TOWARD A GREATER UNDERSTANDING OF SNOWMELT HYDROLOGY IN UTAH

Randall P. Julander[1*] and Jordan Clayton[1]

ABSTRACT

Visual inspection of annual hydrographs from most rivers in the western U.S. supports the notion that snowmelt provides the majority of streamflow in these areas. In Utah, the snowmelt period of April-July provides an average of 71% of annual streamflow with 29% coming in the remaining 8 months, begging the question: what proportion of streamflow comes from snowmelt? Previous estimates have been rough and have ranged from 60% to 80% or so; uncertainty stems from complexities such as rain on snow events, the geographic and temporal distribution of precipitation events, and the partitioning of rainfall/snowmelt into streamflow. However, the quantification of streamflow derived from summer precipitation is fairly simple on streams that have no upstream regulation. It can be reasonably assumed that any rise in flow with a corresponding storm event is due to precipitation, and the event flow can be separated from the base flow component of the hydrograph. We find that the contribution of summer-month precipitation to annual streamflow in Utah is extraordinarily low: typically 1% to 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. We use these data to infer that 98% to 99% of streamflow in Utah watersheds originates from melting snow and associated processes. 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, such as eastern Nevada, western Colorado, portions of Idaho and Montana, and elsewhere. (KEYWORDS: snowmelt, streamflow, Utah, soil moisture, SNOTEL)

INTRODUCTION

Most rivers that drain mountainous terrain in the western U.S. have hydrographs that are strongly driven by snowmelt processes. In Figure 1, the average daily streamflow of the Weber River 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 ~late July where 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 is visible in Figure 1, the period of the Weber River hydrograph from August to April is remarkably steady, suggesting that whatever precipitation falls during this period does not typically manifest in substantial increases in streamflow. This begs the question: what percent of water flowing in typical western streams is generated from snowmelt versus rainfall? We explore this question at length.

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. Previous estimates range from ~60-85%, or "most" for mountainous areas in the West (Campbell et al., 1995; Lins, 1997; Serreze et al., 1999; Pederson et al., 2011; Li et al., 2015; plus others too numerous to list), though some researchers have cited a slightly lower range (e.g. 40-70% value given in Maurer and Bowling, 2014). 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 (SNOTEL), the exact proportion of streamflow that stems from a basin's snowmelt is impossible to derive in any given year due to the complexities of temporal and spatial precipitation across the watershed, the proportion of precipitation that falls as rain versus snow, 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 until the entire snowpack begins to melt during

Paper presented Western Snow Conference 2017
[1] Snow Survey, NRCS, USDA Salt Lake City UT 84116
[*] denotes corresponding author, randy.julander@ut.usda.gov

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 process. 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. As another example, Williams and Ehleringer (1996) stated that only around 18-25% of the annual precipitation in northern Utah was received during summer months. Understanding how much streamflow is derived from summer precipitation can thus be used to derive how much annual flow comes from snow and snow related processes.

In addition, we examine herein the source area of streamflow in Utah watersheds and demonstrate that the vast majority of flow comes from areas proximal to the channel or from areas that have a short distance to an impermeable layer such as bedrock. Thus. higher elevations with shallow soils and high permeability are substantial streamflow contribution areas. Watershed areas that have deeper soils with finer textures and are more distant/remote from the channel contribute little or no flow on an annual basis.

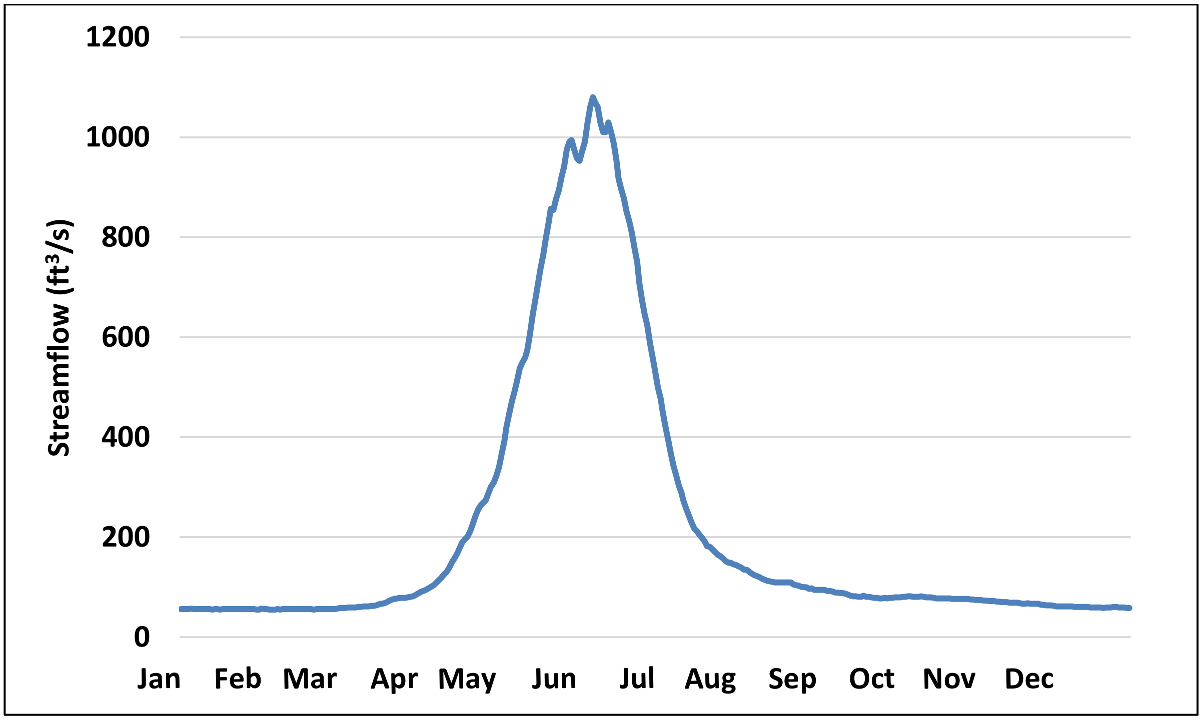

Figure 1. Example of a typical annual hydrograph for rivers in Utah: average daily streamflow of the Weber River. Values are based on the full period-of-record (1904-2017) data at the Weber River near Oakley streamgage (10128500) operated by the U.S. Geological Survey.

