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How sensitive is discharge at the rain-snow transition zone to the spatial and temporal distribution of surface water inputs?

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Changes in rain/snowfall apportionments are already being observed in mountain environments because of climate change. Increases in temperatures are leading to the displacement of rain-snow transition zones towards higher elevations, and are impacting snowpack storage, discharge timing and magnitude and low-flow patterns. To assess sensitivity of discharge to such changes, we investigated variability in surface water inputs (SWI = snowmelt + rainfall) in a semi-arid, 1.8 km^2 headwater catchment in the rain-snow transition zone in Idaho (USA). We used a spatially distributed snowpack model (iSnobal/Automated Water Supply Model, AWSM) to investigate catchment SWI during four years (2005, 2010, 2011, 2014) with contrasting climatological conditions, and compared these results to measured streamflow and soil moisture. Results are evaluated using continuous measurements of snow depths at eleven weather stations, one lidar snow depth survey, and high-resolution satellite imagery (PSScene4Band) used to quantify the persistence of the snowpack across the catchment. We found that the model results agreed well with the spatial (r^2: 0.86 in 2009 compared to lidar-derived snow depths) and temporal (median Nash-Sutcliffe Efficiency for normalized snow depths: 0.76 compared to weather station snow depth measurements) variations of the snowpack. The model results suggested that simulated snow-covered area was a good predictor for simulated SWE (range r^2: 0.60 to 0.78 for all modeled years) during most of the snow-covered season, which indicates the usefulness of snow-covered area to quantify SWE at the rain-snow transition zone. We found that snow drifting and aspect-controlled processes caused large differences in snow depths across the watershed, with some snowdrifts producing SWI that was 3x greater than from nearby low elevation, south-facing slopes. In years with a lower snow fraction of total precipitation, the spatial distribution of SWI was much more homogeneous and stream discharge in spring time was lower, even though significant rainstorms occurred during that time. Indeed discharge response to SWI varied by season: in late spring/early summer, discharge was produced when basin-wide shallow subsurface storage exceeded ~150mm whereas in late fall/early winter, discharge was most responsive to precipitation after the shallow subsurface storage exceeded 250-300 mm. This indicates the

importance of contributions from other, possibly deeper, flow paths, and is also consistent with the observation that years with a lower snow fraction did not have lower discharge nor earlier stream drying in summer. Nonetheless, the dry-out date at the catchment outlet was positively correlated to the last day at which there was snow present in the catchment as derived from the model results for the simulated years, and for four additional years (2016-2019) for years in which the high-resolution satellite imagery was available. This indicates the importance of snowdrifts for sustaining streamflow and the need for spatially-distributed modeling of the snowpack at the rain-snow transition zone, rather than using basin-average values. While extensive data may be required to understand the breadth of catchment responses in rain-snow transition zone, some critical parameters such as dry-out date can be determined from high-resolution satellite images.