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Hydrogeological response to climate change in alpine hillslopes

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Abstract:

Climate change threatens water resources in snowmelt-dependent regions by altering the fraction of snow and rain and spurring an earlier snowmelt season. The bulk of hydrological research has focused on forecasting response in streamflow volumes and timing to a shrinking snowpack; however, the degree to which subsurface storage offsets the loss of snow storage in various alpine geologic settings, i.e. the hydrogeologic buffering capacity, is still largely unknown. We address this research need by assessing the affects of climate change on storage and runoff generation for two distinct hydrogeologic settings present in alpine systems: a low storage granitic and a greater storage volcanic hillslope. We use a physically based integrated hydrologic model fully coupled to a land surface model to run a base scenario and then three progressive warming scenarios, and account for the shifts in each component of the water budget. For hillslopes with greater water retention, the larger storage volcanic hillslope buffered streamflow volumes and timing, but at the cost of greater reductions in groundwater storage relative to the low storage granite hillslope. We found that the results were highly sensitive to the unsaturated zone retention parameters, which in the case of alpine systems can be a mix of matrix or fracture flow. The presence of fractures and thus less retention in the unsaturated zone significantly decreased the reduction in recharge and runoff for the volcanic hillslope in climate warming scenarios. This approach highlights the importance of incorporating physically based subsurface flow in to alpine hydrology models, and our findings provide ways forward to arrive at a conceptual model that is both consistent with geology and hydrologic principles.

KEY WORDS hydrogeology; climate change; integrated modelling; snowmelt dominated

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INTRODUCTION

Climate change is impacting water resources in snowmelt-dependent regions by inducing a precipitation phase shift from snow to rain, as well as an earlier snowmelt period (Bales *et al.,* 2006; Beniston *et al.,* 1997; Cayan *et al.,* 2008; Stewart *et al.,* 2005). The proposed implications stemming from these two climate change impacts are increased spring runoff and decreased groundwater recharge in the mountains, which, if true, would have downstream impacts on flood control, reservoir storage, baseflow volumes, and ecosystem resilience during the dry season (Huntington and Niswonger, 2012; Peterson *et al.,* 2008; Tague *et al.,* 2008). Rising temperatures, and especially and perhaps most adverse to alpine hydrology rising daily minimum temperatures in the winter season, also impact alpine hydrology by increasing the energy available for evaporation at the land surface (Dingman, 1994), increasing evapotranspiration (ET) at energy-limited higher elevations, decreasing ET in water-limited lower elevations (Trujillo *et al.*, 2012), and shifting vegetation distributions (Goulden and Bales, 2014). These land surface feedbacks affect recharge by shifting the relative saturation in the unsaturated zone, which impacts the timing and amount of water that can infiltrate. Despite the increased effort to observe (Nayak *et al.*, 2010) and forecast (Ficklin *et al.,* 2013) the effect of climate change in alpine regions, little has been done to address the question of whether and to what degree subsurface storage can offset the loss of snow storage and spatiotemporal shifts in ET. This, coupled with our lack of knowledge regarding the storage characteristics of mountain block systems and the timescales over which they store and transmit water, introduces cascading uncertainty in water budget projections from the hillslope to the regional scale.

Mountain geology exhibits a large range of porosity and hydraulic conductivity values owing to both the composition and structure of the bedrock. For example, unfractured granite has a hydraulic conductivity (K) range

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of 10^{-13} to $10^{-10}\,\mathrm{ms}^{-1}$ that is potentially 11 orders of magnitude smaller than a transmissive basalt or karst aquifer (Freeze and Cherry, 1979). If that same granite is fractured and the fractures are sufficiently connected, which is not uncommon in heavily folded and faulted mountain belts, the K can range from 10^{-8} to $10^{-4}\,\mathrm{ms}^{-1}$, up to 9 orders of magnitude larger. Low storage fractured crystalline systems such as the Sierra Nevada and Himalaya mountain ranges typically generate runoff via interflow in the soil or saprolite zone, yet multiple studies have observed a scale effect with flowpath (Frisbee *et al.,* 2011) and fracture connectivity (Clauser, 1992) that could allow for deep groundwater to contribute to streamflow significantly up to the watershed scale (Frisbee *et al.,* 2011; Neuman, 1990; Andermann *et al.,* 2012). The contributions of deep groundwater to streamflow in fractured crystalline systems, however, are highly uncertain because of a lack of deep boreholes or geophysical data and the paucity of modelling studies that can deterministically represent fracture heterogeneity in mountain block systems (Neuman, 2005). On the other hand, porous and permeable volcanic systems such as in the Cascade and Andes ranges can store orders of magnitude more water than crystalline rocks and transmit that storage over interrannual timescales (Godsey *et al.,* 2013; Peterson *et al.,* 2008; Rademacher *et al.,* 2005). A higher hydraulic conductivity and porosity leads to a deeper water table but also to greater connection to deep groundwater circulation in these types of alpine systems, which if coupled with increased or decreased recharge because of climate change, would affect baseflow generation differently than in low storage systems (Gleeson and Manning, 2008).

Studies looking at the continuum hydrologic response to climate change in the mountains have done so either by parameterizing the complex hydrogeology in to 'slow' and 'fast-draining' systems using lumped parameter models (Andermann *et al.,* 2012; Tague *et al.,* 2012) or using distributed hydrologic models (Ficklin *et al.,* 2013; Godsey *et al.,* 2013; Huntington and Niswonger, 2012). In the former cases, slow and fast is best conceptualized as diffusivity, which is the ratio of hydraulic conductivity (transmissivity) to specific storage (storativity). Crystalline rocks such as in the southern Sierra Nevada comprise fast-draining, high diffusivity systems with small storage and high-K fracture-driven flowpaths. Alpine volcanic basins, such as in the Cascade Mountains, have a lower diffusivity, despite their higher effective hydraulic conductivity, owing to a much larger storage potential. A recent study observed an annual hysteretic loop between storage and discharge in the fractured crystalline bedrock of the Himalayas using a simple lumped parameter model that routes groundwater based on a characteristic basin response time (Andermann *et al.,* 2012). This finding was significant as it demonstrated the large contribution of deep groundwater to streamflow in mountain systems, while it also highlighted key uncertainties in alpine hydrogeology such as tectonic controls and depth of groundwater circulation. Pohl *et al.* (2015) reiterated this finding, attributing 40% of annual runoff to deep groundwater in a glacier and snowmelt dominated catchment in the Pamir mountains; however, their findings suggested that unsaturated interflow is just as significant and unconstrained in mountain systems. Tague *et al.* (2012) performed a sensitivity analysis in order to identify transfer parameters for several Cascade mountain watersheds, and found that they could adequately replicate streamflow response to warming if provided ample information about the geologic endmembers. Lumped parameter approaches are less computationally expensive and offer hope for predicting response to climate change in remote or ungauged basins; however, these paradoxically rely on parameters, such as basin response time, that require significant understanding of the hydrogeologic setting.

