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Determining the proportion of streamflow that is generated by cold season processes versus summer rainfall in Utah, USA

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ABSTRACT

Study region: The state of Utah, western USA.
Study focus: Analysis of annual hydrographs from most rivers in the western U.S. suggests that snowmelt provides the majority of streamflow in these areas. In this study, we attempt to quantify what proportion of Utah's streamflow comes from cold season processes. Previous estimates have ranged from around 60%–80% of total annual streamflow, with uncertainty stemming from complexities related to rain-on-snow events, the geographic and temporal distribution of precipitation events, and the partitioning of rainfall/snowmelt into streamflow.
New hydrological insights: The proportion of streamflow in the western U.S. that is snowmelt in origin is well-understood to be quite high but has rarely been explicitly quantified. Our data indicate that 98%–99% of streamflow in Utah watersheds originates from melting snow and associated processes. The contribution of summer-month precipitation to annual streamflow in Utah is extraordinarily low: typically 1%–2%. Using soil moisture and well depth data we also demonstrate that vast areas of Utah watersheds are incapable of producing event flow from summer precipitation due to consumptive losses from evapotranspiration and other factors. This analysis is likely representative of areas within other western states that have cool continental climates, abundant snowfall, long-duration snowpacks (meaning that substantial portions of the snowpack do not typically melt during the winter), and sedimentary bedrock.

1. Introduction

The importance of snow as a resource for states in the western U.S. would be hard to overstate (Strum et al., 2017). Most rivers that drain mountainous terrain in the western U.S. have hydrographs that are strongly driven by snowmelt processes. In Fig. 1, the average daily streamflow of the multiple watersheds in Utah exhibits a pattern ubiquitous to many western watersheds: the beginning of snowmelt in April produces the annual rise in flow which typically continues until around late July, at which time streamflow returns to base flow conditions. Snowmelt-driven hydrographs tend to have unimodal peak discharge with modest increases and decreases in flow rates and very little variation in discharge outside the snowmelt runoff period. As shown in Fig. 1, the period of the streamflow hydrographs from August to April is remarkably steady, suggesting that whatever precipitation falls during this period does not typically manifest in substantial increases in streamflow (with the exception of the Virgin River, discussed later). This raises the issue of quantifying what percent of water flowing in typical western streams is generated from snowmelt versus rainfall.

The proportion of streamflow in the western U.S. that is snowmelt in origin is well-understood to be quite high but has rarely been explicitly quantified (Li et al., 2017). Previous estimates range from ~60–85%, or "most" for mountainous areas in the West (e.g.

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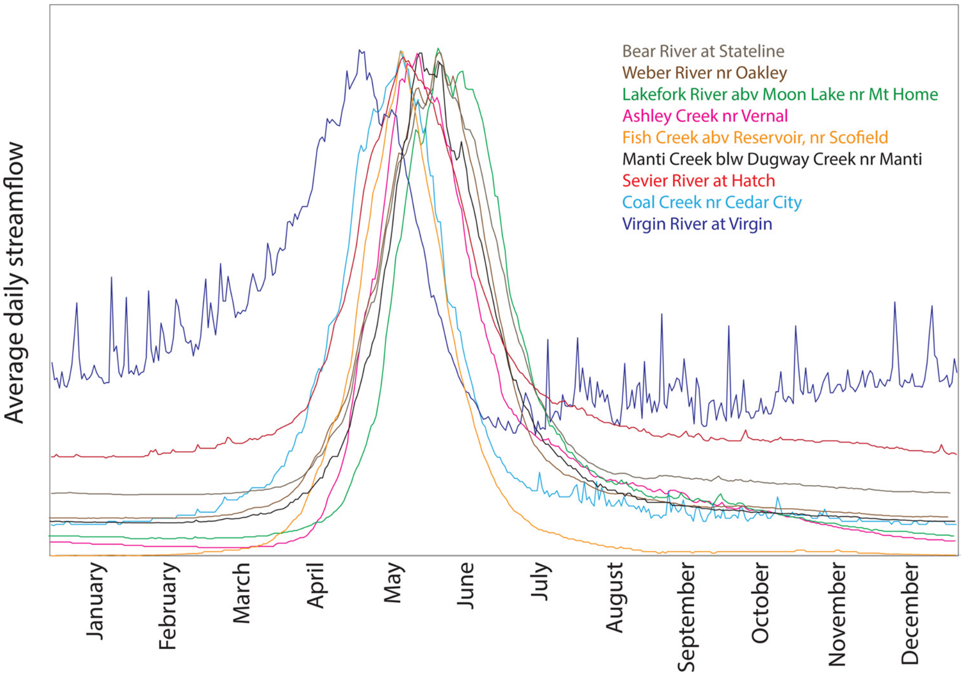

