DISENTANGLING THE IMPORTANCE OF SNOWMELT RATE, TIMING, AND AMOUNT ON RUNOFF PRODUCTION

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EXTENDED ABSTRACT

Mountainous regions are responsible for approximately 32% of global discharge [Meybeck *et al.*, 2001] and within that, snow dominated regions provide water for one-sixth of the global population [Barnett et al., 2005]. Snowpack and the risks associated with a changing snowpack have been valued in the trillions of dollars globally [Sturm et al., 2017], indicating the importance of understanding how changes in snowpack will cascade into changes in runoff production. In the western United States alone, approximately 70% of runoff is derived from snowmelt [Sturm et al., 2017]. Given the social, ecological, and economic value of mountain derived water it is pressing to understand how changes in mountain hydrology will manifest as changes in runoff.

Near surface warming alters the amount of precipitation that falls as snow [Knowles et al., 2006]; changing the amount [Mote et al., 2005], rate [Musselman et al., 2017], and timing [Harpold et al., 2012] of snowmelt across the western United States. Recent work has linked snowmelt rate to streamflow production across the western United States [Barnhart et al., 2016] and linked snowmelt rate to snowpack magnitude and snowmelt timing [Trujillo and Molotch, 2014]. We seek to reveal the dominant runoff production factor by disentangling the relationships between snowmelt rate, timing, and amount.

We use observations of evapotranspiration and specific discharge from Niwot Ridge, CO (CO, Figure 1a), Providence Creek, CA (CA, Figure 1b), and the Valles Caldera, NM (NM, Figure 1c) to parameterize the Regional Hydro-Ecologic Simulation System (RHESSys) [Tague and Band, 2004]. RHESSys models were calibrated against

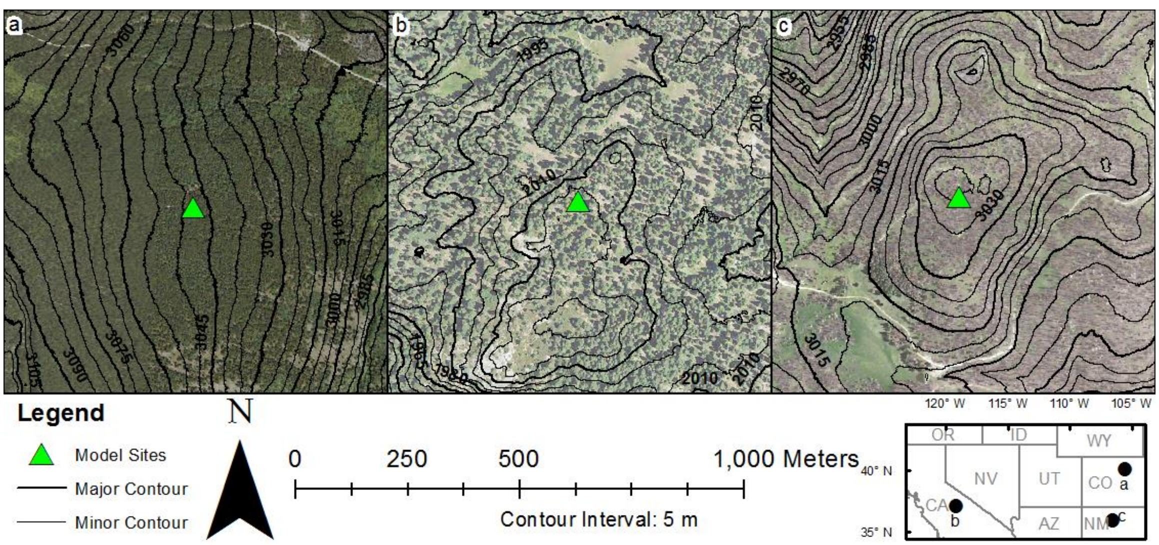

Figure 1. Location and topographic setting of CO (a), CA (b), and NM (c).

Paper presented Western Snow Conference 2017

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both evapotranspiration and specific discharge at a monthly timescale using a multi-objective calibration scheme designed to select the best model parameterization that fit both the evapotranspiration and specific discharge data streams. We also designed 10,000 snow pillow observation-derived (Figure 2 a, b, and c) snowmelt scenarios for each site using uniform probability distributions of snowmelt rate, timing, and amount (Figure 2 d, e, and f). The use of these uniform probability distributions removed any collinearity between snowmelt rate, timing, and amount from the snowmelt scenarios used in conjunction with the RHESSys models parameterized for each site. Snowmelt scenario RHESSys simulation output was analyzed to extract the snowmelt season runoff ratio (R/P_{swe}) and multiple linear regression was used to assess the sensitivity of R/P_{swe} to changes in snowmelt rate and timing.