An alternative to the highly parameterized approach is to employ a distributed hydrologic model, which improves process representation but comes at a cost of large input data requirements and potential for non-unique inverse solutions based on which parameter is tuned or calibrated. Huntington and Niswonger (2012) synthesized an impressive amount of data to construct and calibrate a coupled surface water–groundwater model of a crystalline alpine basin near Lake Tahoe, CA for purposes of assessing climate change impacts to summer low flows. They used statistically downscaled climate data to run ensemble future scenarios and found that baseflow was most sensitive to spring snowmelt timing in the low storage basin. Tague *et al.* (2008) applied a distributed ecohydrologic model for two volcanic basins in the Oregon Cascades, and found that increasing storage simultaneously buffers and amplifies the effects of climate change by sustaining streamflow despite a loss of snow, while exhibiting a greater volumetric decrease in streamflow. Their follow-up study included low storage fractured granite basins from the California Sierra Nevada in their modelling analysis, and further supported the finding that climate change projections are as sensitive to geologic parameterization as to snowmelt timing and amount (Tague and Grant, 2009).

Results from both lumped and distributed approaches address a key unknown in climate change projections of headwaters systems, which is how the snow to rain phase change will impact recharge, storage, and ultimately runoff-generation in different hydrogeologic settings. However, each of these studies relied on some form of parameterization or calibration and did not simulate fully three-dimensional variably saturated flow in the subsurface, thus limiting their ability to identify the dynamic feedbacks by which the hydrologic continuum responds to climate change. Using fully physically based hydrology models will not necessarily change the results presented in the previous work, but rather help us to answer the main research question of whether and in what hydrogeologic settings can subsurface storage compensate for the loss of snowpack in the mountains. Here we address this knowledge gap with a simple 2-D hillslope approach to assess the relative impacts of multiple warming scenarios on snowpack, recharge, ET, runoff, and subsurface storage for two alpine hydrogeologic scenarios using an integrated hydrology model fully coupled to a land surface model.

METHODS

The outline for this work is as follows: (1) we simulate two hillslopes, a high diffusivity, low storage and a low diffusivity, high storage case, using observed meteorological forcings for a mid-elevation alpine setting; (2) we then perturb the climate forcings with progressive temperature increases and tracked the shifting stores of water relative to degree of warming and degree of subsurface storage. We do this in a modelling environment in order to isolate the tightly coupled energy and mass exchanges that would otherwise be exceedingly difficult to tease out in a real world setting.

Integrated hydrology model

This research uses ParFlow (PF), an integrated hydrologic modelling code that solves for variably saturated flow in the subsurface using the 3-D Richards' Equation (Equation 1), where S_s is specific storage in units of time^{-1} (T^{-1}), S_w is relative saturation, h is pressure head in units of length (L), φ is porosity, q is the Darcy flux (L/T), and q_s is a source/sink term (T^{-1}). Equation 2 uses saturated hydraulic conductivity, K_s (L/T), relative permeability k_r, depth below surface z (L), and the local angle of ground surface relative to a flat plane to calculate the Darcy flux q. S_w and k_r are calculated through the van Genuchten relationships (van Genuchten, 1980), which rely on air entry pressure α (L^{-1}), pore size distribution n, and residual saturation S_{res} to establish h in the unsaturated zone.

$$S_s S_w \frac{\partial h}{\partial t} + \phi \frac{\partial S_w(h)}{\partial t} = \nabla \cdot q + q_s \qquad (1)$$

$$q = -K_s(x) k_r(h) [\nabla(\mathrm{h} - \mathrm{z}) \cos \beta + \sin \beta] \qquad (2)$$

$$q = \frac{\partial \|h, 0\|}{\partial t} - \nabla \cdot \|h, 0\| \cdot v + q_r(x) \qquad (3)$$

Surface and subsurface flow are coupled by the 2-D diffusive or kinematic wave equation (Equation 3), where q_r is a source/sink rate (LT^{-1}) and v is the depth-averaged surface-water velocity (L/T) (Ashby and Falgout, 1995; Jones and Woodward, 2001; Kollet and Maxwell, 2006). PF's parallel structure and option for a terrain-following grid (TFG) make it highly suitable for high resolution and complex terrain (Engdahl and Maxwell, 2015; Maxwell, 2013), and it has been applied and validated from the hillslope (Atchley and Maxwell, 2011; Meyerhoff and Maxwell, 2011; Mikkelson *et al.,* 2013) to the continental scale (Condon and Maxwell, 2015; Maxwell *et al.*, 2016).

PF is coupled to the Common Land Model (CLM) to simulate the atmospheric boundary conditions, and near-land surface processes, herein referred to as PF-CLM (Dai *et al.,* 2003; Kollet and Maxwell, 2006; Maxwell and Miller, 2005). CLM communicates with PF via tiles of land cover and vegetation type on the domain surface and 10 soil layers that are coincident with PF cell layers. PF calculates the subsurface pressure and saturation and passes those values to the 10 soil layers within CLM. At the start of each timestep, CLM calculates water fluxes such as snow water equivalent (SWE), ET, and infiltration based on the tile information and passes that flux in the form of q_s, which PF incorporates into the updating of pressure and saturation at each time step. By solving for these fluxes as a boundary condition (q_s) to the 3-D Richards equation, PF-CLM is a fully mass conservative coupling.

