RAPID SNOWMELT LEADS TO GREATER STREAMFLOW ACROSS THE WESTERN UNITED STATES: STREAMFLOW SENSITIVITY TO CHANGES IN SNOWPACK ACROSS TRANS-BASIN DIVERSIONS

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EXTENDED ABSTRACT

Snowmelt is the primary source of surface water in the western United States and for approximately one sixth of the global population (Barnett et al., 2005). Climate change is altering the magnitude of the mountain snowpack and the timing and rate of snowmelt (Mote et al., 2005; Clow, 2010; Harpold et al., 2012). These changes could have profound implications for the water resources of the western United States (Milly et al., 2008). We ask how these changes to the mountain snowpack impact how snowmelt is partitioned between evapotranspiration (ET) and streamflow across the western United States. We hypothesize that rapid snowmelt is able to quickly satisfy atmospheric demand for water and bring the soil column to field capacity, inducing infiltration past the root zone and generating streamflow. Regional- or watershed-scale differences in the sensitivity of streamflow to changes in snowmelt could strain existing water transfer agreements, especially across trans-basin diversions.

We use the Variable Infiltration Capacity (VIC) model run at 1/16 of a degree from 1950-2013 using a gridded meteorological data set to simulate snow water equivalent (SWE), ET, potential evapotranspiration (PET), and baseflow (Q_{bf}) (Livneh et al., 2015). We compute long-term ET/precipitation (P) and PET/P ratios to derive a simulated streamflow anomaly for each model grid cell using an ensemble of Budyko-type (Budyko, 1974) equations relating PET/P to ET/P (Zhou et al., 2015). We use changes in simulated SWE to compute the long-term average snowmelt rate for each model grid cell. Theses surfaces are cropped to the mountainous ecoregions (CEC, 2011) of the western United States (Figure 1), which generate streamflow for much of the downstream communities in the region (Bales et al., 2006). To examine streamflow sensitivity to changes in snowmelt rate across trans-basin diversion we also compute streamflow efficiency (Q/P) for twelve trans-basin diversion basin pairs representing 23 total trans-basin diversions (Figure 2).

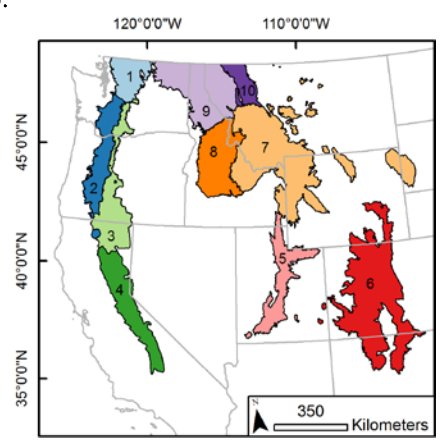

Figure 1. The simulation domain covers the mountainous ecoregions of the western United States. Included ecoregions are (1) North Cascades, (2) Cascades, (3) Eastern Cascades Slopes and Foothills, (4) Sierra Nevada, (5) Wasatch and Uinta Mountains, (6) Southern Rockies, (7) Middle Rockies, (8) Idaho Batholith, (9) Northern Rockies, and (10) Canadian Rockies.