METHODS

The first issue is to define what constitutes "summer precipitation streamflow" (SPS). This necessitates an arbitrary delineation of some kind. In this case, it is defined as event flow during the summer months, meaning that there has been a non-negligible response (increase) in the stream's hydrograph, with a timeline for such events from when the annual snowmelt hydrograph approaches base flow (and SNOTEL sites have melted out) to that time in the fall when precipitation is recorded as snowfall at representative SNOTEL sites within the watershed. The overall time period in any given year is therefore variable depending on the length of the snowmelt season and the arrival of snowfall later in the year. This delineation works well in Utah as June/July are typically the driest months of the year resulting in the occurrence of relatively few precipitation events concurrent with the declining limb of the snowmelt hydrograph. In the fall and early winter as rainfall changes to snowfall, the number of storms producing discernible increases in streamflow declines dramatically until there are none. We used this definition of SPS to quantify all flows not related to snowmelt processes for rivers and streams throughout Utah for the period of 1981 to 2011. The volume of water attributed to each SPS event was determined by totaling all flows from the initial streamflow increase over its base flow to the point when the flow had declined back to the previous (base flow) level. We omitted fluctuations in base flow if they oscillated above and below steady levels as these were most likely due to sensor error or diurnal patterns, but retained all non-zero increases in discharge indicative of a stream response—even if no associated precipitation was captured at SNOTEL sites in the basin. SPS events were summed to obtain an annual total which was then compared to the total flow for that year for each stream.

Streamflow discharge data was obtained from U.S. Geological Survey gaging stations- these span all major and most minor watersheds in the state- a list of locations is provided in Table 1. We removed any gaging stations with significant upstream controls (e.g. diversions); a few were retained that have minor upstream flow regulation but also have sufficient unimpaired areas to allow the streamflow to reflect both rainfall and snowmelt generated streamflow. These sites represent a huge diversity in soils, vegetation, aspect, geology and topography from the high elevation metamorphic bedrock of the Uinta Mountains, the sandstone slick rock of the Virgin River headwaters, the dense clay soils overlying limestone bedrock of the Wasatch Plateau, etc.

In addition, period of record soil moisture data for Utah were analyzed for all ~130 SNOTEL sites in the state to determine how frequently these soils were saturated and capable of producing SPS. The only sites that were excluded from this analysis were 5 locations (Buck Pasture, Burts Miller Ranch, EF Blacks Fk, Buck Flat, and Spirit Lake) where the soil moisture data is collected in a permanently wet environment and does not reflect watershed conditions.

Finally, well log data from the state of Utah's Division of Water Rights were used to determine the overall depth to the surface of the water table, including both those that were located near/adjacent to streams and more distant locations close to watershed divides. These data were obtained in order to determine the potential for subsurface water to contribute to observed variations in SPS.

Table 1. Stream gage locations used in this study. All are operated in Utah by the U.S. Geological Survey.

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	9289500	2493	201.8
Ashley Creek nr Vernal	9266500	1899	261.6
Fish Creek abv Reservoir, nr Scofield	9310500	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	9406000	1067	2476.0

RESULTS AND DISCUSSION

In Figure 2, the percent of April-July flow is compared with streamflow for the remaining 8 months of the year for 17 major rivers in Utah. The average percentage of April-July flow of the annual total flow for these watersheds across Utah is 75%; conversely, only 25% of the annual flow occurs during the remainder of the water year (Figure 2, at right). Generally-speaking, the proportion of annual flow that occurs from April-July was greater for higher elevation watersheds, such as the Bear and Weber Rivers, than for lower elevation watersheds, such as Blacksmiths Fork. However, a couple exceptions were Manti Creek and Fish Creek, two mid elevation watersheds that receive more than 80% of their total annual flow between April and July. This may be due to the thick, clayey soils, sedimentary geology, and comparatively modest relief of the Wasatch Plateau where these watersheds are located that (together) augment water retention in the basin and (i.e. minimize runoff generation) during summer months. These proportions suggest that snowmelt constitutes the dominant input in these basins' supply, and—given that these rivers have hydrographs similar to Figure 1—implies that the August-April flow is predominantly baseflow with minimal input from SPS events. We explore this possibility below by examining the average percent of annual streamflow that was contributed by SPS events in each watershed (Figure 3).