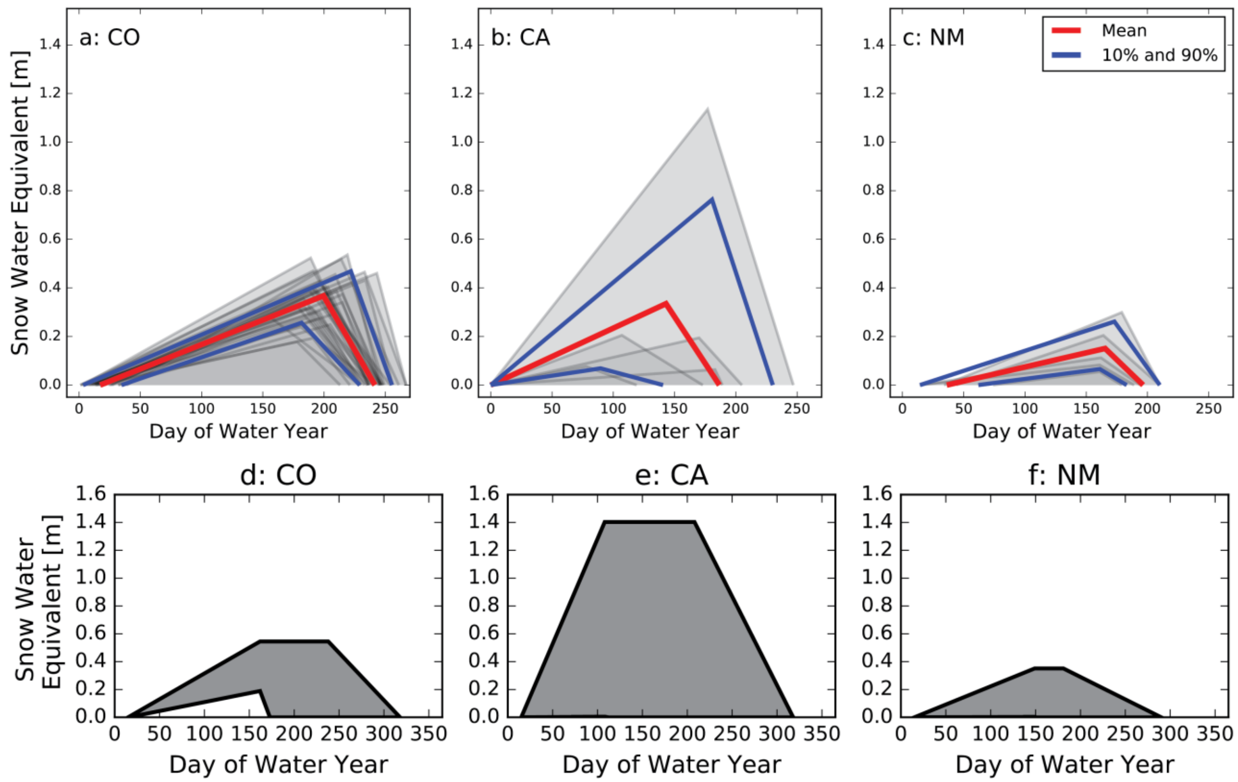

Figure 2. Observed simplified niveographs from CO (a), CA (b), and NM (c). Simplified niveographs distil a time series of snow water equivalent over a water year into two components: the accumulation season (i.e. the left leg of each triangle) and the ablation season (i.e. the right leg of each triangle). The peak of each triangle represents the magnitude (y-axis) and timing (x-axis) of peak snow water equivalent. The slope of the right leg of each triangle represents the mean snowmelt rate for the water year. Snowmelt scenario domains in terms of snowmelt rate, timing, and amount are shown for CO (d), CA (e), and NM (f). The shaded portion of each polygon indicates the ranges of snowmelt rate, timing, and amount that the snowmelt scenarios cover.

Snowmelt experiment results show general trends wherein R/P_{swe} increases with snowmelt rate at CO and CA (Figure 3 a and b) while R/P_{swe} is less responsive to changes in snowmelt rate at NM (Figure 3c). There are also notable gradients in the R/P_{swe} response to changes in snowmelt timing at a variety of snowmelt rates at CO and CA (Figure 3 a and b). For CO and CA, these patterns suggest that as snowmelt rate increases runoff production also increases, but that there is also a competing influence from snowmelt timing wherein early snowmelt leads to greater runoff generation and later snowmelt leads to diminished runoff generation. The lack of sensitivity at NM (Figure 3c) may be due to the limited range covered by the snowmelt scenarios prescribed to the site (Figure 2f), which is ultimately a function of the snowpack observational record at the site (Figure 2c). The snowpack observational record at NM shows little variability over the period of record, which translates directly to less snowmelt scenarios that span a limited range of snowmelt rate, timing, and amount.