Domain configuration

The numerical experiments were configured to represent two mid-elevation (1500 to 2200 m) alpine hillslopes: a high diffusivity, low storage, crystalline and a low diffusivity, high storage, volcanic system. We tested numerous hillslope configurations of various depth, layering, and heterogeneity, but for the purposes of this paper, elected to use homogenous hillslopes representing upscaled values of porosity and permeability to make clear distinctions between the two with respect to climate perturbations without introducing potential confounding effects of geologic variability. The elevation range was chosen as it encompasses a region where hydrologic processes are perhaps most responsive to climate change because of a retreating snowline and increasing forest ET. PF-CLM simulated a 5000 m (x-direction) × 100 m (y-direction) × 50 m (z-direction) 2-D hillslope, shown in Figure 1. The domain was discretized by $dx = dy = 100$ m and a variable dz with finer (<1 m) resolution near the surface and coarsening (~10 m) with depth, making a total of 2500 nodes. A no-flow boundary condition was imposed on all sides except for the top surface, which was set to a specified flux boundary condition, with overland flow handled by PF (Equation 3). The input and

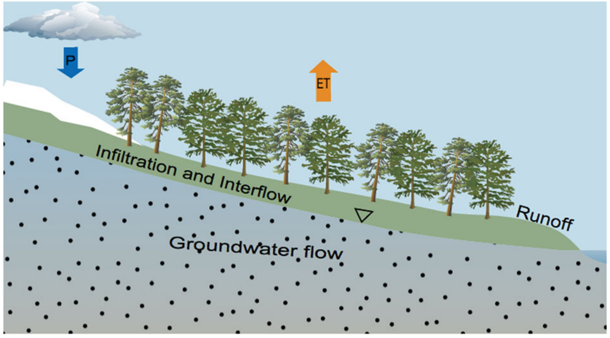

Figure 1. Conceptual diagram of the mid-elevation hillslope, showing the major storage and flux components simulated by PF-CLM. The two hillslopes are identical in land cover, depth, and slope, but with upscaled porosity and hydraulic conductivity values to represent a low storage and greater storage setting

output fluxes such as precipitation and evaporation were determined by CLM. To isolate cause and effect in the simulations, we assume geologic homogeneity with isotropic hydraulic conductivity (K) values of 10^{-9} and 10^{-8} ms^{-1} and constant porosity values of 0.02 and 0.10 for the two hillslopes. We base these values on previous work estimating effective parameters in fractured granite (Huntington and Niswonger, 2012; Welch and Allen, 2014) and volcanic systems (Arumi *et al.*, 2012; Saar and Manga, 2004), respectively. The effect of lower porosity despite lower permeability makes the granite hillslope more responsive to precipitation events than the volcanic hillslope, which is why previous studies have used fast and slow draining to describe these systems.

We use upscaled parameters to represent two models of unsaturated zone flow in alpine hillslopes: a high retention model representative of flow in weathered alluvium and a lower retention model representative of fracture-driven flow. We based these parameters on values from Maxwell (2010), who estimated retention parameters for a hypothetical fractured tuff. The variably saturated flow formulation included van Genuchten parameters of $\alpha = 2.45$ (2), $n = 2$ (3), and $S_{res} = .14$ (.001) for the alluvium and fracture model, respectively. This not only sheds light on model sensitivity to unsaturated flow parameters at the hillslope scale, but also provides an envelope of projected response to a warming climate, where, for example, greater retention may result in a positive feedback effect of greater ET and significantly less recharge.

Land surface and forcings

The land cover in the model is predominantly mixed conifer and evergreen forest, with a low order stream at the downslope end, and an imposed treeline at an elevation of 2000 m (Figure 1). The CLM climate forcings for the numerical experiments were selected for a medium elevation hillslope near Mt. Lassen in the Cascade Range of Northern California. Gridded (1/8°) hourly measurements of temperature, precipitation, long and short wave radiation, humidity, wind speed, and barometric pressure were downloaded from the North American Land Data Assimilation System (NLDAS-2) and distributed across the hillslope for the calendar year (CY) 2000. This year was chosen for its average climatic-behaviour, relative to the period of record for mean temperature and precipitation in the region, where period of record mean annual precipitation for the region is 52.3 cm and for the selected time period is 46.4 cm (Figure 2). We performed other multi-year simulations to observe the effects of interannual variability of precipitation superposed with climate change, however the purposes of this study we elected to use one year in order to minimize those potentially confounding effects and

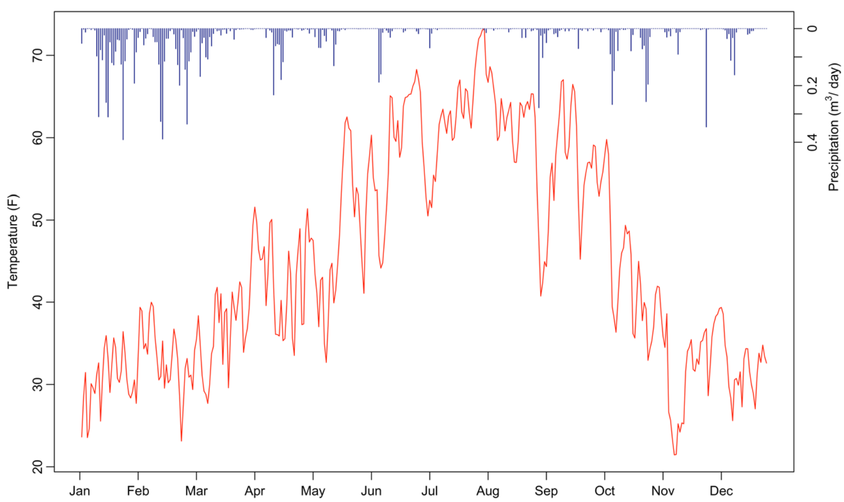

Figure 2. Precipitation and temperature for the base climate forcings

focus on the feedbacks from just warming on storage. The distinct wet and dry season of Mediterranean climates are ideal for this study not just because of the applicability to snowmelt-dominated systems in the western US and in Chile, but also because late summer streamflow can be assumed to be entirely comprised of baseflow, and thus proportional to the volume of storage (Brutsaert, 2008).