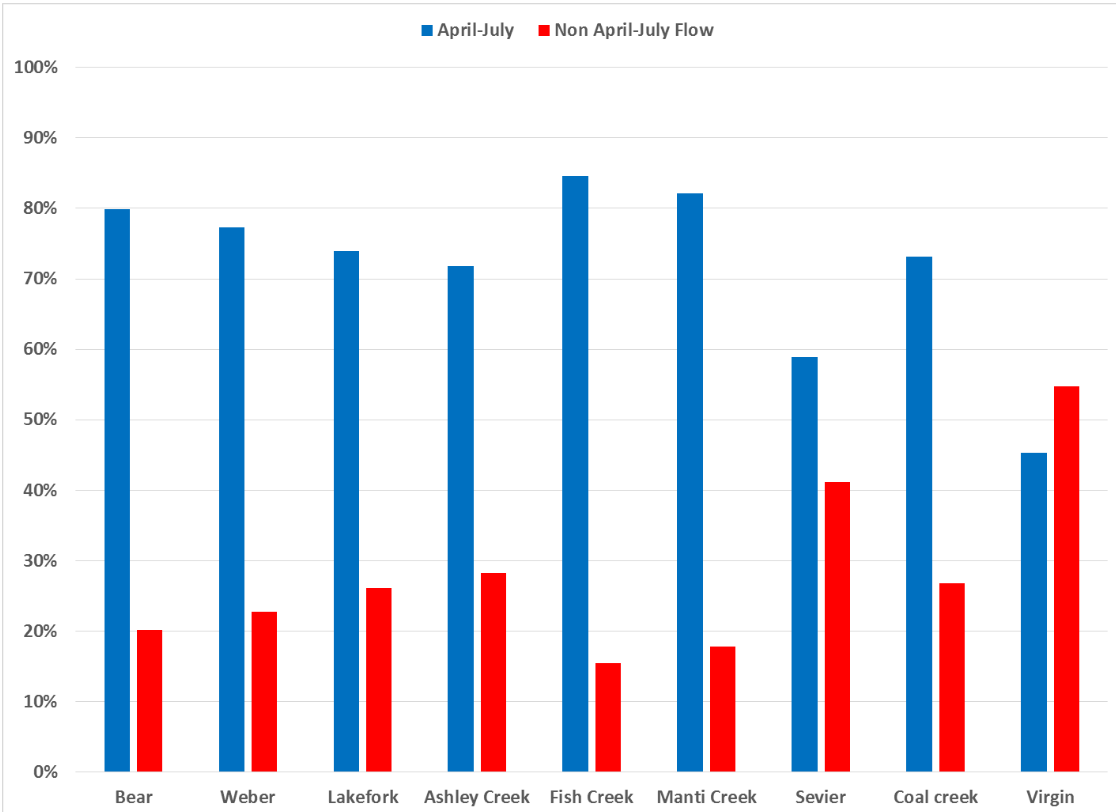

Figure 2. Percentage of annual streamflow occurring in snowmelt runoff season (April-July) versus the rest of the year for rivers in Utah.

Total average annual streamflow from SPS events ranged from about 0.5% to about 2% for Utah rivers, except for the Virgin River where SPS contributed to about 7% of annual flow. Differences in basin characteristics provide some explanation for the higher SPS contribution for the Virgin River, including: a large proportion of the basin is impervious rock (primarily sandstone with cliffs and exposed bedrock close to the stream channel), soils are very coarse (sandy textures from the sandstone parent material) allowing little water retention, and the watershed is in the southwestern corner of the state and is more susceptible to high intensity, convective precipitation during the summer monsoon. Conversely, given the (generally) lower elevations and warmer climate of the Virgin River basin relative to the others considered here, there is a comparatively large proportion of the watershed that may receive winter rain outside of (below) the snow accumulation zone, which would have the effect of overestimating the snowmelt contribution to annual flow, so the 7% SPS value presented above may be an underestimation.

Every basin had years where there was very little streamflow response to SPS- as low as ~0.02% of the annual total flow for the majority of basins and ~0.87% for the Virgin River. Conversely, the maximum SPS varied regionally: ~4-5% for northern Utah basins, and ~0.75-1.25% for central Utah streams—particularly those draining the Wasatch Plateau, (Fish Creek and Manti Creek). The maximum annual SPS contribution to overall flow was much higher for the Virgin: ~19-22%.

Regional differences in summer precipitation are fairly minor between northern and central Utah watersheds (around 12 to 15 centimeters for both areas), so differences in runoff production are most likely attributable to other factors. For example, the central Utah basins draining the Wasatch Plateau have clay-rich, thick soils and comparatively modest relief, which improves their capacity to retain rainfall. However, for southern Utah—particularly the Virgin watershed—high intensity precipitation over small areas and short time periods produces overland flow leading to higher SPS values. Still, the exceptionally minimal streamflow response to summer rainfall for most basins in Utah implies that snowmelt (and snowmelt-related processes such as rain on snow) supply the remainder of water available to supply the annual streamflow—typically 98 to 99% of the average annual total flow.

