlled by drainage efficiency but is also influenced by a priori timing of melt (Figure 4b).

[15] For reference we plot the four watersheds selected from the Oregon Cascades and California Sierra Nevada to capture specific landscapes with differing elevations and geology on the response surface (see Table 1 for additional

Table 1. Description of Study Watersheds and Summary of RHESSys Model Estimates of Streamflow and Snow Characteristics for Each Watershed

	Lookout Creek (LOC)	McKenzie River at Clear Lake (MC)	Sagehen Creek (SAGE)	Upper Merced River at Happy Isles (YOS)
Location	Oregon	Oregon	California	California
U.S. Geological Survey gage number	14161500	14158500	10343500	11264500
Geology	Western Cascade basalt	High Cascade basalt	Sierra granite, with Miocene andesite cap	Sierra granite
Elevation range (m)	410–1630	920–2035	1928–2653	1200–3997
Drainage area (km^2)	64	239	2.6	465
Mean annual streamflow (cm/a)	176	169	45	67
Estimated k	0.028	0.01	0.027	0.038
Average peak SWE (mm)				
Historic	254	430	311	703
1.5°C	85	172	176	616
Average day of peak SWE (year day)				
Historic	73	83	90	88
1.5°C	63	64	62	77
Average day of 50% of peak SWE (year day)				
Historic	135	139	137	153
1.5°C	116	124	122	144
Change in peak SWE (mm) with 1.5°C warming	−169	−257	−134	−87
Change in day of peak SWE (days) with 1.5°C warming	−10	−19	−28	−11
Change in day of 50% peak SWE (days) with 1.5°C warming	19	15	15	9