Four climate scenarios were generated by perturbing the original 2000 CY based on statistically downscaled global climate model projections for the California region, which predict an increase of 2.3 to 5.8 °C by the end of the century relative to the 1990 levels (Hayhoe *et al.,* 2004). We applied a 'warm' 1 °C, a 'hot' 2.5 °C, and a 'hotter' 4 °C perturbation to the base temperature dataset in order to capture potential hydrologic thresholds, as well as long term warming feedbacks (Cayan *et al.,* 2008). Owing to the difficulty in cloud parameterization and resolving grid resolution, orographic effects, and computational power, global climate models show less agreement on future changes in precipitation amounts in alpine regions, especially for regional scale applications (Cayan *et al.,* 2008; Hayhoe *et al.,* 2004). Therefore, the climate scenarios in this study maintain the precipitation timing and amount from the base climate dataset. All other forcings and land cover specifications were also left unperturbed from the base dataset. The base year was initialized with a lowered water table and was then spun up repeatedly to equilibrium, where final head change between spin up years fell below a threshold value of 1%. The final base run was then used as the initial state for the warm simulations, and each subsequent warming scenario used the final state of the previous as initial conditions (Ajami *et al.,* 2014). The modelling results included in the analysis are hourly (summed to daily) outputs of subsurface pressure, saturation, and overland flow calculated by PF and land surface fluxes of actual evapotranspiration, potential recharge, and snowpack

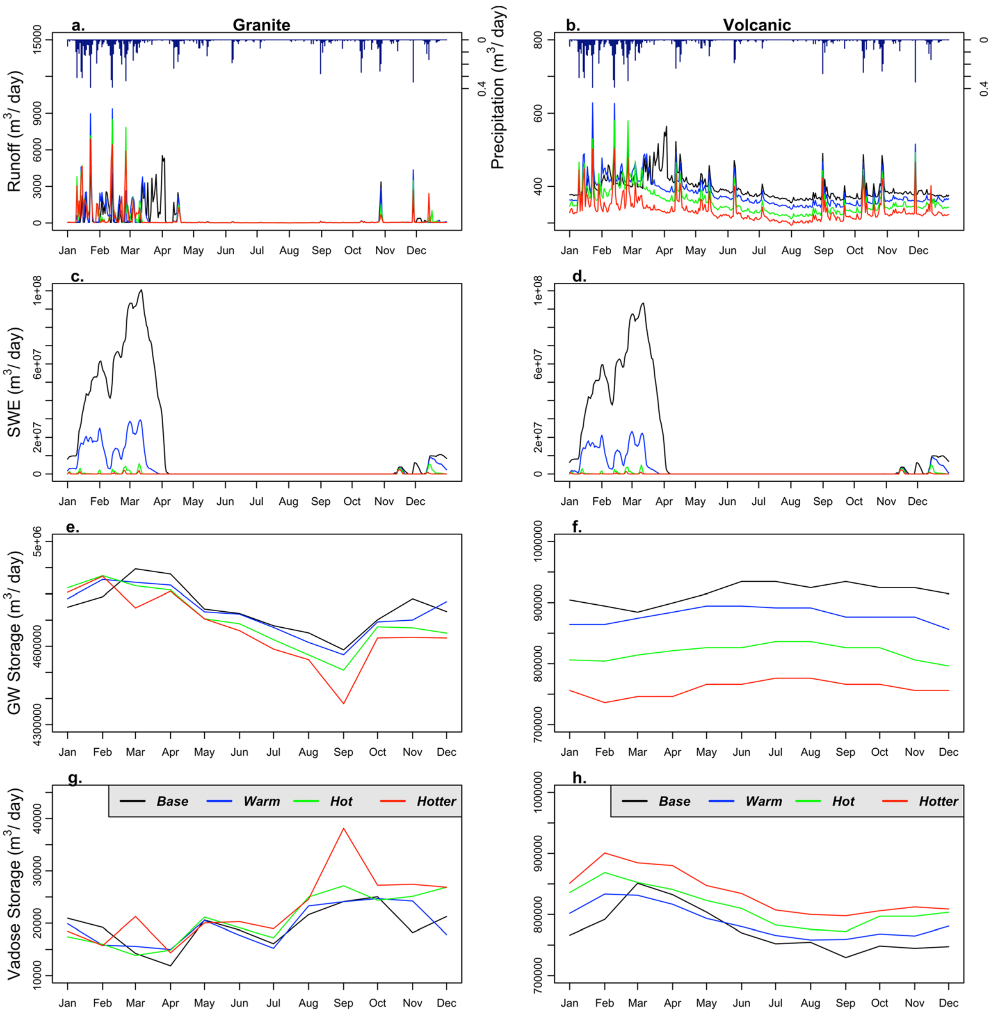

Figure 3. Summary figure of the storage values for the two modelled hillslopes, showing the base (black), warm (blue), hot (green), and hotter (red) scenarios. Note the y-axes are different scales between the granite and volcanic hillslopes

calculated by CLM. We selected these outputs for comparison and validation to previous observational and modelling based studies of climate change impacts to alpine hydrology.

RESULTS AND DISCUSSION

Snowpack

Past studies have shown that the rate of snowmelt is important for recharge in that the infiltration rate does not exceed soil or bedrock permeability, and can thus maintain vertical fluxes through the fractured bedrock (Flint *et al.,* 2008). Figures 3c and 3d show the snow water equivalent (SWE) for the two hillslopes for the base and three warming scenarios based on the calendar year 2000 climate forcings. The strong sensitivity of SWE to moderate (1 °C) warming and near complete phase transition to rain with 4 °C of warming demonstrates the vulnerability of snowpack as a major store of water, which has been observed in previous field and modelling studies (Bales *et al.,* 2006; Singh and Bengtsson, 2004). Furthermore, the persistence of snowpack noticeably shifts from the warm to the hot scenario, with the latter possessing multiple discrete snow accumulation periods followed by a complete melt out, potentially exacerbated by rain on snow events. This has implications for the land surface energy budget, because snowpack and bare ground have significantly different albedos, and also for recharge. Godsey *et al.* (2013) suggested that these spatiotemporal changes in melt would alter recharge timing, making the permeable baseflow-dominated systems more vulnerable. We explore these dynamics further in the following sections.

