HYDROGRAPH CHARACTERISTICS IN RELATION TO LOW, NORMAL AND HIGH SNOWPACKS IN UTAH – A WATER MANAGEMENT TOOL

Randall Julander [1]

ABSTRACT

Long term (>30 year) daily snow water equivalent (SWE) observations enable researchers to establish relationships between various SWE and hydrograph characteristics. The shape and magnitude of snowmelt hydrographs in Utah depend predominantly on the magnitude of the snowpack being melted. As observed, years with low snowpacks melt out earlier, have lower peak flows and lower total flow volume than average or high snowpack years, and vice versa for high snowpack years. However, in relation to melt-out dates at SNOTEL sites, a higher proportion of the annual April-July flow in low years is shifted toward the end of the hydrograph, whereas a larger proportion of flow occurs prior to melt-out in higher snowpack years. This paper examines the timing of peak flow and the proportion and distribution of flow relative to the timing of snowpack melt out at selected watersheds and SNOTEL stations across the state of Utah. The ability to predict the temporal distribution of streamflow based only on the magnitude of snowpack and the melt out date at specific SNOTEL sites could improve water management, especially where limited or no seasonal water supply forecasts are available. (KEYWORDS: SNOTEL, Snow Survey, SWE, hydrograph, peak flow)

INTRODUCTION

In response to the Dust Bowl of the 1930s, the Soil Conservation Service (SCS) was mandated to measure mountain snowpack in the Western U.S and to forecast the water supply for this region. The SCS has since been renamed the Natural Resources Conservation Service (NRCS), and since the late 1970s has converted or added new equipment to nearly 800 of its manual snow courses with automated hydrometeorological stations called SNOTEL for SNOw TELemetry. These stations consist of a snow pillow to measure the snow water equivalent of the snowpack, and a precipitation gage, as well as air temperature, and in many cases snow depth and soil moisture. The SNOTEL network represents the largest network of near real-time hydrometeorological stations in the mountainous regions of the Western U.S. With long-term daily observations, correlations between downstream hydrograph and SWE characteristics can be explored and used for water management.

Water management across the West can generally be put into a few categories: 1) systems with no storage (diversion only), 2) small systems with limited storage, 3) intermediate systems with multiple storage facilities, and 4) large systems with storage close to or greatly exceeding average annual flow. In case 1, water supply forecasts may be used in a general sense to predict whether a given year will be more productive or less productive but the water user has few options to actively manage the resource and simply takes what is available when it is available. However, knowledge about amount and timing of flow can still be valuable in agricultural production. In case 2, the typical management strategy is fill and spill, i.e. to use the direct streamflow as long as possible until supplemental water from the reservoir is required. Of 50 reservoirs and storage systems monitored by the NRCS in Utah, 28 fall in case number 2: fill and spill operations with little or no flood control and mostly hay production (e.g. Big Brush Creek, Ashley Creek and the San Pitch River). Having information about the distribution of seasonal flow (in addition to the total volume from a standard forecast) would allow managers and producers to plan how much acreage and what crops are likely to be most productive. With case 3 (intermediate systems with multiple storage facilities and a flood control requirement, such as the Weber and Sevier Rivers), management becomes more critical, mostly in large snow/flow years. With average or low flow years, management tends to fill storage units where possible, with little potential for spill. In this case, having information on the timing and distribution of flow would be beneficial in minimizing risk. Movement of water from one reservoir to another is possible – in low years keeping the water as high on the watershed as possible allows greater flexibility in delivery, and in high years creating space is the goal. Flow timing and monthly distribution can be critical. On larger systems, (case 4) such as the Bear River, where storage capacities far exceed the seasonal water supply, water management becomes one of distribution. Seasonal forecasts are used to allocate a particular season's water supply or, in the rare case of the system being near capacity when a large runoff year is forecast, management strategy is to release water to