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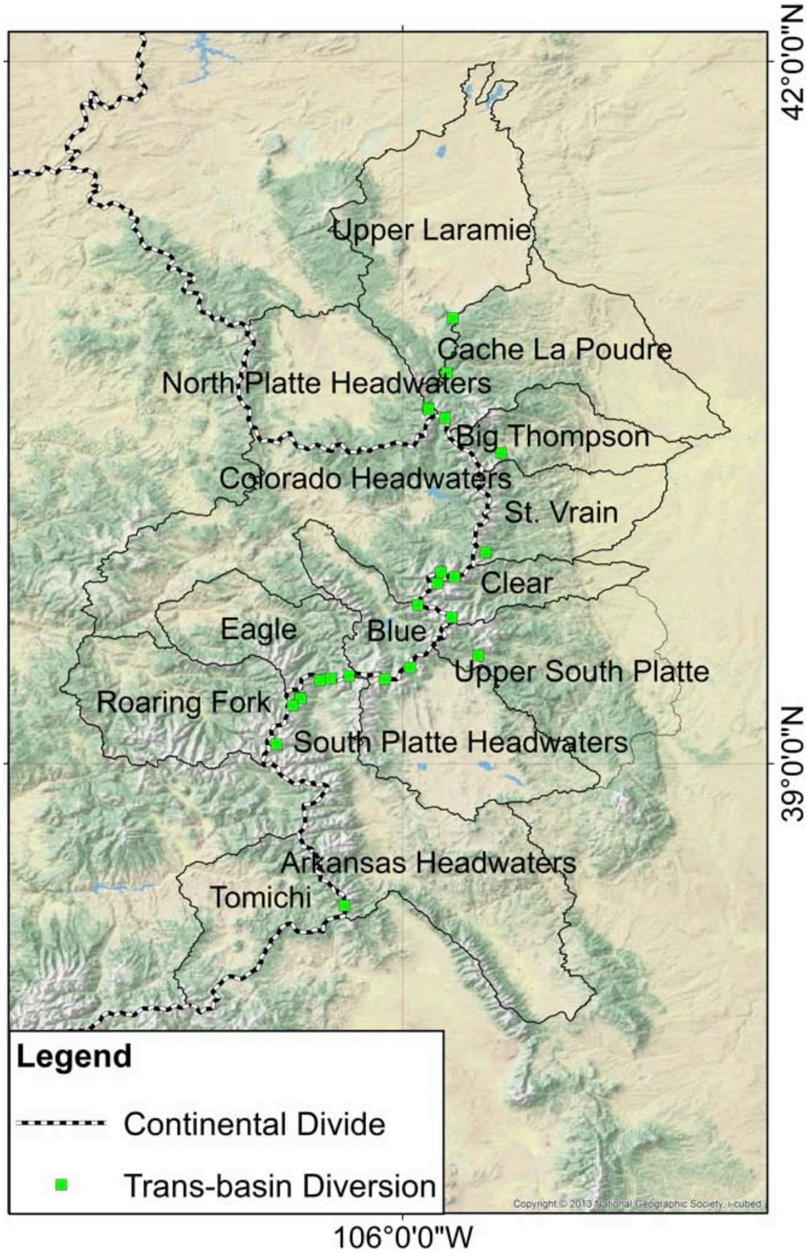

Figure 2. Simulation domain covering the trans-basin diversions. Green squares represent each of the 23 trans-basin diversions.

Simulation results show a significant positive relationship between snowmelt rate and simulated streamflow anomaly (r^2=0.42, p<0.001) (Figure 3). There is also a significant, non-linear relationship between snowmelt rate and simulated Q_{bf}/P (r^2=0.73, p<0.001) showing that grid cells with rapid snowmelt partition more water to Q_{bf} (Figure 4). Furthermore, we see that grid cells with high Q_{bf}/P have correspondingly high streamflow anomalies (r^2=0.64, p<0.001) (Figure 5). This shows that rapid snowmelt causes greater infiltration below the rooting zone to produce streamflow and positive streamflow anomalies within the Budyko framework, confirming our hypothesis. Due to these relationships, we can expect early, slower snowmelt (Trujillo and Molotch, 2014) driven by climate change to produce less streamflow across the western United States. Across the component ecoregions of the domain we see a range of slopes and explained variance for the snowmelt rate – streamflow anomaly relationship suggesting that streamflow production in some ecoregions is more sensitive to a change in snowmelt rate than in other ecoregions (Figure 6).

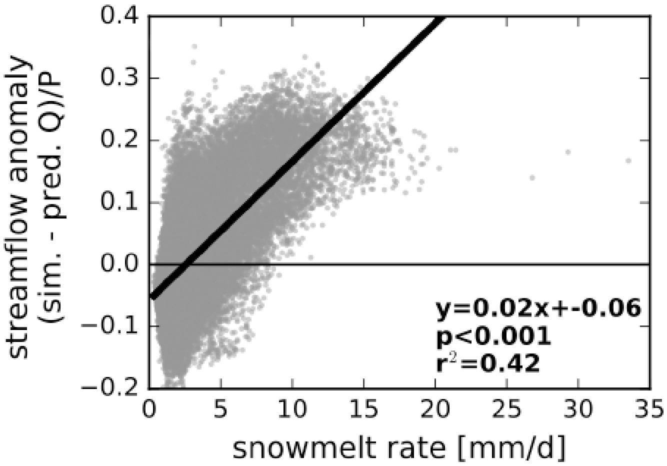

Figure 3. Relationship between simulated snowmelt rate and simulated streamflow anomaly

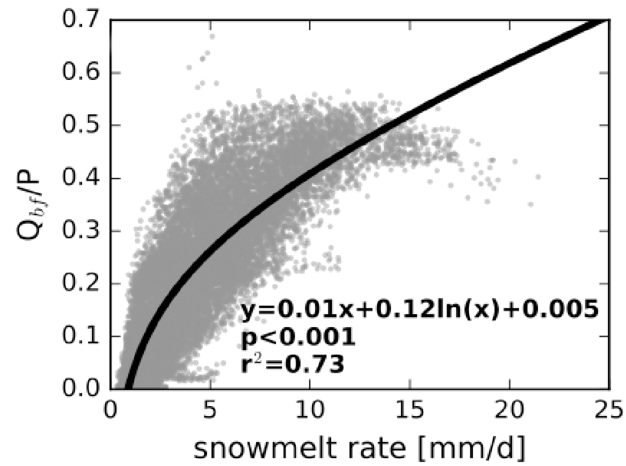

Figure 4. Relationship between simulated snowmelt rate and baseflow efficiency (Q_{bf}/P)