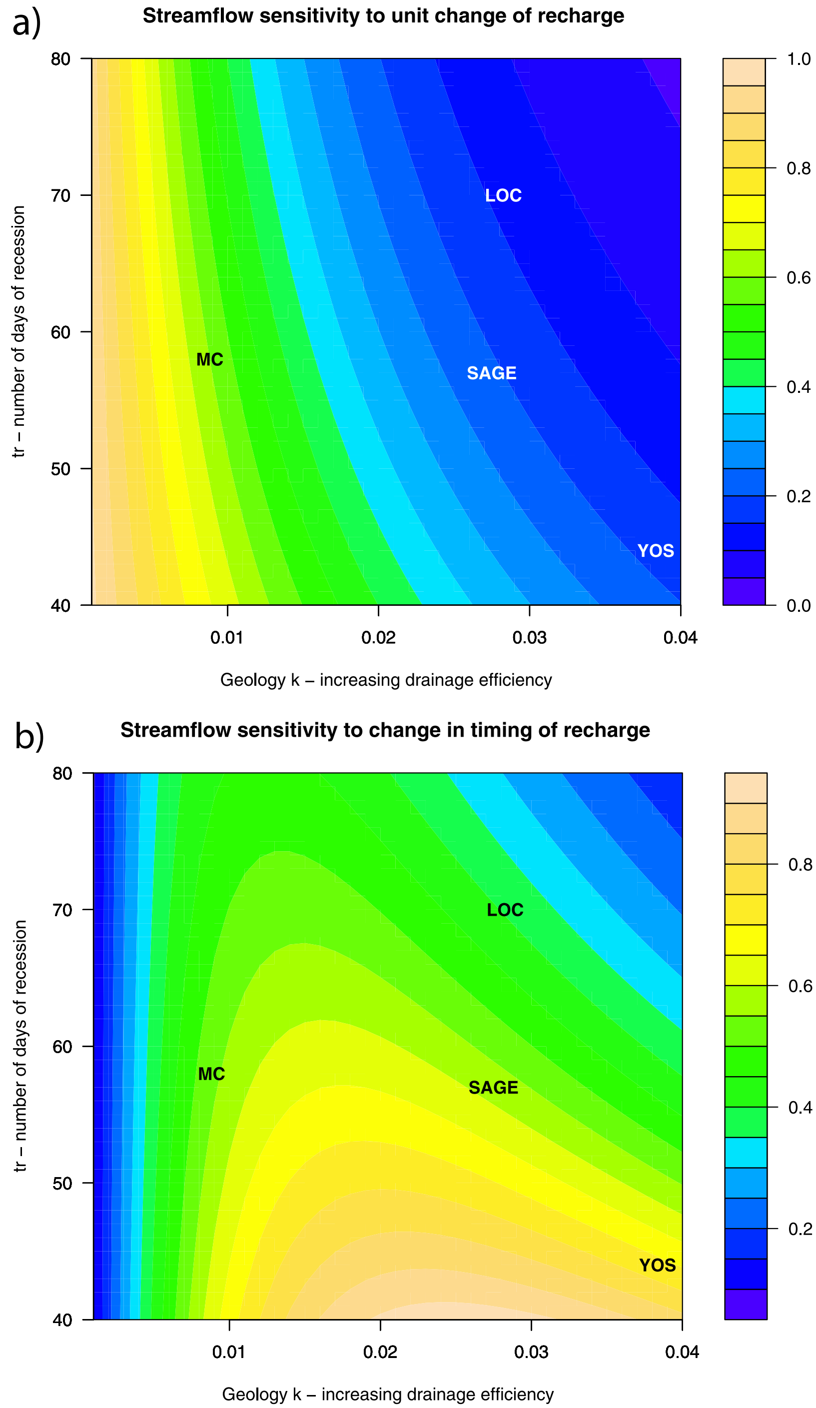

Figure 4. Response surface from conceptual model of the sensitivity of summer streamflow to (a) changes in the magnitude of recharge ($pk_{15\text{-day}}$) and (b) changes in the timing of recharge ($pk_{15\text{-day}}$), assuming an initial recharge volume of 1 mm. Change is given as a unit change in daily streamflow (mm/d). Lighter colors (yellow) denote greater sensitivity.

description). The plotting position of these representative watersheds within the response surfaces predicts significant differences among these watersheds in terms of the change in summer streamflow for some arbitrary late summer date (e.g., 1 August) given similar changes in the magnitude (Figure 2a) and timing (Figure 4b) of recharge. Further, the response surface links these differences to both drainage efficiency and the timing of snowmelt. Our simple conceptual model suggests that the relatively high sensitivity of MC to both changes in the magnitude and timing of melt (Figures 4a and 4b, respectively) is due to its relatively low drainage efficiency. The relatively high sensitivity of YOS to a change in the timing of melt is due to its relatively late melting snowpack. SAGE is similar to MC in terms of the timing of melt but drains more quickly. This difference means that relative to MC, SAGE has less sensitivity to changes in the magnitude of melt input. LOC has similar drainage efficiency to SAGE but shows less sensitivity to a change in $pk_{15\text{-day}}$ or t_r due to its earlier melt (greater initial t_r).

4. Predicted Responses of Watersheds to Climate Warming Using a Physically Based Hydrologic Model

[16] The response surface derived from the conceptual model defines a broad spectrum of drainage efficiencies and timing of recharge that might be expected across the western United States. The conceptual model is limited, however, in that it oversimplifies the system. First, our conceptual model examines the response of a single snowmelt pulse. In reality, snowmelt is distributed over weeks to months. Moreover, as temperatures warm in the future, precipitation shifts from snow to rain in fall and winter periods, further altering the time distribution of inputs in complex ways. Summer precipitation does occur but is not considered in the conceptual model. Finally, the subsurface hydrology of most watersheds is dominated by spatially and temporally variable source areas and the connectivity between them. These mechanisms are not well represented by a simple linear reservoir model [*Dingman*, 1994]. To assess the robustness of our conceptual model, we apply a complementary set of analyses to the case study watersheds where available data sets permits us to parameterize a spatially distributed hydrologic model. RHESSys (described in more detail in the next paragraph) accounts for both varying timing and phase (rain versus snow) of water inputs, summer precipitation, and both soil and deeper groundwater storage as well as the covariance and interaction between recharge and spatially varying subsurface response units. We first examine the relationships between snowmelt and streamflow for each of the four example watersheds to verify the impact of drainage efficiency on the sensitivity of streamflow to changes in recharge. Our conceptual model suggests that with slower drainage efficiency, greater sensitivity to changes in snow accumulation and melt is expected.