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[1] USDA, NRCS Snow Survey Program, Salt Lake City, Utah, randy.julander@ut.usda.gov

accommodate forecast flows. As such, water managers typically want to have information on the volume, peak flow timing, and distribution of seasonal water supply (normally April through July). Hydrologic models such as those run by the National Weather Service provide this information for calibrated points but are very expensive to operate and maintain. Seasonal (April-July) water supply volumetric forecasts are available from the NRCS on a monthly basis from January through May or June but these give no information on the peak flow timing or distribution of seasonal flow. This paper utilizes historic snow data from SNOTEL and streamflow data from the USGS to determine hydrograph patterns of timing and flow distribution (similar to Fassnacht et al., 2014) that water managers in Utah and perhaps other similar areas can use based simply on snowpack magnitude. This paper investigates the connection between snowpack conditions during high, normal, and low snowpack years, the subsequent time of snowpack melt out, and streamflow characteristics in Utah watersheds. Historically, many water managers in the Western U.S. have used observed snow characteristics at a particular point in time to predict flow, even if such connections were anecdotal. For example, if the "Snow Horse" is visible on the northern Wasatch Mountains above Davis County in Utah in the month of May, it has long been observed that there will be sufficient irrigation water for the year. The "Snow Horse" is a large feature in the snowpack on a ridge that resembles the outline of a horse complete with head, body and legs. It is visible in most years as snowmelt progresses, after which the body disappears and finally the legs. There are many such features that water managers have used as indicators of water sufficiency or insufficiency that have typically been reasonably reliable as a proxy of overall snowpack conditions. With 30+ years of daily snow water equivalent data from the SNOTEL system, specific, quantifiable indicators (such as melt out dates) can be utilized to predict hydrograph characteristics. This allows better water management-particularly in areas that have little streamflow data. Snowmelt streamflow behaves in fairly predictable ways based on the magnitude of the snowpack. Low snowpacks produce hydrographs with smaller flow volumes and peak flows, and normally melts earlier in the season. High snowpacks produce larger flow volumes and peak flows which typically occur later in the runoff season. Based on low, average, or high snowpack conditions, proportions of April-July streamflow can be determined via melt out dates at specific SNOTEL sites along with peak flow characteristics. Another factor that can substantially alter hydrograph characteristics is dust on snow. Dusty snow surfaces decreases the surface albedo, thus increasing short wave energy into the pack greatly accelerating snowmelt. Dusty snow surfaces can significantly change the melt rate of snow and the timing of hydrograph characteristics (Bryant and Painter, 2010).

METHODS

Watersheds were selected by using only those streamflow measurement sites in Utah that had little or no diversions or storage above the USGS station thereby minimizing the effect of basin management on flow (similar to Regonda et al., 2005). There were 17 such unimpaired sites selected and these were fairly evenly distributed across the state. Both high and low elevation watersheds were included and had a variety of aspects and sizes (see also Cooley and Palmer, 1997). SNOTEL sites within or immediately adjacent to these watersheds were selected for SWE data. Annual streamflow data from the USGS were ranked from low to high over the period of 1979 to 2015 (SNOTEL period of record) and the 5 highest, 5 lowest and the 5 years about the median were used to create the high, low and average categories for both streamflow and SWE, hereafter referenced as high, low and average years. It is noted that given many more years of data, a range and probability distribution could be created for each of these classes. These data were then analyzed for timing of SWE melt out, peak flow and distribution of flow by month across the typical April-July snowmelt runoff season. A monthly proportion of April-July flow was also calculated. Peak SWE data were also correlated with melt out dates using linear regression.

RESULTS

A basin average SWE melt out date of the SNOTEL stations used was calculated for high and low years. The average basin melt out date was calculated using the period of record data. The average peak flow date for high, low and average years was also calculated. In low snowpack years, SWE data from the sites investigated indicate that on average melt out dates are accelerated by about 15 days across all watersheds with a range of 9 to 22 days earlier than the average period of record melt out date (Figure 1). Each watershed is slightly different depending on geographic location (south to north), average elevation, aspect and the respective location of each SNOTEL site within the basin. This early melt out has a direct impact on the timing of the peak flow as well as the overall distribution of flow by shifting all streamflow parameters earlier in the season. In the high years, melt out

dates were, on average, nearly 20 days later than the average period of record melt out date for the various sites with a range of 14 to 28 days.