Runoff

The lack of a persistent snowpack (Figure 3c and 3d) to 'hold' water until the spring snowmelt season should result in increased winter runoff; however, the extent to which this could be compensated for by groundwater recharge and increased ET rates with warming remains unexplored in a fully process-based model. In examining the earlier snowmelt season, runoff volumes for the different scenarios can be compared by normalizing to cumulative flow and looking at the centre of mass timing (CT), or the time that 50% of total annual flow (TAF) passes the outlet (Cayan *et al.,* 2001; Stewart *et al.,* 2005). An earlier snowmelt season induced by warming would shift this cumulative curve earlier, and the more responsive granitic system indeed exhibits an earlier CT timing by 36 days with just 1 degree of warming, shown in Table I. The subsequent warming of 2.5 and 4 degrees only shifts the CT by 3 days earlier, suggesting a temperature and thus snow presence threshold where runoff timing may become insensitive to warming in mid-elevation fast-draining systems. The baseflow-dominated volcanic hillslope CT does not show a significant shift with warming. This would suggest that large storage systems are less vulnerable to a snow to rain phase change in terms of streamflow timing. While the granite hillslope is more vulnerable in terms of streamflow timing, the consistent reductions in streamflow over time and with warming shown in Figure 3b indicate that volcanic systems may be more vulnerable in terms of late summer baseflow volumes. Studies have shown that absolute reductions in baseflow-dominated streams have consequences for water supply and hydropower generation even when the relative or percent reductions are much less than in runoff dominated streams (Tague and Grant, 2009; Vicuna *et al.,* 2007). This is exacerbated by the fact that demand for water and electricity is highest during the hot dry summers in a Mediterranean climate. In the hillslope simulations, the TAF reductions increase with warming, with the granite hillslope exhibiting slightly greater percent and absolute reductions for each scenario (Table I). Previous work in crystalline headwaters systems found warming to mainly affect streamflow timing, because the granite hillslope streamflow is dominated more by snowmelt runoff than by baseflow; however, these hillslope results suggest an additional feedback is causing a magnitude decrease (Stewart *et al.,* 2005; Jefferson *et al.,* 2008; Tague and Grant, 2009). One explanation for this is that the lower permeability and porosity results in a shallower water table and thus greater water availability for ET. This has been shown in the field for fractured crystalline systems, where saturation excess can lead to ponding and interflow at the saprolite–bedrock interface provided that the precipitation rate exceeds the bedrock permeability (Banks *et al.,* 2009; Flint *et al.,* 2008; Welch and Allen, 2014).

Table I. Centre of mass timing (CT) expressed as a shift (days) from the base scenario and total annual flow (TAF) expressed as a percent of the base scenario

	Granite			Volcanic		
	Warm	Hot	Hotter	Warm	Hot	Hotter
CT	36	39	39	3	3	−1
TAF	94%	86%	79%	96%	91%	84%

Evapotranspiration

A plot of average monthly ET for the eight simulations supports the above interpretation that more water exits the subsurface of the granite hillslope and that much of this occurs during the spring runoff season, shown by the warmer colours in Figure 4. Further, both hillslopes exhibit increased ET rates with warming, which are expected because of the increased energy available for vaporization as well as increased water stress in trees. CLM calculates bare ground evaporation using a mass transfer approach, which relies on PF variables such as water vapour and saturation in the near surface tiles. CLM calculates ET by the vegetation type and associated root density specified for each tile, and in the case of the conifers, dormancy is explicitly represented by increasing stomatal resistance with decreasing temperature in the deeper soil layers. Validation of the spring ET values was not possible owing to the hypothetical nature of the hillslopes; however, the comparison of response to warming is useful for understanding timing and amount water availability because of climate change. Tague and Peng (2013) found interannual precipitation to be a dominant control of actual evapotranspiration (AET) in Sierra Nevada forest, and our results support this finding where the most significant increases in ET occur in the wet season of Winter and early Spring. There is a growing body of work looking into tree physiological response to increasing temperatures, which could alter the volume of ET significantly especially when considered concurrently with earlier spring snowmelt periods (Goulden and Bales, 2014; Harpold *et al.,* 2014). Apart from an elevation shift in the treeline in response to warming, changes in soil moisture and water table position could also result in longer-term changes in vegetation, which would impact water fluxes from the subsurface. Future simulations will incorporate forest disturbance to capture this important response to warming in the mountains.

Baseflow

Summer low flows comprised of baseflow provide refugia for fish and other aquatic species during drought years and late summer, and warming will likely cause an increase in the number of days that baseflow drops below certain thresholds. Streams in crystalline systems are more vulnerable to losing ‘connectivity,’ especially because an earlier snowmelt period has been shown to drain bank storage earlier in the dry season (Huntington and Niswonger, 2012). The consistent baseflow volumes of volcanic systems, which can be orders of magnitude larger than crystalline, make them more resilient to climate change, and the degree to which progressive warming affects low flows in the hillslope experiments is shown by the violin plots in Figure 5. The granite hillslope baseflow approaches zero in the late summer, and so the progressive warming exerts minimal change in mean and variance. On the other hand, the lower diffusivity volcanic hillslopes have larger volumes of baseflow, an average of 366 cubic metres per day as opposed to 20 cubic metres per day in the granite hillslope, in late summer and fall, and show a clear decline in average August flow with warming. Further, the variance increases in this hillslope, where the ‘hotter’ scenario exhibits a wider distribution than the base case, which has implications for species dependent on steady flow volumes and temperatures. The apparent bimodal distribution in Figure 5 is a result of the climate dataset used in the simulations, where there was a precipitation event that was intense enough to cause a peak in runoff. Plotting August baseflow over multiple years would likely shift this plot to a lognormal distribution more common in streamflow trends. Nevertheless, this declining baseflow trend with warming in the volcanic hillslopes could be related to the shifting recharge dynamics from snow to rain phase change (Godsey *et al.,* 2013; Huntington and Niswonger, 2012; Tague and Grant, 2009) but also sensitive to the model parameters for saturated and unsaturated flow, as shown later in this paper. Additionally, previous modelling studies have