Fig. 1. Annual hydrographs for rivers in Utah used in this study, from the average daily discharge at each gage location. Values are based on the full period-of-record data for each site (details in text) and have been scaled to match peak flow magnitude in order to compare hydrograph patterns between sites. Each river's hydrograph corresponds with the same color in the legend.

Campbell et al., 1995; Lins, 1997; Serreze et al., 1999; Pederson et al., 2011; Li et al., 2015; Strum et al., 2017, see additional details in Li et al., 2017, Table 1), though some researchers have cited a slightly lower range (e.g. 40–70% value given in Maurer and Bowling, 2014). In an analysis that spanned the western U.S., Li et al. (2017) concluded that roughly 50% of all runoff in the region began as snowmelt; that proportion was much higher (~70%) for mountainous areas. In Utah, the estimates have ranged from 80% to close to 100% (Barnett et al., 2005). However, the majority of these estimates are rough guesses instead of exact proportions based on regional factors.

Even with widespread, high-quality point data from high altitude weather stations (NRCS snow telemetry network, SNOTEL), the exact proportion of streamflow that stems from a basin's snowmelt is problematic to derive in any given year due to the complexities of temporal and spatial distribution of precipitation across the watershed, the proportion of precipitation that falls as rain versus snow (Kormos et al., 2014), subsequent redistribution of snow, heterogeneities in soil types, depths, and antecedent water content, spatial and temporal variations in snowmelt rates, and other factors. In addition, some distinctions may be semantic; for example, a rain-on-snow event midwinter that did not generate melt water is not relevant to streamflow and effectively becomes part of the watershed's snow water equivalent (SWE) until the entire snowpack begins to melt during the spring melt season. As such, we elected to sidestep this issue by: (1) quantifying the contribution of summer precipitation to annual streamflow, and (2) lumping all of the hydrological phenomena associated with snow water accumulation and snowmelt (such as warming, rain on snow, rain on the watershed but not on snow, etc.) together as one category called "cold season processes" (CSP). A similar approach to this seasonal partitioning of precipitation was used by Stage (1957) who found that 98% of the flow originated as "winter precipitation" for Benton Creek within the Priest River Experimental Forest, Idaho. Similarly, Yenko (2003) found that close to 100% of the water contributing to streamflow in a small Idaho watershed could be accounted for by cold-season precipitation occurring in the basin. Williams and

Table 1
Stream gage locations used in this study. All are operated in Utah by the U.S. Geological Survey (https://ut.water.usgs.gov/).

Station Name	USGS ID	Elevation (m)	Watershed area (km^2)
Bear River at Stateline	10011500	2428	445.5
Weber River nr Oakley	10128500	2024	419.6
Lakefork River abv Moon Lake nr Mt Home	09289500	2493	201.8
Ashley Creek nr Vernal	09266500	1899	261.6
Fish Creek abv Reservoir, nr Scofield	09310500	2338	155.7
Manti Creek blw Dugway Creek nr Manti	10215900	1981	68.4
Sevier River at Hatch	10174500	2094	880.6
Coal Creek nr Cedar City	10242000	1829	209.5
Virgin River at Virgin	09406000	1067	2476.0