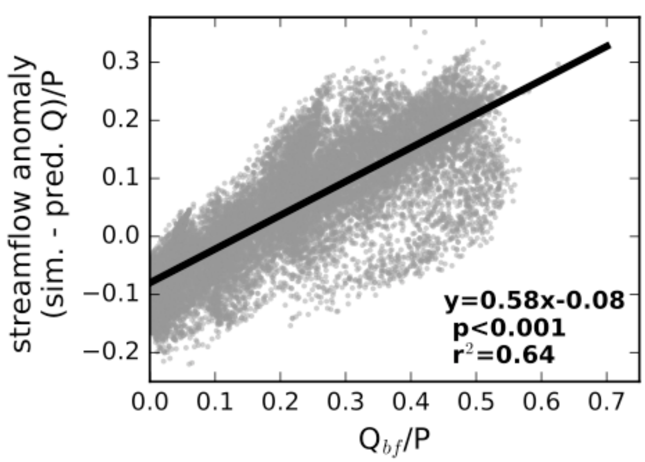

Figure 5. Relationship between baseflow efficiency (Q_{bf}/P) and simulated streamflow anomaly

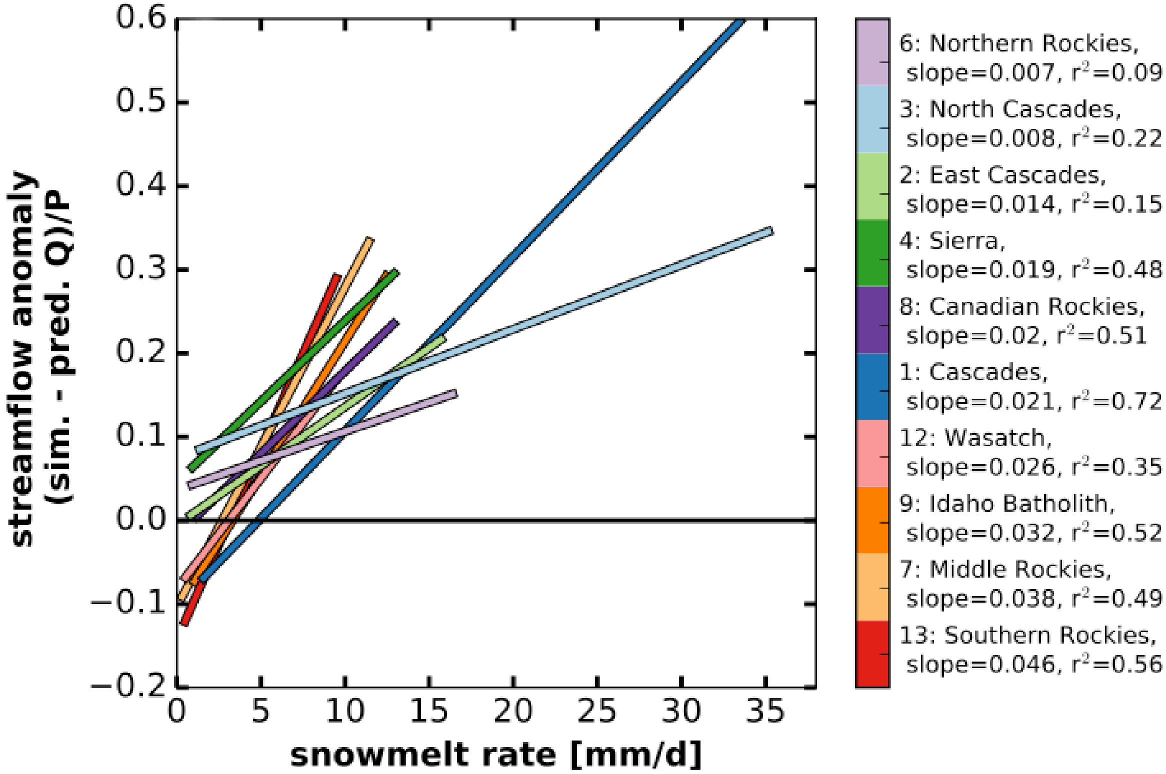

Figure 6. Snowmelt rate – streamflow anomaly relationships by ecoregion

A similar analysis of the trans-basin diversions of Colorado and Wyoming show a range of sensitivities of streamflow efficiency to changes in snowmelt rate (Figure 7). Over this smaller domain, the streamflow efficiency of basins contributing to trans-basin diversions tended to be more sensitive to changes in snowmelt rate than the basins receiving water from trans-basin diversions. The differential in streamflow efficiency sensitivity to snowmelt rate across trans-basin diversions could strain existing water transfer agreements in the region.