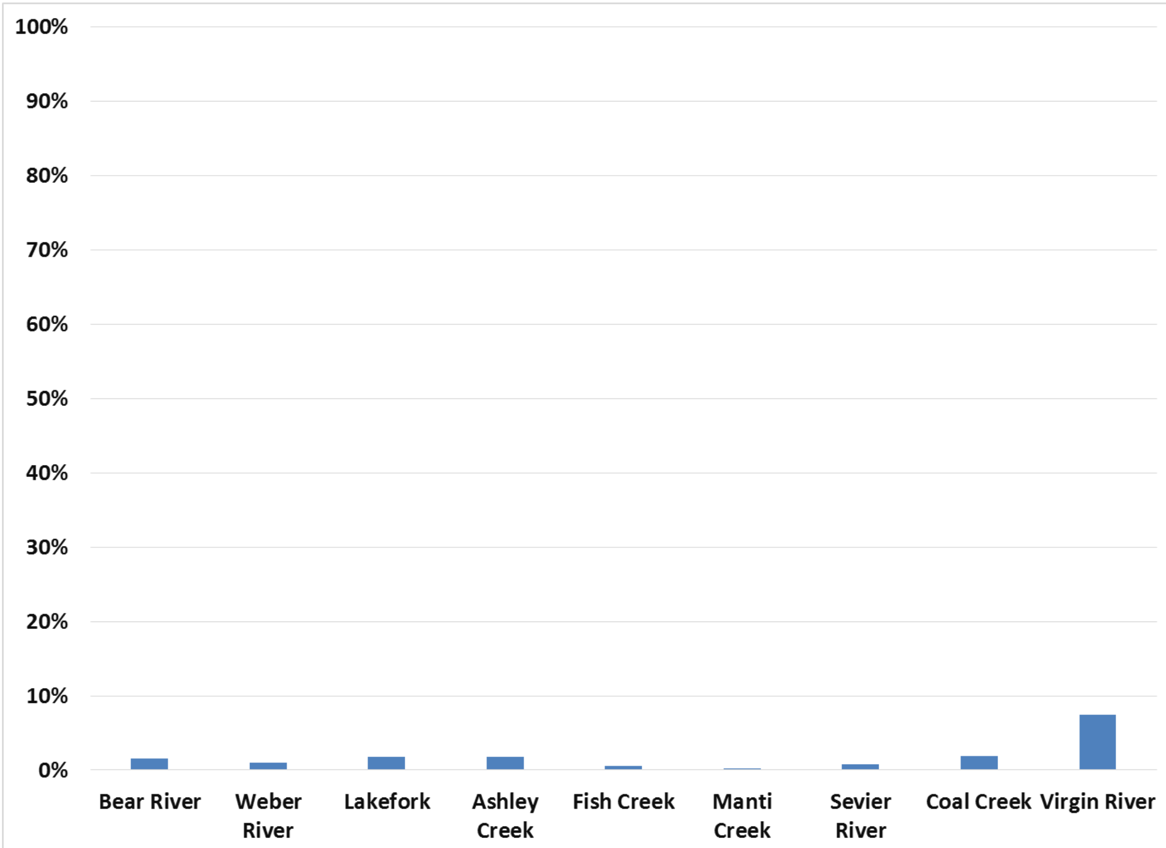

Figure 3. Average percent of annual streamflow derived from SPS events for rivers in Utah.

As noted in Figure 4, summer precipitation constitutes ~15% to 25% of the annual total precipitation across Utah watersheds, with an average of 20%, reflecting as aspect of the climatology of the state: summers are typically drier than winters. However, the 20% of the annual total precipitation that is received during the summer months generates just 1.6% of the annual streamflow (Figure 3), indicating that the runoff efficiency during the summer is substantially lower than that of other seasons. This stems from comparatively small precipitation amounts relative to high evapotranspiration (from warm temperatures and active vegetation) that combine to produce a substantial soil moisture deficit during summer months. Soils across a large portion of the watershed (except for a narrow band along stream corridors) are sufficiently dry to infiltrate and retain nearly all of the summer precipitation that falls. The vast majority of this precipitation is subsequently consumed by the watershed's vegetation and from evaporation.

To examine this point further, we examined regression coefficients between summer precipitation amounts and SPS values per year for each site. The resulting r^2 values were very low (from <0.00 for the Manti basin to 0.36 for the Sevier basin). We also found poor statistical relations between SPS and watershed area, which was not surprising considering the typical Utah basin characteristics described above. Moreover, we examine in subsequent analysis (below) the possibility that small areas within Utah watersheds disproportionately contribute to their stream's annual flow, and that the vast majority of this water is derived from snowmelt processes.

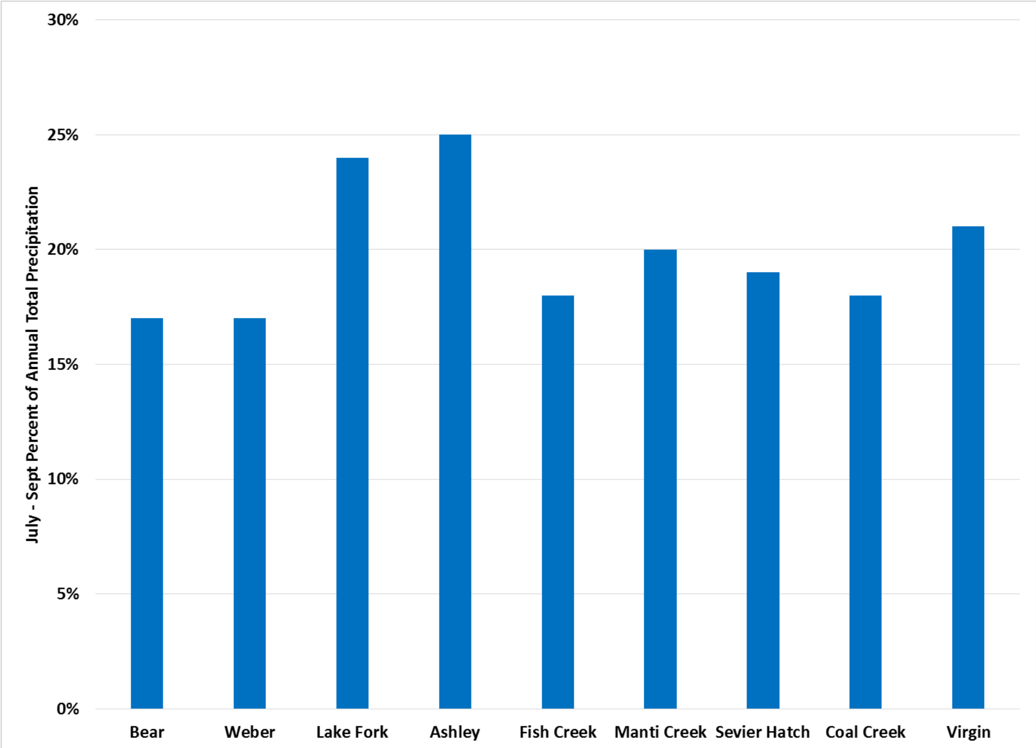

Figure 4. Seasonal percent of average annual precipitation for various Utah watersheds.