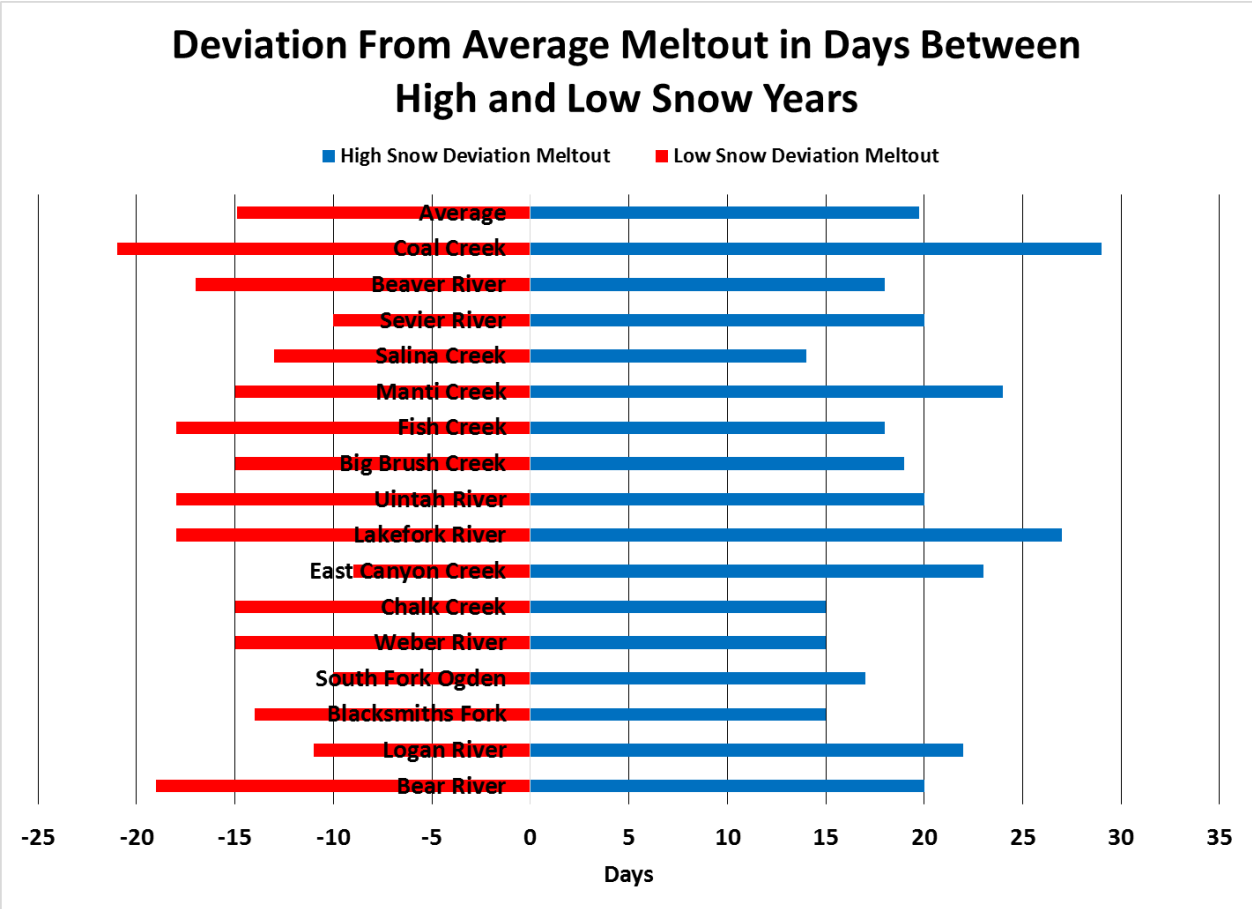

Figure 1. Average deviation in days from period of record average melt out date in high and low snow years for Utah watersheds, with the average positive or negative deviation shown at the top in blue and red, respectively.

R^2 values from simple linear regression between peak SWE and Julian melt out dates for a given watershed range between a low of 0.15 and a high of 0.81 with an average R^2 of 0.55 for all SNOTEL sites in Utah with 20 or more years of data (similar to Fassnacht et al. (2014) for sites in Colorado and Wyoming). Higher elevation sites that accumulate more snow in significant water producing areas generally had higher R^2 values and lower elevation, low snowfall, early melt out sites were generally not as well correlated. Many of the higher elevation sites had R^2 values in the 0.7 to 0.8 range indicating that there is a high degree of predictability in these sites with respect to annual snowmelt characteristics regardless of any other factor. Climatic conditions after the peak SWE accumulation date would likely be the next most significant factor. These results are consistent with other findings for the region and for the intermountain West (e.g. Cooley and Palmer, 1997).

Peak flow data show much the same relationships as do melt out dates: in low years the average peak comes early and in high years, the average peak flow comes much later (by about 13 days each) (Figure 2). The range is very large, however, with low year streamflow peaks between 3 and 33 days prior to normal and the high years between 3 and 22 days after the normal date of peak flow. In some cases (Sevier River and Blacksmiths Fork) there is no definitive snowmelt-induced peak flow in low snowpack years. The low flow hydrograph barely registers any increase in flow during these years, thereby precluding the possibility of obtaining a meaningful peak flow date.