[17] We model the effects of warming using RHESSys [*Band et al.*, 2000; *Tague and Band*, 2004], a physically based spatially explicit model of relevant hydrologic processes including snow accumulation and melt, interception, infiltration, evapotranspiration, and vertical and lateral subsurface flow routing. RHESSys has previously been applied to a number of snow-dominated mountain catchments and has shown that it can successfully model both hydrologic behavior [*Baron et al.*, 2000; *Tague and Band*, 2001a, 2001b; *Mackay et al.*, 2003] and carbon cycling dynamics [*Zierl et al.*, 2007]. The version of RHESSys used in this study includes an explicit subsurface routing module, similar to that used by the distributed hydrology soil vegetation model (DHSVM) [*Wigmosta et al.*, 1994] that routes water between spatial patches as a function of topography and soil conductivity. In addition, a proportion of subsurface water is allocated to hillslope-scale deeper groundwater reservoirs. We note that the inclusion of multiple connected patches, whose responses and connections vary as a function of moisture condition, allows RHESSys to estimate hydrologic responses that could not be captured by a simple linear reservoir model. We also note that this approach explicitly links hillslope variation in snow accumulation and melt, at the scale of 30–120 m patches, with spatial variation in travel time to the stream. A more detailed description of RHESSys is given by *Tague et al.* [2008] and *Tague and Band* [2004]. For this study, RHESSys was driven by daily time step meteorologic data for each site. The resulting approach requires calibration of four hydrologic parameters (see *Tague et al.* [2008] for details on calibration procedures). We use daily streamflow records at each site for parameter calibration. Comparisons between model estimates and observed gage data show that the model adequately captures daily, seasonal, and annual variability. Model results for all watershed show an R^2 of >0.8, for daily flows, $R^2 > 0.6$ in interannual variation in August flow, and <5% error in estimating mean annual flow for 10–20 year validation periods.

[18] The RHESSys snowmelt module uses a combination of an energy budget and degree-day snowmelt model to estimate snow accumulation and melt trajectories. RHESSys estimates of snowmelt have been validated by comparison with Moderate Resolution Imaging Spectroradiometer (MODIS) satellite estimates of percent basin snow cover (R^2 of greater than 0.9, for 2000–2004, for YOS basin), as well as Natural Resources Conservation Service Snowpack Telemetry (SNOTEL) point measurements of snow water equivalent depth for individual patches within the study watersheds ($R^2 > 0.8$).

5. Results: Physically Based Modeling of Case Study Watersheds

[19] For each of our four sites, we compared basin-wide estimates of seasonal peak snow (using a 15-day running average of snowpack water equivalent depth) and summer streamflow (Figure 5). Results confirm that in the slower draining High Cascade (MC) watershed in contrast to the more rapidly draining Western Cascades (LOC), there is a greater change in August streamflow for the same change in seasonal snowpack. Other studies that compare SNOTEL estimates, rather than modeled snow data, with August streamflow have shown similar differences between High and Western Cascade watersheds [*Jefferson et al.*, 2006]. The high-elevation watershed, YOS, also shows greater change in August streamflow for a given change in snowpack (relative to SAGE and LOC), but this sensitivity diminishes for September flows. This pattern is consistent with the response surface from the conceptual model that links greater relative changes in August streamflow with later snowmelt timing in YOS, but also predicts rapid reduction in this sensitivity as the season progresses (in comparison with MC) due to the high k value associated with YOS. Note that shifting to September from August in the response surface would effectively increase t_r and move all labeled sites upward in Figures 4a and 4b. It is clear that in moving upward to a t_r associated with September flows, the net change in streamflow of YOS, for example, decreases more rapidly than that of MC. The shape of the response surface confirms that MC shows a relatively high sensitivity of streamflow to changes in timing and magnitude of recharge for a broader range of t_r, i.e., over a longer time period through the summer months.

[20] To further examine how these different watersheds might respond to warming, we use RHESSys to compare streamflow estimates for historic climate conditions with