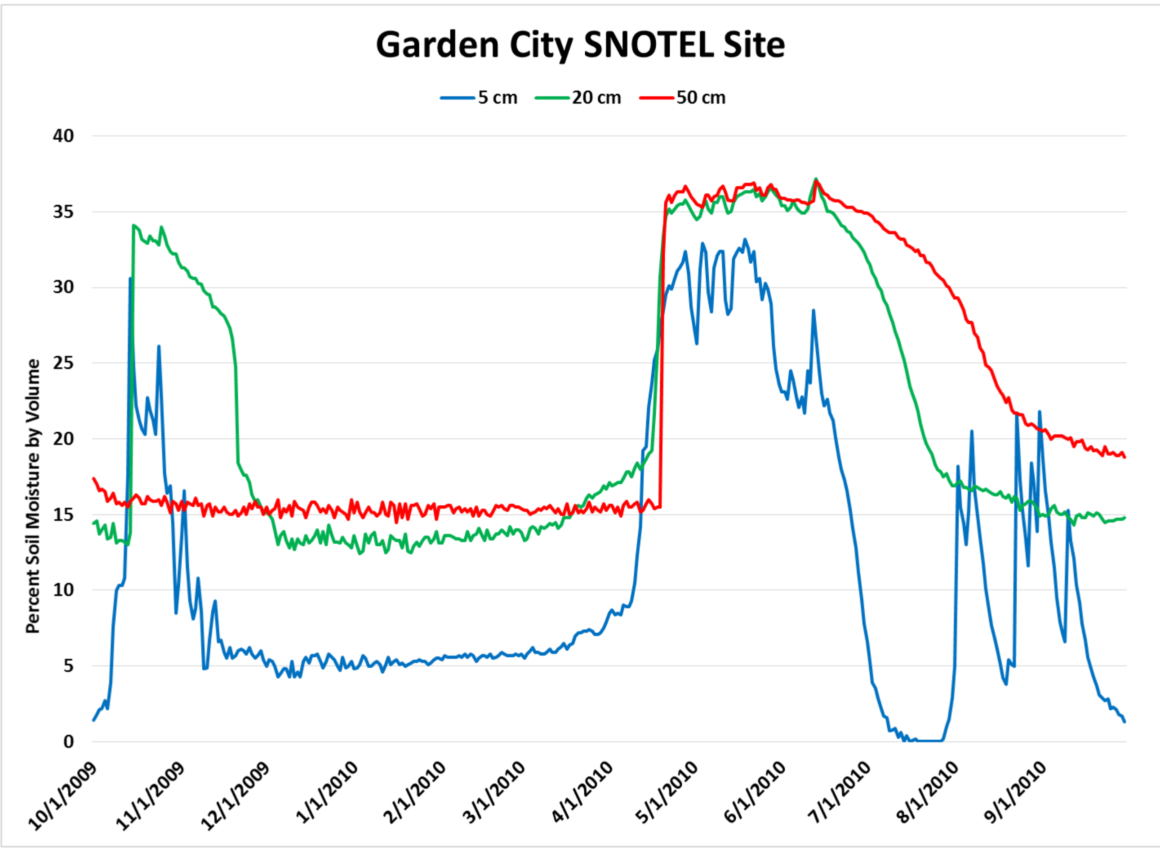

Figure 5. Garden City SNOTEL site hourly percent volumetric soil moisture at 5, 20 and 50 centimeter depths for the 2010 water year.

As all Utah SNOTEL sites are equipped with soil moisture sensors, we explored the low runoff efficiencies discussed above from an examination of typical annual soil moisture patterns in these basins. Soil moisture at the Garden City SNOTEL site (Figure 5) depicts a common pattern at many sites across Utah: soils wet up during the spring season when snowmelt begins and soils become saturated (or nearly so) for a couple of months. At the end of the snowmelt influx, soils rapidly dry—the rate of which decreases with depth in the soil column (Clayton, 2016). Midsummer soil moisture values are quite low until a resurgence of soil moisture in the fall as temperatures and transpiration rates decrease and occasional large-magnitude precipitation events increase soil moisture percentages. As rainfall changes to snow, soil moisture decreases and then stabilizes through the winter months. In Figure 5, there are several summer precipitation events where the 5 cm soil moisture sensor increases substantially. Note that this moisture doesn't reach the 20 and 50 cm sensors as they continue to slowly dry. It is common that summer precipitation will induce a response in the 5 cm sensor, far less frequently at the 20 cm sensor and occasionally at the 50 cm sensor though these responses at the deeper sensors are much less in magnitude and duration compared to the runoff producing season and not nearly sufficient to bring soils to a state of saturation capable of producing runoff. Moisture that reaches the 50 cm sensor has a short residence time before being consumed either through transpiration or deeper percolation, and results shown in Figure 3 suggest that little, if any, of this moisture makes it to streams as base flow (or that the residence time of the water from these precipitation events exceeds the 3 month summer season). Most summer-season precipitation is consumed in shallow portions of the soil profile and is not detectible at the 20 cm soil moisture sensor (much less the 50 cm sensor). Substantial runoff generation is only plausible when soils are saturated or near-saturated, which typically only occurs during the snowmelt season (Stage, 1957). Thus streamflow generated by summer precipitation (SPS) is most likely to occur from precipitation falling directly on/near the wetted stream perimeter, or from very high intensity precipitation events that exceed infiltration capacity, thereby generating some overland flow.