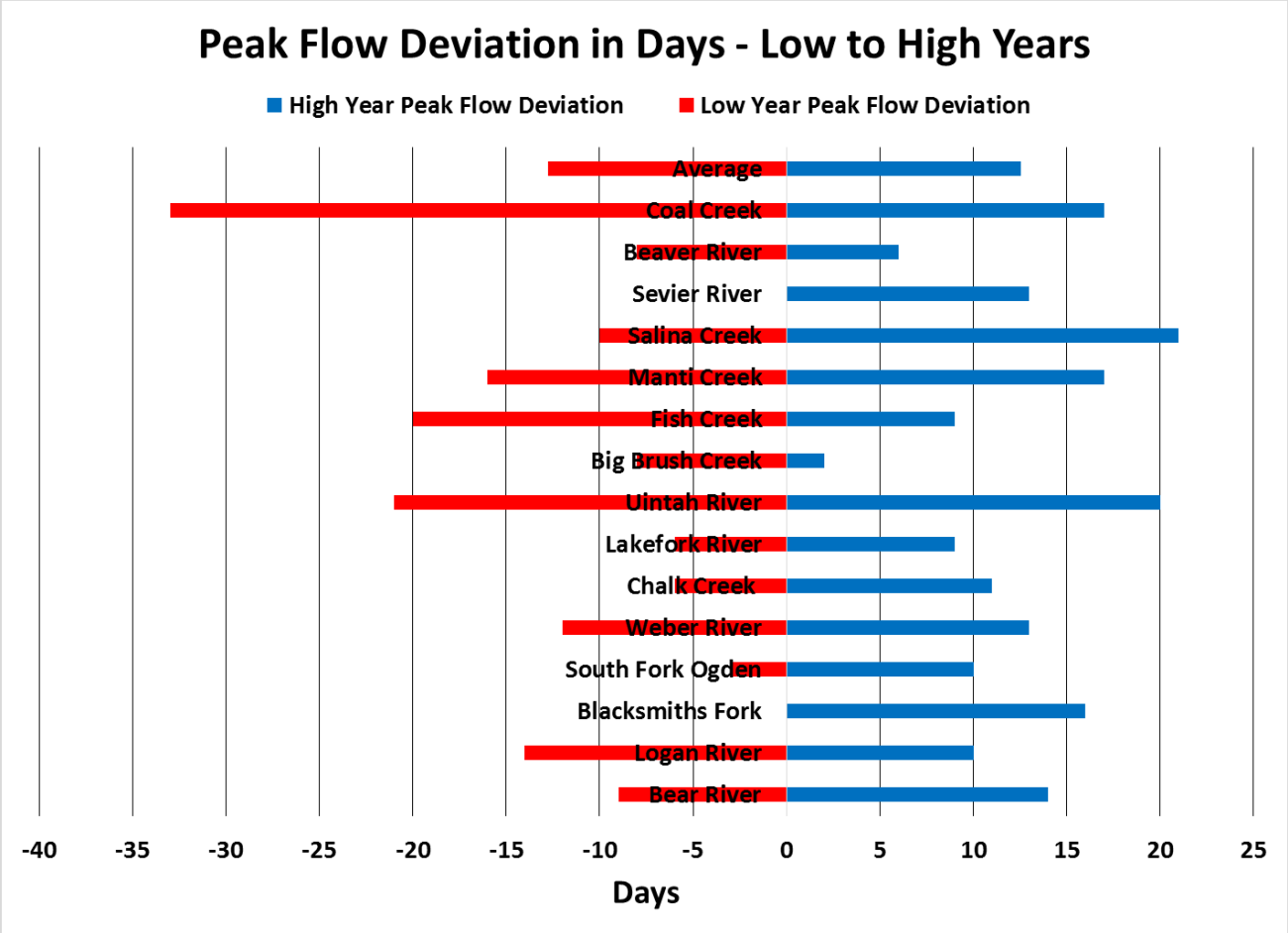

Figure 2. Deviation in days from average Peak Flow date in high and low snow years.

Figure 2 shows the average deviation from the peak flow date of average years of both high and low years for the various watersheds across Utah. For example, the average peak flow date of low years is 14 days earlier on the Logan River and in high years, the peak date is, on average 10 days later than normal.

An example is illustrated in Figure 3 which shows the average daily flow for the low, normal, and high snow year hydrographs for Coal Creek near Cedar City, Utah, and gives a good sense of the magnitude and timing of streamflow under those various conditions. Other, mostly smaller streams may have less defined low flow peaks.