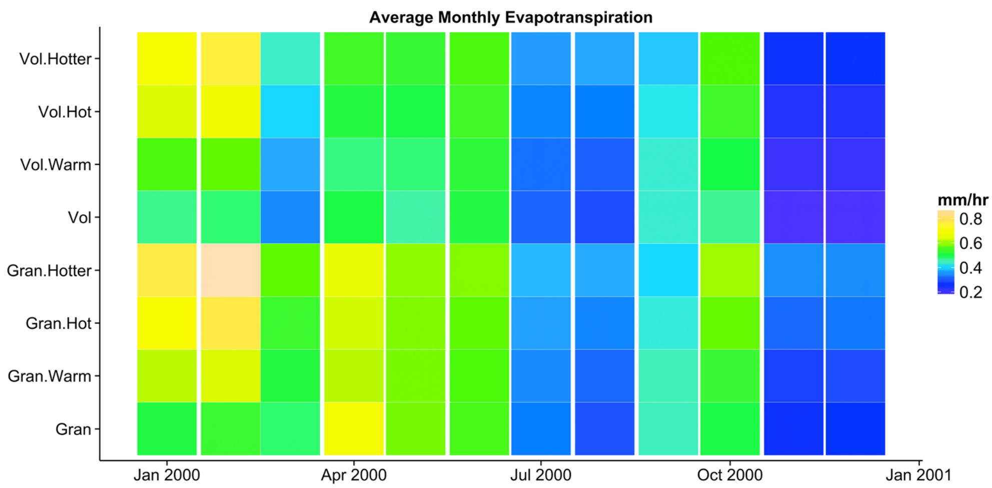

Figure 4. Average monthly ET for the eight hillslope simulations

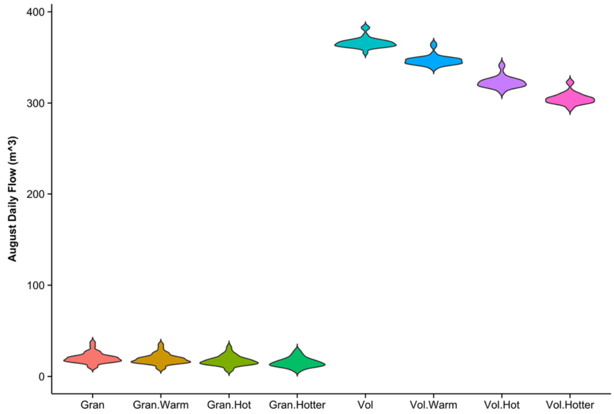

Figure 5. Violin plot of August daily runoff totals for each of the eight scenarios. The daily flows are represented by a probability density curve that is rotated and mirrored for purposes of interpreting mean and variance

shown that increasing K leads to a greater proportion of deep (regional) flowpaths contributing to streamflow, thus increasing the average groundwater residence time (Gleeson and Manning, 2008; Rademacher *et al.,* 2005). It stands to reason then that shifting recharge dynamics would perturb the flowpaths both intra and interannually, the latter of which would be most noticeable during the summer low flow period. Because these hillslope models were run with the progressive warming scenarios, the 'hotter' scenario represents the intrannual effects of a 4-degree warmer climate, but also incorporates the memory from previous stages of warming.

Groundwater storage

For both hillslopes, warming leads to a decrease in groundwater storage (Table II) and the seasonal groundwater storage shows slight shift in recharge season with warming, because of an earlier melting snowpack and greater fraction of rain (Figure 3). For the volcanic hillslope, the decreased peak in recharge magnitude results in a slightly smoother storage graph, because the recharge timing is not only moved earlier, but also stretched out over the full rainy season. The persistent snowpack in the base case is able to capture and store precipitation as snow until the spring melt season, and this can be seen by the storage minimum and maximum occurring pre and post spring pulse, respectively. The low storage granite hillslope shows far less temporal and magnitude shifts in groundwater storage, for example 4 degrees of warming led to a 1% decrease in storage relative to the base, which begs the question if there is a permeability threshold below which subsurface storage becomes insensitive to a snow to rain phase change. Because total annual runoff decreases in both hillslopes amidst each warming scenario, the main driver of this decrease in recharge is ET. However, the reduction in groundwater storage does not necessarily contribute directly to increases ET, but rather higher ET rates lead to drier soil moisture and thus less water to infiltrate deep to the water table. Thus, the decrease in recharge combined with a longer baseflow recession period leads to the reductions in groundwater storage observed in these hillslopes.

Table II. Average groundwater storage expressed as a percent of the base scenario

	Warm	Hot	Hotter
Volcanic	96%	90%	83%
Granite	100%	99%	99%

Unsaturated zone storage

Inverse to groundwater storage, the unsaturated zone storage increases with warming for both hillslopes because of a deeper water table and thicker vadose zone, most notably in the volcanic scenarios (Figure 3h). The amount of increase, however, does not offset the decrease in groundwater storage, and thus total subsurface storage decreases with warming for both hillslopes, most notably for the higher storage volcanic hillslopes, shown by Figure 6. Engdahl and Maxwell (2015) observed this same phenomenon in a mountain headwaters catchment by applying reduced recharge scenarios as a simplified boundary condition to their coupled hydrologic model, and they observed longer residence times which were almost entirely explained by a thicker unsaturated zone (Engdahl and Maxwell, 2015). This could be a function of the precipitation phase transition, where discrete snowmelt events or rain pulses are not large enough to overwhelm the soil water retention capacity. Montgomery *et al.* (1997) observed a similar precipitation intensity-duration required to overcome vadose zone storage and begin to generate recharge and runoff in a rain-dominated,

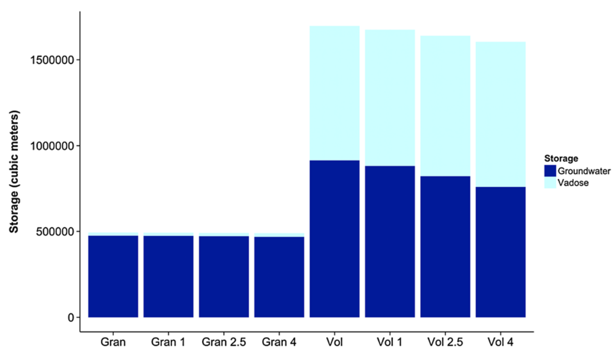

Figure 6. Average annual subsurface storage for the two hillslopes, compartmentalized by groundwater and vadose zone storage, for the base, warm, hot, and hotter scenarios

steep, unchanneled catchment of the humid Oregon Coast Range. Such a threshold is key for understanding how water budget components will shift with a shifting fraction of rain in snow-dominated catchments. Additionally, the partitioning of subsurface water in to the saturated and unsaturated zones is likely very sensitive to the soil water retention parameters used in the hillslopes, which we explore further in the next section.