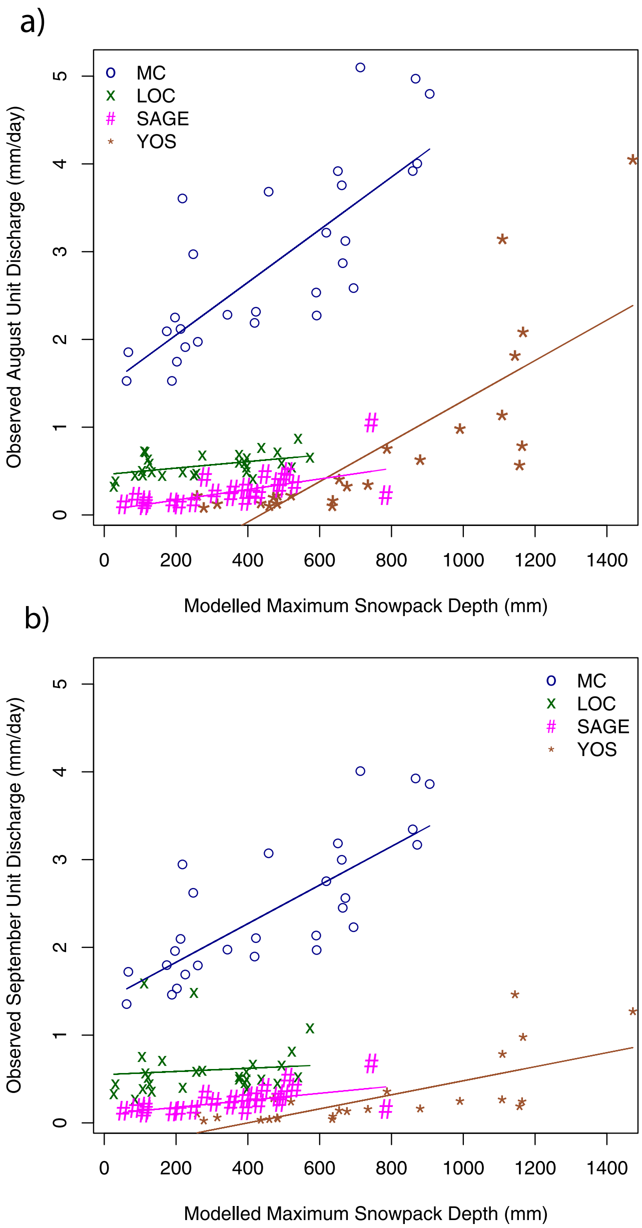

Figure 5. Mean daily discharge for (a) August and (b) September against annual maximum 15-day running average of mean watershed SWE depth. SWE is estimated using the RHESSys hydrologic model. Slopes of the relationship between annual maximum SWE and streamflow are all statistically significant ($p < 0.01$) in a linear regression model.

those for a moderate 1.5°C warming scenario. Most global circulation models models for the western United States predict increases of at least 2°C within the next 50 years. Precipitation predictions are less certain, with some models predicting small increases and others predicting decreases [*Hayhoe et al.*, 2004]. We used a simple 1.5°C warming, rather than downscale global circulation model (GCM) predictions, because the latter may include changes to precipitation regimes and more complex spatiotemporal patterns of warming. By focusing on a simple warming effect, we can more clearly demonstrate the relative contributions of snow (and changes in snow) as recharge and drainage efficiency as controls on streamflow. More complex climatic forcing will change the timing and magnitude of recharge and hence position of the watershed along the *y*-axis of the response surfaces for the simple conceptual model, but will not alter drainage efficiency.

[21] With the 1.5°C warming, snow melts earlier and snow peaks are smaller for all watersheds (Table 1, Figure 6). The greatest changes in magnitude of melt occur for MC, and greatest changes in timing of melt occur for LOC. Modeled hydrographs show daily flow averaged over the historic period of record for each gage (Figures 6a–6d). The slower rates of recession associated with MC and later snowmelt timing of YOS are clearly evident in the historic hydrographs (Figures 6a–6d). With a 1.5°C warming, all four watersheds show increases in winter flows and decreases in summer flows (Figure 6d). But recharge timing and rate of recession strongly influence these streamflow responses to warming. For the slower draining MC watershed, decreases in summer flow are smoothed and extended in time, and thus show the greatest reductions in flow for much of August (Figure 6e). The late timing of melt in YOS means that this watershed also shows large reductions in August flow, but these effects reduce dramatically in September. Thus for the high-elevation YOS we have larger changes in summer streamflow in August, even though the magnitudes of change in snowpack peaks were relatively small for this watershed (Figure 6e and Table 1).

[22] Climate models differ substantially in the magnitude of projected warming, and warming trends are likely to be more complex than uniform temperature increases [*Hayhoe et al.*, 2004]. Nonetheless, the spatial differences in response to a 1.5°C warming shown here suggest patterns that are likely to be found (and amplified) by greater and more complex climate changes.