We also examined elevation controls on the percent of summertime days (July-September) that soils reached saturation (when all three soil moisture sensors (5cm, 20 cm and 50 cm) attain their saturated values). Considering all 130 SNOTEL sites in Utah, above ~2900 meter elevation (~9500 feet), soils are saturated only around 0.8% of the time between July 1 and September 30—the vast majority of which is during years when snowmelt is still active in July. Below 2900 m elevation, soils are almost never saturated in the summer months (<0.01% of the time) and thus have the capacity to infiltrate most precipitation moisture. In order to produce substantial runoff, soils must either be saturated or experience precipitation rates that exceed infiltration capacity, which is particularly rare where soil textures are coarse (e.g. with sandstone parent material).

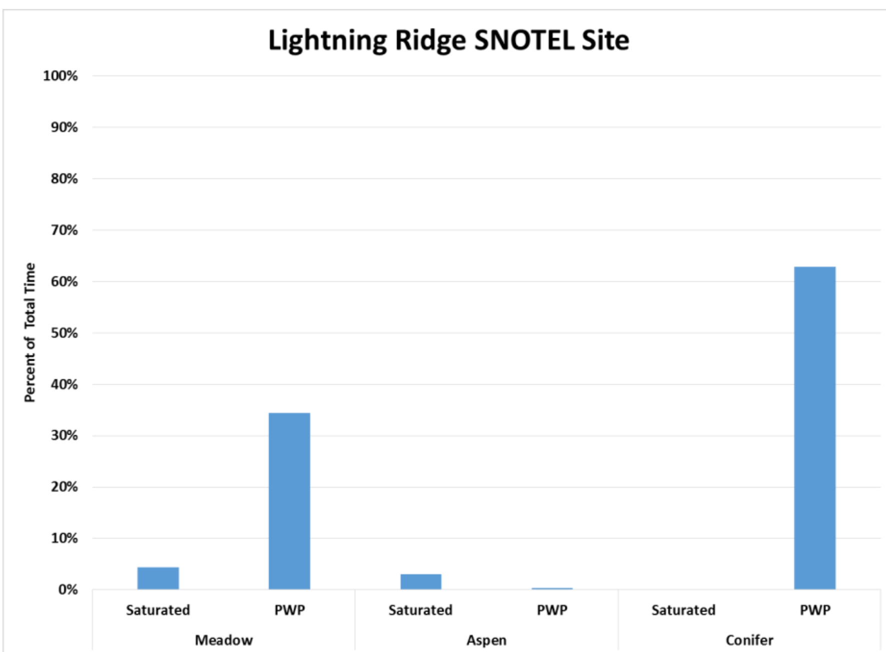

Figure 6. Percent of time that soils are either saturated or at permanent wilting point (PWP) for 3 different vegetation cover types at the Lightning Ridge SNOTEL site, Utah. Data are for the 1 meter depth soil moisture sensors at each location.

The Lightning Ridge SNOTEL site in Utah has additional (1 meter depth) soil moisture sensors at three different sampling environments: 1) in an open meadow, 2) in an aspen stand and 3) in a conifer stand. These have been used previously to compare vegetative impacts on soil moisture (Burke and Kasahara, 2011). Here, the effect of vegetation type on soil moisture thresholds is examined where differences between other factors (e.g. precipitation inputs, soil parent material, etc.) are minimal. Figure 6 shows the percent of the time that soils are either saturated or at permanent wilting point (PWP) under three different vegetation types at the Lightning Ridge site. At the one meter depth, soils are saturated under the meadow about 4% of the time, in the aspen setting about 3% of the time, and almost never underneath coniferous tree cover—times when soils are saturated at these settings are almost exclusively during the snowmelt season and not during summer months. Conversely, assuming that PWP is at 10% volumetric soil moisture for all 3 locations (based on graphical analysis of the period of record data), soils that underlie the meadow, aspen, and conifer vegetation reach PWP around 33%, 1%, and 63% of the time, respectively. These data suggest that soils that underlie meadow and coniferous forest frequently have strong soil moisture deficits and are not likely to produce runoff except during the snowmelt season—this is less clear for soils underlying aspen forest. A nearby SNOTEL site, USU Doc Daniels, also has a soil moisture sensor at the 1 meter depth (in addition to the standard sensors at 5, 20, and 50 cm depths). Soils are saturated at 1 meter depth at the USU Doc Daniels SNOTEL site around 45% of the time and nearly saturated (at or above 90% saturation) more than 80% of the time. However, the 50-cm sensor shows the pattern described above (Figure 5) of saturation during snowmelt and subsequent drying due to evapotranspiration. These data indicate that a low permeability layer exists between 50 and 100 cm (in this case due to a heavy clay layer in the soil) that reduces vertical water movement and thus increases the potential for runoff.

Clearly, site-specific differences in pedogenic factors, vegetation, bedrock type, soil thickness, or other variables will impact a given location's soil saturation threshold. Moreover, water delivered to Utah basins from snowfall is redistributed during winter months (reflecting dominant wind patterns) which does not necessarily coincide with spatial patterns in soil saturation and PWP thresholds (Williams et al., 2009). Understanding this, we present in Figure 7a the ratio of average April 1st (peak snowpack) snow water equivalent (SWE) to soil saturation (where the percent volumetric values are converted to a depth over 1 meter soil column thickness) for all SNOTEL sites in Utah. We also present ratios of the maximum (b) and minimum (c) April 1st SWE relative to soil saturation at these sites to explore regional differences in the capacity for soils to infiltrate snow water during melt for a range of water year conditions.