Sensitivity to unsaturated flow parameters

These initial simulations appear to refute the hypothesis that subsurface storage in volcanic systems can offset the loss of snow storage with warming, owing to less recharge and a longer baseflow recession period. Mountain terrains have heterogeneous soil development, with alluvial fill in valleys and stream banks behaving like porous media and fractured saprolite or highly weathered bedrock influencing flow along hillslopes (Banks *et al.,* 2009; Welch and Allen, 2014). Here we modify the unsaturated flow parameters to have a greater pore size distribution ($n = 3$) and lower specific retention ($S_{res} = .001$) to reflect a fractured shallow subsurface. We do not distinguish between tectonic or weathering controls on shallow fractures, but rather use parameters representative of less water retention expected regardless of fracture aperture and orientation. We test the sensitivity of subsurface storage, runoff generation, and snow storage to the two conceptual models for both hillslopes. Table III shows that the fracture flow conceptual model indeed resulted in reduced ET and vadose zone storage, and increased recharge and runoff for both hillslopes. These results agree with a previous study using ParFlow in which a discrete fracture network (DFN) was mapped to a stochastic continuum hillslope by Maxwell (2010), who found that the presence of fractures transported water below the root zone at a far greater rate than a homogeneous hillslope with upscaled soil water retention parameters for a fractured tuff (Maxwell, 2010).

Table III. Storage and fluxes for the two conceptual models of unsaturated zone flow. ‘Matrix’ shows results for the original unsaturated zone parameters representative of a porous matrix, while ‘Fracture’ uses parameters representative of fractured rocks. The SWE, ET, and runoff values are cumulative, while GW and Vadose storage are average values

	Granite base		Volcanic base	
	Matrix	Fracture	Matrix	Fracture
SWE (m^3)	1.71E+04	1.80E+04	1.70E+04	1.83E+04
Runoff (m^3)	1.21E+05	1.33E+05	1.47E+05	1.92E+05
GW (m^3)	4.74E+05	4.87E+05	9.14E+05	1.24E+06
Vadose (m^3)	1.86E+04	1.02E+04	7.83E+05	4.00E+05

The granite hillslope was less sensitive to perturbations in the unsaturated flow parameters, and so here we focus on the progressive warming scenarios that were run for the low diffusivity volcanic hillslope (Figure 7). Recharge and thus groundwater storage still decreases for the warming scenarios, however to a much lesser degree with the fracture flow parameters, and this subsurface storage acts to buffer decreases in runoff. The earlier simulations representing greater retention resulted in 17% reductions in groundwater storage and annual runoff for the hotter scenario, while the low retention simulations decreased by 7 and 8% for groundwater and runoff with the same amount of warming. This is partially because of the greater availability of water for root water uptake in the former scenario, but also to the higher relative permeability rates in the latter scenario. Less retention, which would be expected in weathered bedrock, results in the vadose zone transmitting significantly more water laterally to runoff and vertically for recharge, which results in larger runoff peaks during the wet season and greater baseflow volumes in the summer, respectively.

IMPLICATIONS

Our results show that not only are the basic water budget components sensitive to soil water retention parameters, but the projected feedbacks from climate change are significantly different depending on the hydrogeologic setting and which conceptual model of shallow subsurface flow one chooses. In this work we show that an upscaled retention function representative of greater retention, such as an alpine hillslope with greater soil development or weathered alluvium, is significantly more vulnerable to climate change than a fractured shallow subsurface, especially for hillslopes with greater storage capacity. As subsurface storage capacity decreases, the hydrologic components become less sensitive to unsaturated zone retention parameters.

This leads to the question of which conceptual model is the most realistic for alpine hydrogeology. Volcanic rocks are likely a mix, with brecciated interflow zones exhibiting matrix flow and retention and subvertical fractures as a result of cooling joints or faulting (Birdsell *et al.,* 2005). The scarcity of borehole data in alpine volcanic regions limits our understanding of the distribution of porous and fractured units, and so instead modelling studies tend to assume simplified, upscaled properties, including anisotropy favouring vertical flow in the fractured rock portions (Birdsell *et al.,* 2000). Various approaches have confirmed this anisotropy assumption while inferring permeability ranges in the Cascade volcanics, such as coupled heat and groundwater modelling (Ingebritsen *et al.,* 1992), spring discharge models (Saar and Manga, 2004), and environmental

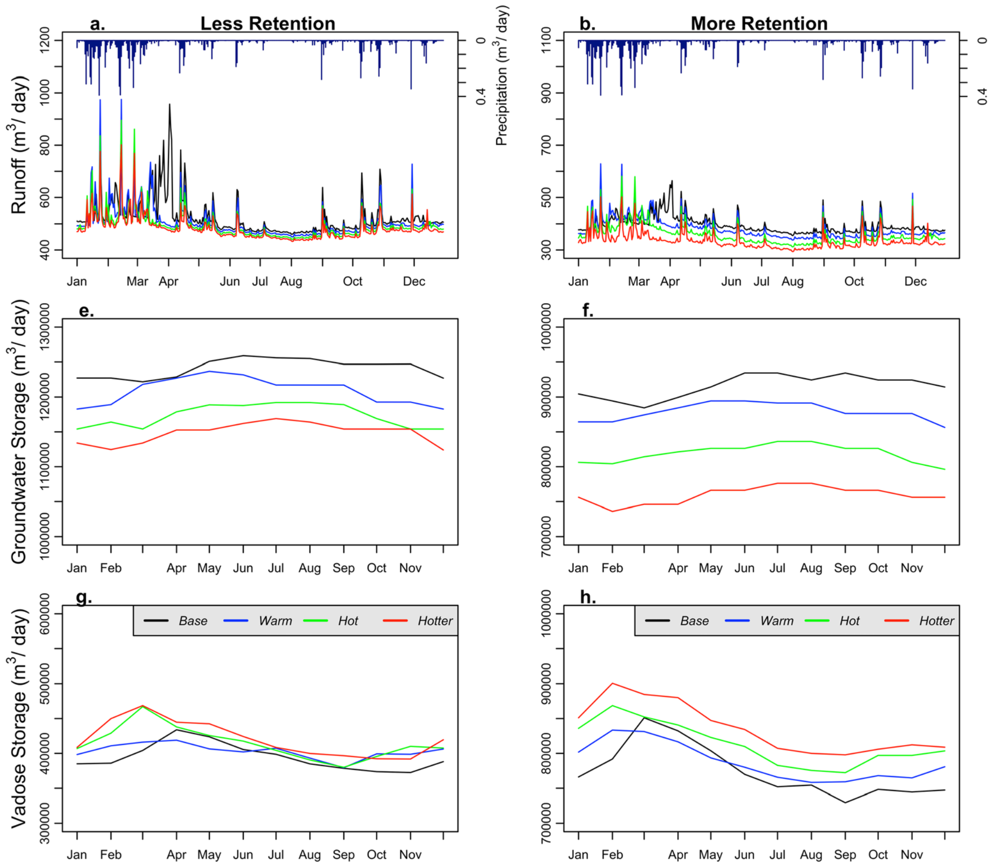

Figure 7. Summary figure of the storage values for the two conceptual models of soil water retention for the volcanic hillslope, with the base (black), warm (blue), hot (green), and hotter (red) scenarios