[23] These streamflow changes will have implications for water resources. Response surfaces and streamflow changes discussed thus far refer to volumetric changes; such absolute changes are important because they bear directly on water supply from these individual watershed as well as contributions to downstream reservoirs. Headwater streams in the Cascades and Sierra are the major sources of water supply for urban centers and agriculture throughout the West, and also provide the water for hydropower throughout the region. For example, the average August flow at MC represents 10% of the unregulated flow at the water intake for Eugene, Oregon (population 150,000). Relative or percent changes in streamflow can also be important, however. Percent reduction in summer streamflow tends to be greater for the faster draining watersheds (Western Cascades and Sierras), whereas absolute changes tend to be greater for the much slower draining High Cascade system (Figures 7a and 7b). Timing of snowmelt adds additional complexity to this relationship, leading to high absolute August reductions in flow for YOS as discussed above. Faster draining and earlier melting streams such as LOC intrinsically have lower summer streamflows; consequently, small volumetric changes translate into large percent changes. Where summer water is scarce, large percentage reductions in flow can translate into sharp ecosystem responses, even though absolute flow decreases are small. Critical stream habitats, such as the location of channel

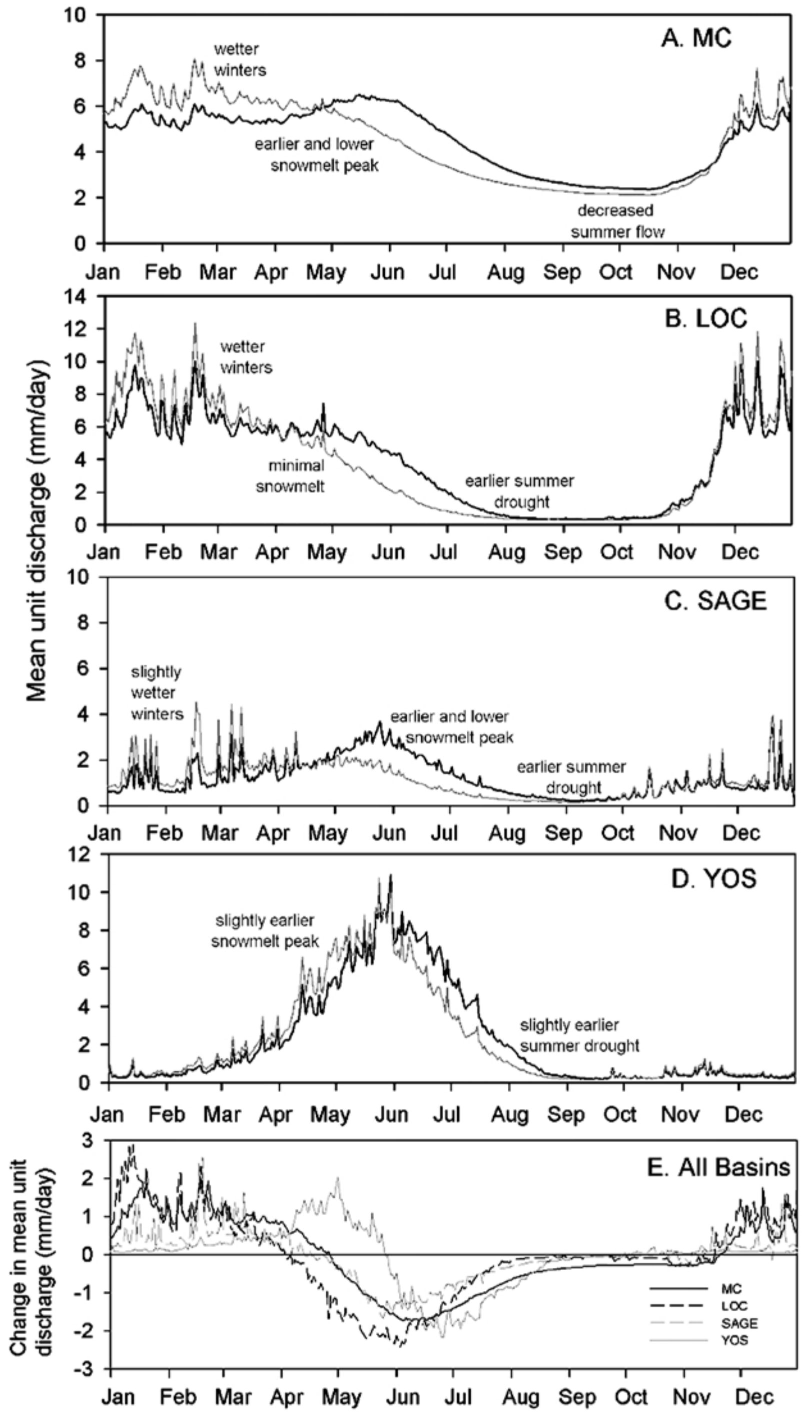

Figure 6. RHESSys estimates of annual hydrograph and its sensitivity to climate warming for four study catchments. Figures 6a–6d show mean unit discharge. Mean unit discharge is computed by averaging RHESSys estimates of daily streamflow (normalized by drainage area) for each day of year for the 30-year climate record. Black lines show streamflow estimated using baseline meteorologic data and gray lines show estimated streamflow given a 1.5°C warming. Figure 6e shows modeled change in average day of year flow between baseline and a 1.5°C warming scenario.

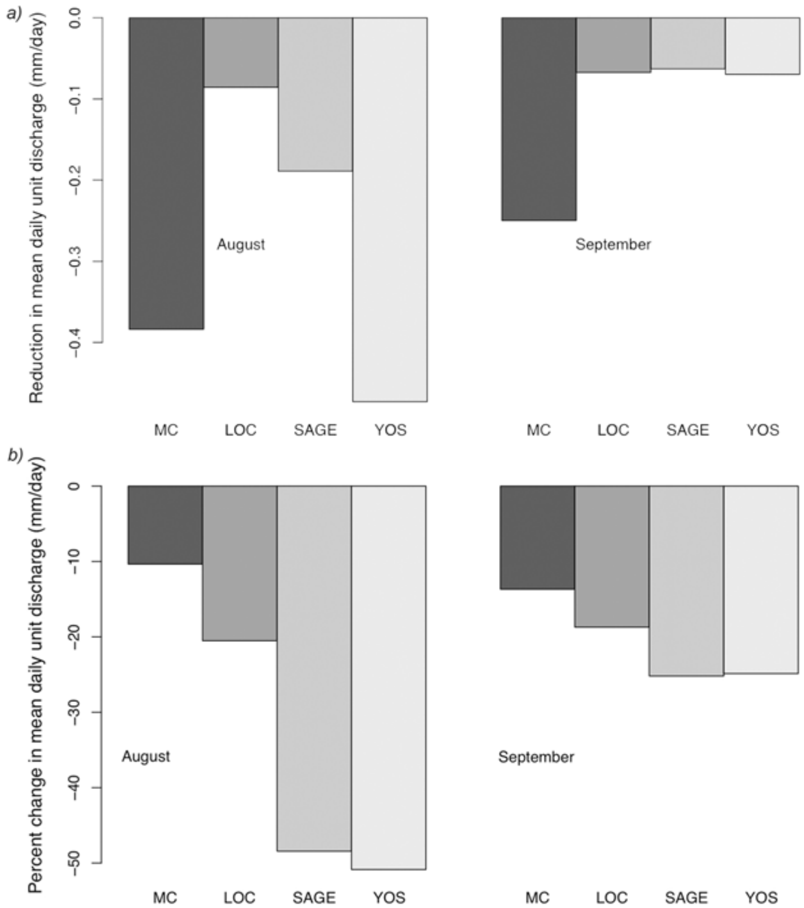