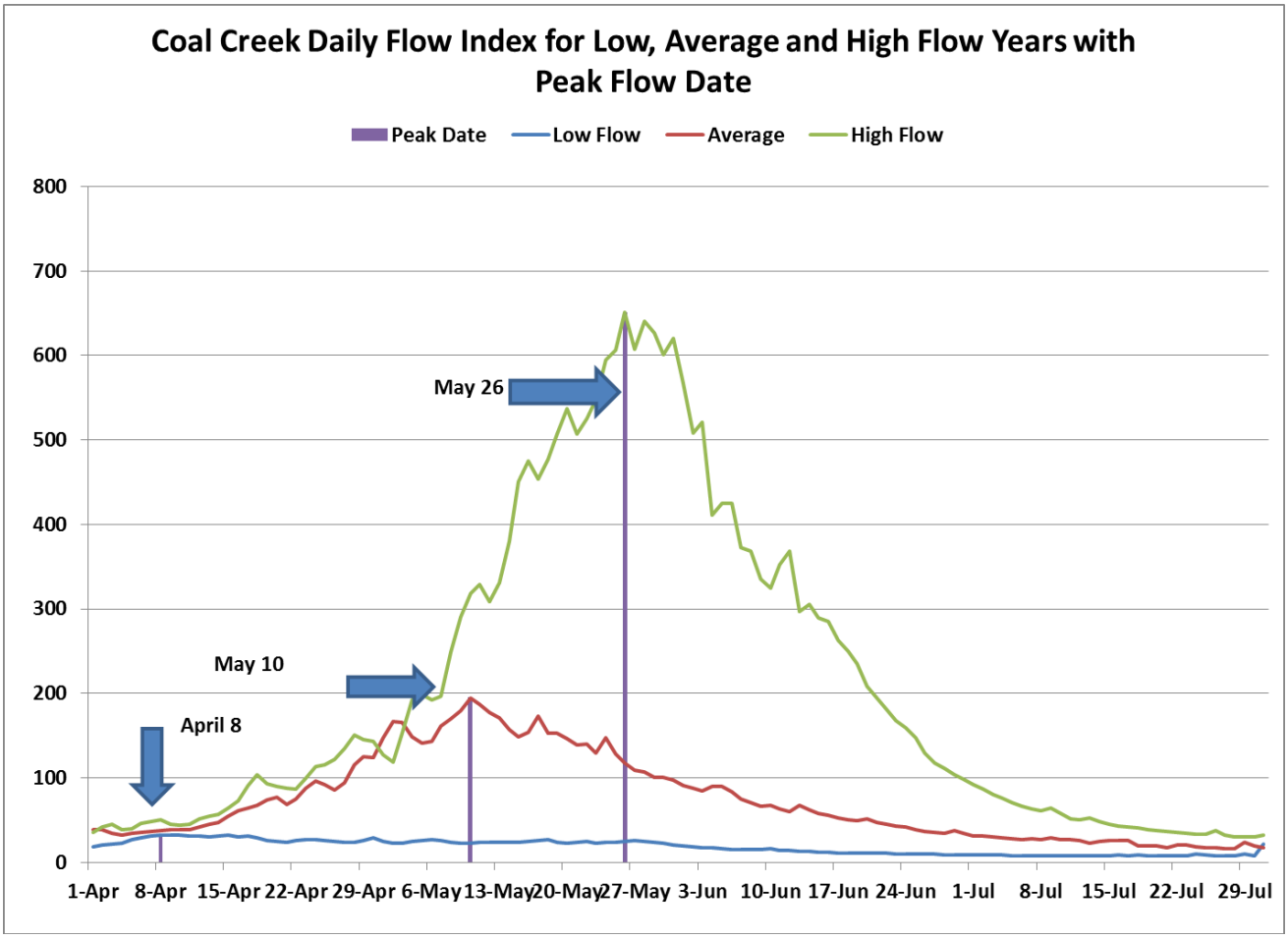

Figure 3. Coal Creek near Cedar City daily average flow index for low, average and high flow years with the associated average peak flow date.