tracers (Davisson and Rose, 1997; Rose *et al.,* 1996). One such study in the alpine volcanics of the Mt. Lassen area used stable isotopes and found that vertical ring fractures transmit snowmelt rapidly to lateral conduits, which can be lava tubes or brecciated interflow zones, and ultimately to large volume springs (Davisson and Rose, 1997; Rose *et al.,* 1996). Similarly, the presence of hot springs in non-volcanic alpine regions supports the assumption that subvertical fractures act as conduits for water to travel deep enough to heat up and then return to the surface. These independent approaches provide key supplementary information that may constrain the unsaturated zone conceptual model for fully-integrated hydrologic models, which is a next step for this work.

Our results suggest a range of possible conceptual models that now need to be tested with field data in real hydrologic systems. A key test will be how well the models represent baseflow, which has been difficult for watershed models owing to their simplified representation of underlying groundwater systems. Furthermore, baseflow as a signal for testing efficacy of groundwater representation in a hydrologic model can be fraught with difficulty in systems lacking distinct wet and dry seasons, because in such systems the portion of the streamflow representing groundwater discharge is commonly not well quantified. Fortunately however, in Mediterranean climates such as occur in California and the Chilean Andes, annually there is a prolonged dry season in which nearly all the streamflow can be ascribed to baseflow stemming from shallow and deep groundwater flowpaths. In such systems, that dry season baseflow signal provides excellent opportunities for constraining and perhaps validating integrated hydrologic models that include both the surface hydrology and the bona fide subsurface hydrology.

Comparing our modelled baseflow to observed data is not practical for these 2-D hillslope numerical experiments because of their hypothetical nature; however, our results identify multiple ways forward to validating both the geology and hydrologic process representation in models. We identified storage and unsaturated zone parameters as dominant controls on response to climate warming, and these parameters are tightly coupled to ET, where greater retention or less storage results in greater water available for root uptake. The feedbacks from this are less recharge, decreased runoff, and a thickening vadose zone. Thus, concurrent monitoring of soil moisture, forest ET rates, and baseflow for real domains could provide a good strategy for validation of process-based watershed models. Another model component that could be tuned to produce this recharge response are ET parameters such as leaf area index (LAI), rooting depth, and stomatal conductance, which would integrate physiological response to warming and increased CO_2 concentrations with the soil moisture representation in PF. In alpine basins, ET consumes upwards of 50% of the total annual precipitation (Bales *et al.,* 2006; Huntington and Niswonger, 2012); thus, shifts in vegetation structure and forest cover with warming would alter recharge and streamflow significantly (Goulden and Bales, 2014). Accordingly, future work should also address land surface parameterization of this dynamic process.

Finally, while 2-D hillslope simulations are useful for efficiency and hypothesis testing, they limit our results in terms of spatial response. Faults and fractures have been shown to act as significant conduits or barriers to flow, and can be parallel to the surface because of unloading and weather, as well as subvertical because of structural or brittle-rock controls (Wilson and Guan, 2004). Therefore, a 3-D domain is necessary to capture these larger patterns, which invariably would influence alpine watershed response to a snow to rain transition. Further, the impacts to baseflow found in the 2-D results may have greater ecological implications using a 3-D domain, such as a loss of connectivity, depending on where the declines in flow occur along the stream reach.

CONCLUSIONS

Previous research concerning vulnerability to climate change in snowmelt-driven basins focused on streamflow response, where an earlier melt season and a longer baseflow recession lead to significant concerns for water resource management (Barnett *et al.,* 2005; Beniston *et al.,* 1997; Berghuijs *et al.,* 2014; Maurer *et al.,* 2010; Stewart *et al.,* 2005). Streamflow-generation is inexorably linked to subsurface storage, regardless of bedrock storativity, and numerous studies confirm that interflow and deeper groundwater flowpaths are the dominant mechanisms from the hillslope to the mesoscale basin (Andermann *et al.,* 2012; Banks *et al.,* 2009; Freer *et al.,* 2002; Frisbee *et al.,* 2011; Welch and Allen, 2014). By explicitly modelling variably saturated flow coupled with a comprehensive land surface model, this study is able to build on previous studies to elucidate some key aspects of the subsurface response to climate warming, including the complementary dynamics between the unsaturated and saturated zone, and the resultant runoff response.

All hillslopes, regardless of geologic parameterization, exhibited a decrease in groundwater storage and runoff volumes with climate change, owing to decreased recharge and increased ET rates. In warmer scenarios with large decreases in snowpack, the greater storage volcanic hillslopes do exhibit hydrogeologic buffering by way of streamflow timing and amount, however that sustained baseflow comes at a cost of reductions in groundwater storage. Low storage systems such as granitics are far less dependent on the phase than of the amount of precipitation for recharge, however the lack of a snowpack reservoir to hold water until spring significantly affects streamflow timing in these systems. Both hydrogeologic settings were sensitive to water retention characteristics in the unsaturated zone; however, the volcanic hillslope was noticeably more sensitive. The use of upscaled parameters that are more representative of fracture flow conditions resulted in greater recharge that helped offset the loss of snow storage by mitigating the loss of groundwater storage. This sensitivity highlights the advantage to using a fully process-based, variably saturated, subsurface flow model when exploring the dynamic feedbacks of climate change. It also exposes the need for independent sources of conceptual model development and validation and careful monitoring and modelling of soil moisture, ET, and baseflow in Mediterranean-type climates where the dry-season baseflow clearly represents the deep and shallow groundwater behaviour.

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