Figure 7. (a) Absolute volume reduction (normalized by drainage area) and (b) percent change in mean daily streamflow for August and September for a 1.5°C warming scenario. All reductions are averaged over a 30-year climate record.

heads and the wetted perimeter of streams, are highly sensitive to flow regimes [*Poff et al.*, 1997].

6. Discussion and Implications

[24] Results from the more detailed modeling of our four study sites spanning a range of drainage efficiencies and snowmelt timing are broadly consistent with the response surfaces predicted by the simple conceptual model. While it is perhaps not surprising that hydrograph behavior is influenced by the geologically mediated recession characteristics represented by k, and the timing of recharge (t_r), these results clearly demonstrate that assessing summer streamflow response to climate warming requires that these factors be considered explicitly; to date this has not been sufficiently incorporated into future streamflow predictions, which have tended to focus almost exclusively on climate-mediated changes in snowpack regimes. Results show that the magnitude of variation due to k, both within and between mountain landscapes across the western United States, warrants equal attention as the timing and magnitude of snowmelt in predictions of climate-driven changes in streamflow regimes. Further, the implication of variations in k to streamflow sensitivity to warming is somewhat counterintuitive. A superficial analysis might suggest that the slower, groundwater system of the High Cascades, for example, will buffer the system's response to climate change, when in fact the opposite is true. Slow draining systems are buffered in the sense that they are likely to continue to have late season water under climate warming, but will show the greatest absolute decreases in streamflow. Our simple conceptual model disentangles these effects and shows that within the Cascades and Sierras, difference in drainage efficiency are critical controls on how water availability and stream habitats will be influenced by a warmer climate. This important finding needs to be factored into climate mitigation strategies focused on water supply and hydroelectric energy production, for example.