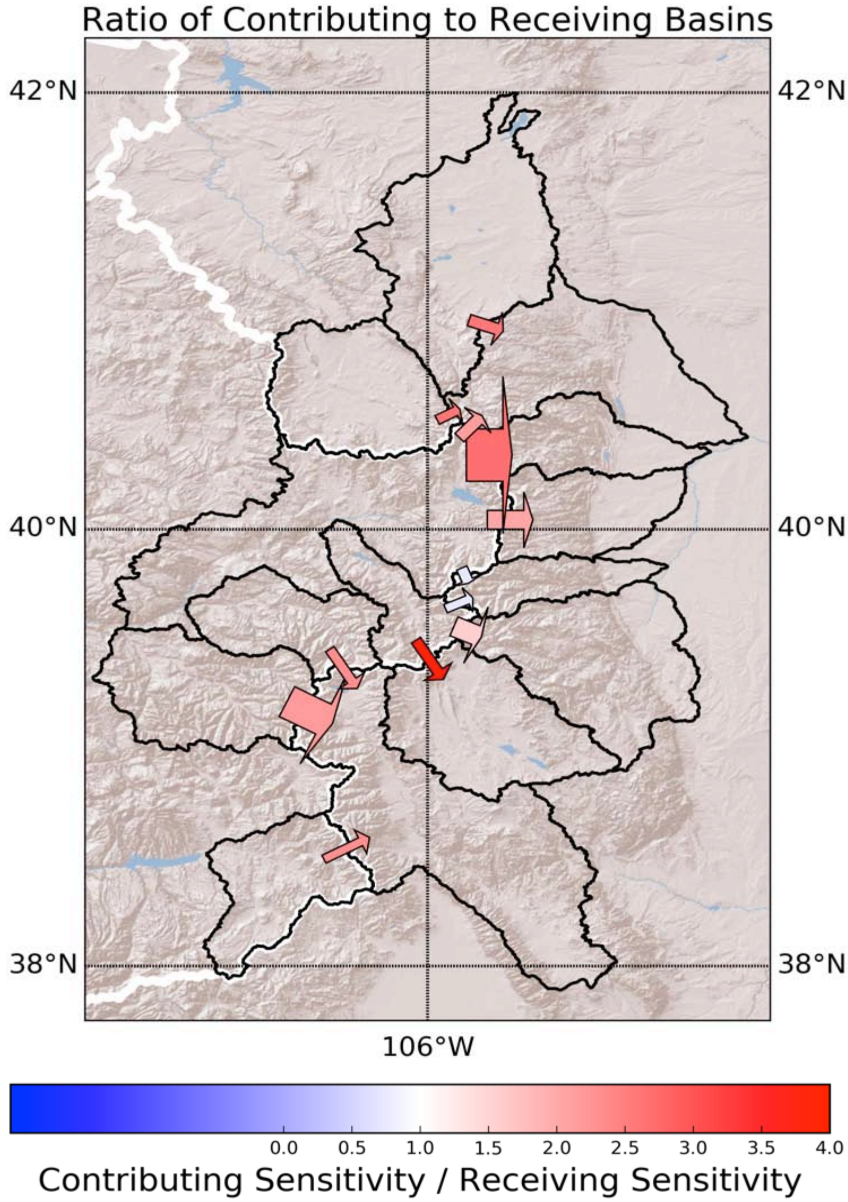

Figure 7. Map showing the ratio of contributing basin streamflow efficiency sensitivity to snowmelt rate to receiving basin streamflow efficiency sensitivity to snowmelt rate (arrow color) and relative trans-basin diversion size (arrow width). Basin outlines are the same as in Figure 2.

This work highlights a possible snowmelt rate control on streamflow generation across the western United States. Furthermore, this work shows that different ecoregions within the western United States have different streamflow anomaly sensitivities to changes in snowmelt rate. We also show that there are differential sensitivities of streamflow efficiency to changes in snowmelt rate across trans-basin diversions in Colorado and Wyoming. The sensitivities shown by this work have possible water management implications at the ecoregion scale and may strain existing water transfer agreements at the watershed scale. (KEYWORDS: Budyko, hydroclimatology, water, climate change, snow, water resources)

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