Figure 7a shows each SNOTEL site's theoretical ability to saturate one meter of soil depth if the average SWE observed on April 1st was infiltrated as one continuous input. There are around 40 stations, which under average snowpack conditions, do not have sufficient SWE to bring 1 meter of soil to saturation (shown by the red, orange, and yellow circles). In Figure 7b, nearly all sites are not only able to saturate the soil, but many of them have sufficient excess water to fill the soil's pore spaces several times over (dark blue circles). Alternatively, as shown in Figure 7c, during extremely dry water years only a few sites in Utah are theoretically able to saturate one meter of soil (green circles). Regional trends shown in Figure 7 are more reflective of broad geologic/soil character differences than spatial variations in precipitation/snowfall.

As SNOTEL sites are usually located in uplands/headwater locations far from stream corridors, these data support the idea that there are large portions of Utah watersheds that do not contribute substantial quantities of water to streamflow discharge on an annual (or shorter) basis. We explored this point further by using well log data from the Utah Division of Water Rights (https://www.waterrights.utah.gov/) to obtain the distance from the ground surface to the water table prior to any pumping (artificial) drawdown (Table 2). The data were available for wells that were located at various cabins and summer homes in several northern Utah watersheds (including the closest

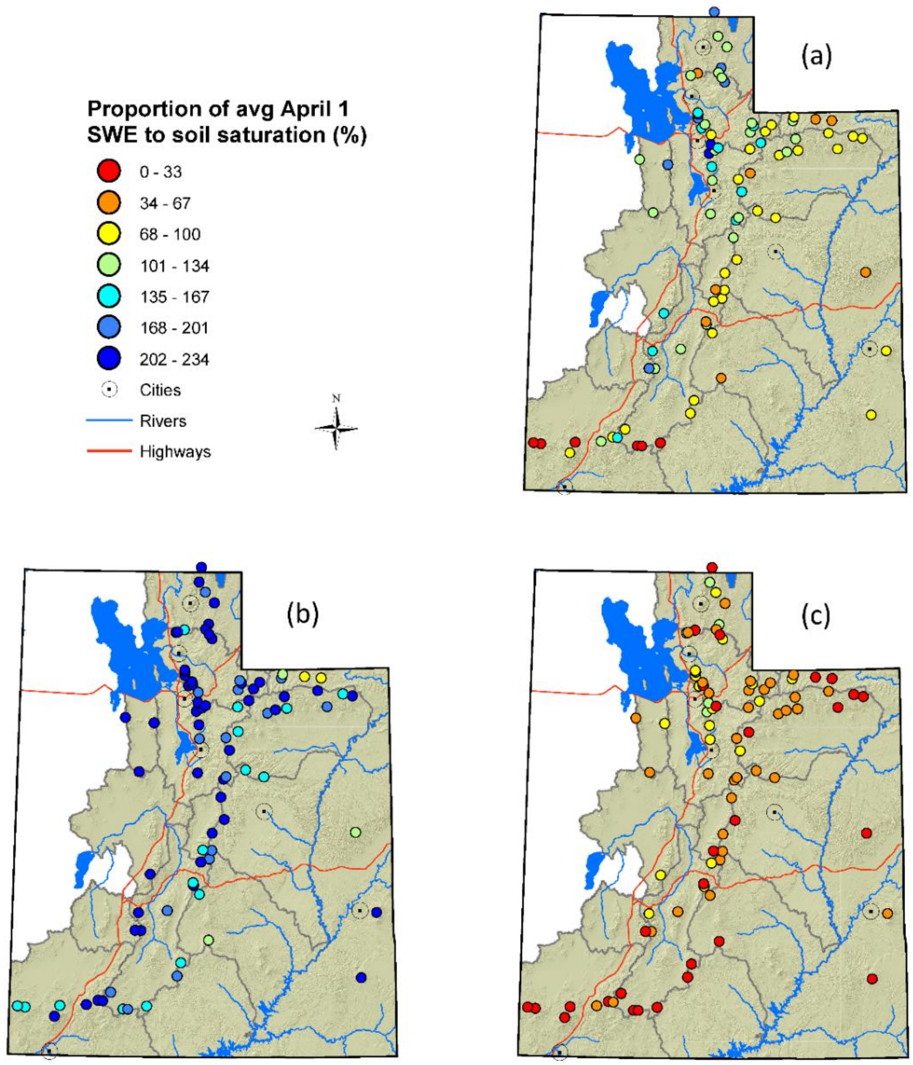

Figure 7. Average (a), maximum (b), and minimum (c) April 1 snow water equivalent relative to soil saturation for all SNOTEL sites in Utah.

stream elevation): Weber River (2347 m and 2408 m), Bear River (2530 m), Ogden River (1951 m), Provo River (2073 m), and Dry Fork Creek (2134 m). We selected well data for 3 regions in each watershed: adjacent or close to the stream, intermediate distance from the stream (in a direction perpendicular to the channel), and in the headwaters. While data quality varied (see details in link provided), the well data showed that the depth to the water table increased with distance from the stream channel. For those wells closest to the channel, depths to water table were around 5 to 10 meters. For farther wells (100s of meters from the channel), depths to the water table were around 20 to 60 meters. For the most distant wells from the stream (nearest the headwaters), depths to the water table were between 50-100 or more meters. This suggests that any moisture not consumed by ET or held in place by upland soils must travel either vertically downward tens to hundreds of meters through unsaturated, unconsolidated material or horizontally hundreds to thousands of meters (through the same medium) to reach the stream channel These data suggest that the travel time required for water received during precipitation exceeds the 3 month summer season and helps to explain the extremely low SPS values described herein. Moreover, it is likely that the portions of the watershed immediately adjacent to the stream corridors are the only areas of the basin with travel times less than one year. Stated differently, the majority of the variability in annual discharge for these streams must therefore come from portions of the watershed that produce (at least) annual runoff. It follows that the greatest annual runoff-producing areas in Utah watersheds would be those that are rather close to stream channels, with high snow accumulation, high elevation, and shallow soils.