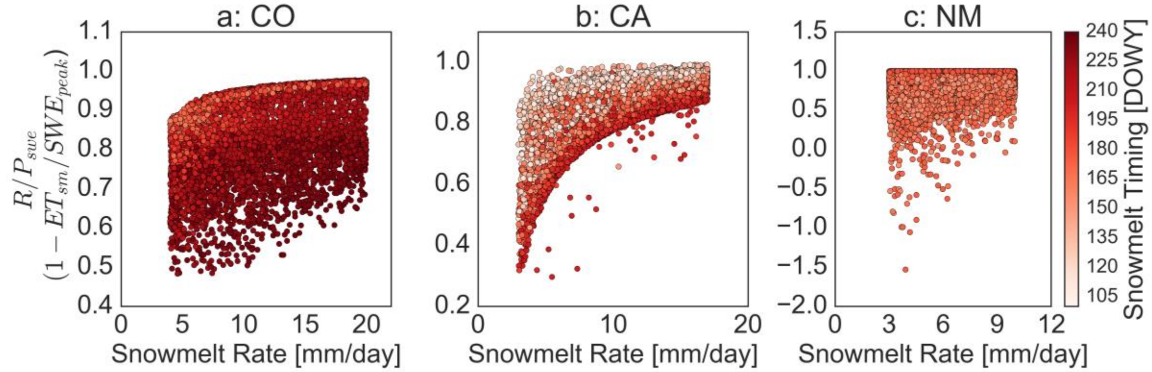

Figure 3. Relationships between snowmelt rate and runoff production at CO (a), CA (b), and NM (b) colored by snowmelt timing. At both CO and CA, runoff production increases as snowmelt increases while early snowmelt timing corresponds to greater runoff production while late snowmelt timing corresponds to lower runoff production.

Multiple regression results for CO show that snowmelt timing has a greater influence on R/P_{swe} than snowmelt rate while results for CA show that R/P_{swe} was most sensitive to changes in snowmelt rate (Figure 3). Snowmelt rate and timing explain 68% of the variance in R/P_{swe} at CO and CA and explain only 5% of the variance in R/P_{swe} at NM ($p<0.001$ at all sites, Figure 4). At CO and CA, regression model coefficients for snowmelt rate were both positive while coefficients for snowmelt timing were negative (Figure 4). This pattern fits with our intuition in that when water is added to a system more rapidly greater runoff generation occurs. For snowmelt timing, when snowmelt occurs before the period of high plant water use, greater runoff is generated, while when snowmelt occurs during the period of high water use, less runoff is generated.

The competition between these two factors, snowmelt timing and snowmelt rate, appear to dictate how runoff production at a site will respond to a change in snowmelt. More rapid snowmelt, when controlled for snowmelt amount and timing, leads to greater runoff generation, while later snowmelt, when controlled for snowmelt rate and amount, leads to less runoff generation. How a particular site responds to changes in snowmelt will then depend on the relative changes in snowmelt rate and snowmelt timing. These patterns, taken together and within the context of expected declines in snowmelt rate [Musselman et al., 2017] and earlier snowmelt timing [Harpold et al., 2012] across the western United states, suggest that runoff declines due to slower snowmelt may be partially to fully offset by changes in snowmelt timing. (KEYWORDS: snowmelt rate, snowmelt timing, RHESSys simulation model, runoff)

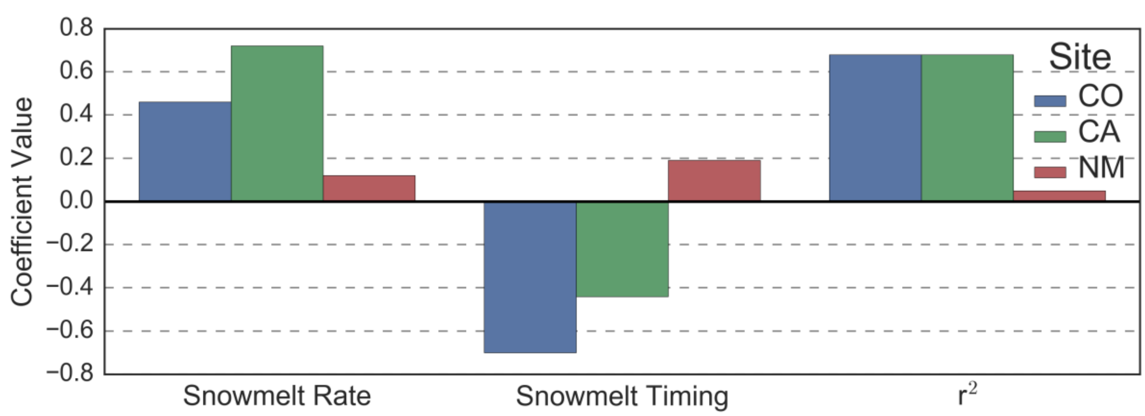

Figure 4. Multiple linear regression coefficients for CO (blue), CA (green), and NM (red) showing the sensitivity of runoff production at each site to changes in snowmelt rate (left) and snowmelt timing (center). Regression r^2 values are reported to the right. P-values for all sites are <0.001.

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