[25] A critical challenge facing water managers is to identify areas of greater or lesser vulnerability to changing streamflow regimes. Clearly, differences in snowpack and drainage efficiency must be incorporated into such forecasts. The key obstacle in meeting this challenge is the estimation of drainage efficiency parameters at appropriate spatial scales and with acceptable accuracy. Our conceptual model provides for a heuristic understanding of relative controls on summer streamflow sensitivity. The conceptual model, however, is overly simplified and cannot be used for prediction. Spatially distributed hydrologic models, such as RHESSys, can, but these require calibration of subsurface drainage parameters (that are reflected by k in the conceptual model). Estimating these parameters at large spatial scales poses enormous logistical and statistical problems, since drainage efficiency is not just a soil property but

reflects rock permeability, porosity, degree of fracturing, etc. The standard approach is to estimate drainage parameters from long-term gage records, as we have done here. Ideally, we would begin by identifying unregulated gaged basins that were representative of particular geologies, and then calculating recession coefficients. In our example, the Cascades offer a relatively straightforward analysis of this sort, where a simple age classification of the rocks provides a very robust basis for estimating key hydrologic parameters, such as recession coefficients [*Tague and Grant*, 2004]. This classification also corresponds to differences in drainage density [*Luo and Stepinski*, 2008]. For the Sierras, however, a more complex geology complicates determination of unique values of subsurface drainage parameters for larger basins. For example, neighboring basins to SAGE have different proportions of exposed granite and volcanic caprocks. A coordinated analysis is needed to (1) identify unregulated gaged basins with single geologies to serve as end-members, and calculate drainage parameter values for these basins; and (2) determine whether drainage parameter values for gaged basins with mixed lithologies can be estimated using the proportion of area in these end-member geologies. New data sets of basin characteristics, including geology for U.S. Geological Survey (USGS) gaged streams, offer an excellent starting point for this analysis (see http://water.usgs.gov/osw/streamstats/).

[26] An obvious corollary to this is that assessing spatially varying vulnerability to water resources due to climate warming requires a widely distributed, long-term, and climatically and geologically representative stream gaging network. The USGS stream gage network is one of the most spatially intensive in the world, and yet it still underrepresents the diversity of geology found in the western United States [*NRC*, 2004]. This is not surprising, as the network evolved in response to a multidecadal history of funding opportunities and shortfalls, societal needs, and operational and management limitations. It was never deliberately designed to capture the full range of hydrologic, geologic, and climatic variability, and the long attrition of gage sites and termination of records has only exacerbated this problem [*Wahl et al.*, 1995; *USGS*, 1998]. New investments in intensive regional monitoring sites and networks, however, such as the U.S. National Science Foundation–sponsored hydrologic and critical zone observatories (CZOs) and the National Ecological Observation Network (NEON), offer an opportunity to reverse this trend and improve water resource predictions in the future. Our results argue strongly for the need to explicitly utilize a geological as well as climatic and elevational framework in the design of these monitoring networks.

[27] Finally, although our analysis has focused on the western United States, numerous studies have shown that mountain systems throughout the globe are similarly vulnerable to climate-driven changes in snow accumulation and melt [*Barnett et al.*, 2005; *IPCC*, 2007], and we would expect the same dependency on geologically mediated factors to apply as in the western United States. In many of these regions, stream gage networks are very sparse and resources for monitoring can be quite limited. Initiatives within the hydrologic sciences community, for example, the international effort to improve prediction in ungaged basins (PUB), seek to find better ways of assessing drainage behavior where long-term records are unavailable [*Sivapalan*, 2003]. But it is unlikely that improved monitoring and modeling techniques alone can replace the critical need for an expanded streamflow measurement network to assess the predicted effects of global warming on vital streamflows. Strategic streamflow monitoring and development of cheaper monitoring techniques should be core foci for programs designed to monitor and mitigate projected climate impacts on water resources.

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