Table 2. Location and characteristics of groundwater well data used in this study. All data were obtained from the Utah Division of Water Rights (https://www.waterrights.utah.gov/).

Basin, location	Well number	Depth to water (m)	Proximity to stream
Weber River, Weber Canyon	e5222	29	near
	e4261	33	middle
	e5274	55	far
Weber River, Holiday Park	e1268	2	near
	e2769	58	middle
	e4842	84	far
Bear River, nr Bear River Resort	21-1035	4	near
	21-1611	33	middle
	21-1695	70	far
Ogden River, Sourdough	e3283	2	near
	e3800	23	middle
	e4916	44	far
Provo River, Woodland	55-9227	37	near
	55-8793	43	middle
	55-9226	122	far
	55-9237	91	far
	55-9239	111	far
North Wasatch Plateau, Electric Lake	e-1691	152	far
Fish Lake, Mytogee Mt.	95-5278	396	far
Box Creek, Monroe Mountain	61-2647	53	far
	63-4688	64	far
	61-1958	20	far
	63-4126	24	far
Tommy Creek, Duck Creek region	61-1673	20	far
	61-1554	64	far
	61-1921	60	far
Uintah Basin, Ashley Creek region	43-8193	3	near
	43-12162	12	middle
	43-4959	23	far

The water table for many wells in Utah that are located far from stream channels is 100s of meters deep, and groundwater in these locations is not typically being recharged by annual snowmelt. For example, the depth to water in the Humbug Well near Oakley is approximately 400 meters and advertises the water's age to be at least 10,000 years old (when Utah had a cooler, wetter climate that filled many pluvial lakes). Taken together, we have included the preceding discussion of the soil moisture and groundwater levels to reinforce that the farther a rain or snowmelt droplet of water is from the stream channel, the lower the probability of that water ever becoming streamflow. In fact, in many cases that water is not likely to percolate farther down than one meter of soil depth. The majority of the snowmelt and rainfall in these locations is consumptively used over time by evapotranspiration processes. With only a couple exceptions, Utah SNOTEL sites do not have soil moisture data deeper than 50 cm, so we have no information regarding exactly how deeply the zone of saturation extends below that depth when conditions are very wet, but the data presented above suggest that water that does infiltrate to such depths is probably not transmitted to streams over short timescales. Moreover, the transition between portions of Utah watersheds that provide annual recharge to groundwater (where streams are gaining) and those where the water table is lower than the stream level (losing stream reaches) may be higher in the watershed than previously thought, in addition to varying over time (Lambert et al., 2011). Not only do our data support the claim that relatively small portions of the watersheds contribute to annual flow, but these areas may grow or shrink according to antecedent hydrologic conditions. This may explain why, for certain Utah watersheds such as the Bear River, forecasts overestimate discharge during below-normal water years and, conversely, tend to underestimate flow after a series of average or above-average years of snowpack have occurred.

CONCLUSIONS

The contribution of summer precipitation to streamflow in Utah watersheds is extremely low—roughly 1% to 2% of the annual total streamflow for each basin, with the exception of the Virgin River where summertime precipitation produces around 7% of the annual flow. The remaining 98% to 99% of total annual flow is derived from snowmelt and snowmelt related processes. Event flow from direct snowmelt during the April-July season contributes, on average, about 71% of total annual flow. The remaining discharge is baseflow during the remaining 8 months of the year, and the vast majority of this baseflow is also snowmelt in origin. Summer precipitation contributes little to streamflow in Utah river's, as shown from our examination of discharge, soil moisture, and well data. Soil moisture deficits and large depths to groundwater in upland areas also indicate that streamflow typically originates from areas close to the channel or from portions of the watershed that have shallow depths to low permeability (e.g. bedrock or clay layers).

Implications of this research include: 1) As many previous studies have concluded that Utah snowpacks may be thinning and will continue to get smaller in future years due to climate warming (see review in Julander and Clayton, 2015), it is of great concern to be able to quantify the proportion of streamflow that originates during the winter/spring versus summer season. These data suggest that during low snowpack years, a greater amount of the annual precipitation—that portion that falls as rain—could wind up not making it to area streams, thereby reducing the already-small SPS contribution. Water managers can use as guidance the proportion of streamflow and reservoir recharge that can be expected from snowpacks relative to summer rain, as well as recent efforts (e.g. Scalzitti et al., 2016) to define elevation thresholds below which reductions in snowpack are attributable to warming temperatures and above which variability in precipitation will remain the main driver of snowpack size. 2) The location of hydro-climatic instrumentation for water supply analyses in Utah (particularly precipitation-runoff relations) would be best-suited in areas proximal to stream channels (where runoff is produced). Similarly, hydrologic modeling of Utah watersheds should focus on small water-producing areas rather than the average of the entire watershed, as the movement of water to deep storage changes from year to year and by location in the watershed. Large portions of the watersheds may not contribute to streamflow either directly or through base flow. 3) Water managers interested in improving water yield from Utah watersheds by increasing the snow catch (e.g. by forest thinning, snow fencing, etc.) may have limited success outside those areas immediately adjacent to stream channels.

As noted by Loik et al. (2004), until quite recently there were an insufficient number of long-term soil moisture datasets in the Western U.S. to explore these relationships. In 2016, the period-of-record editing and quality-control was completed for the hourly soil moisture and temperature data for all SNOTEL sites in Utah. For most sites, the sensors were installed between 2002-2006, though a couple sites' data extend back to 1999, and the average period-of-record length is >10 years. These data provide important support for research projects, water supply forecasting, and other uses and are freely available online (https://wcc.sc.egov.usda.gov/reportGenerator/).

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