Average daily snowmelt rates were calculated for low, average and high years by starting on that date where a consistent decline in SWE is evident until the site is completely melted out, calculating the total melt for each day and then calculating the average melt rate over that period. Daily snowmelt rates in high years are nearly 1.25 centimeters per day greater (Figure 4) than in low years with a range of over 2 centimeters per day. Also note in figure 4 that there are two watersheds in which low snowpack years have melt rates that are above or close to the average years (Lakefork Basin and Big Brush Creek). A possible explanation is that these two watersheds are primarily southerly in aspect and have only low elevation and high elevation SNOTEL sites. In low years, the lower elevation sites melt out long before runoff begins and typically have very little snow to melt over a short period of time thus potentially over weighting the higher elevation sites in daily melt calculation.

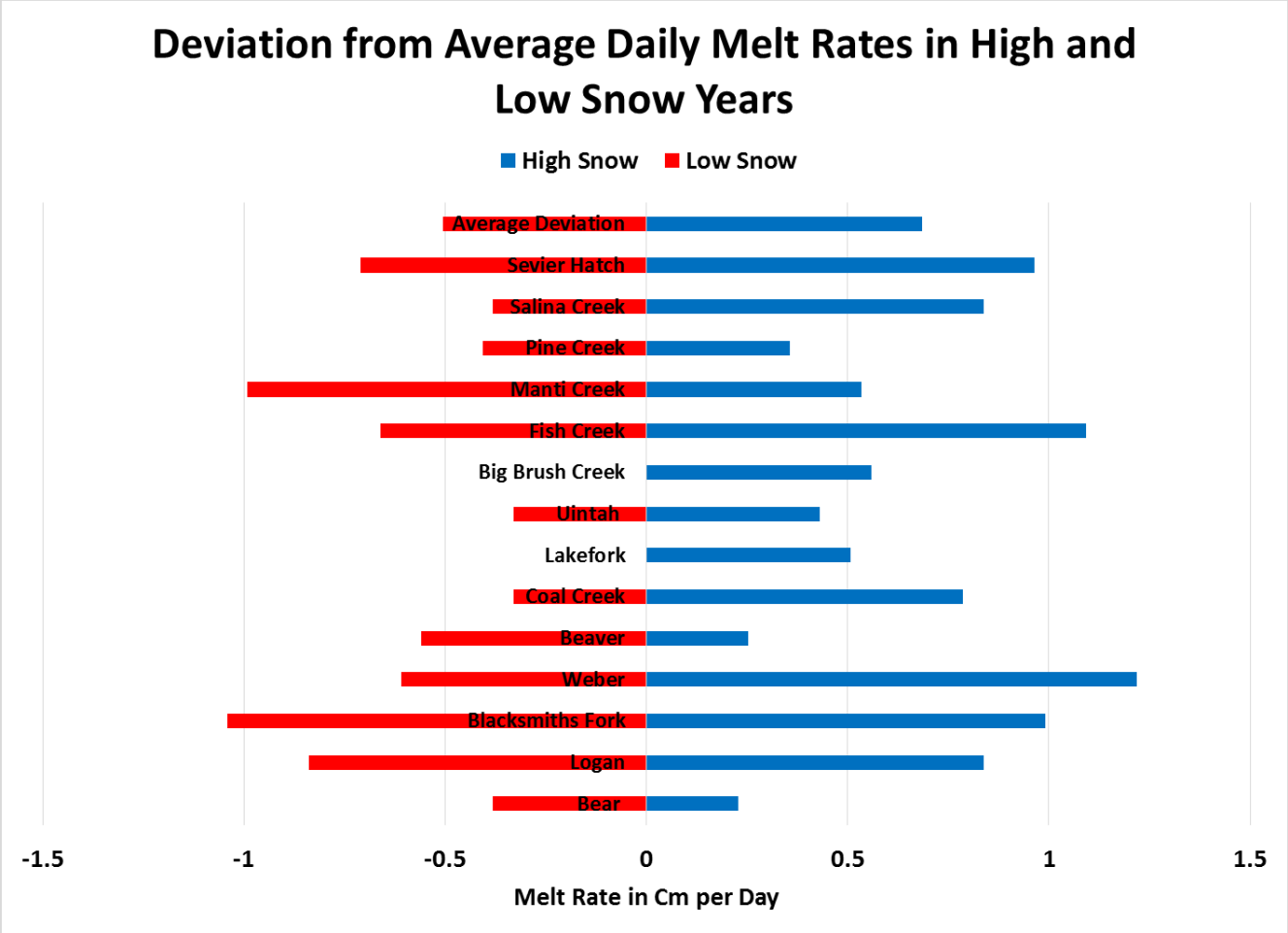

Figure 4. Deviation from Average Daily Melt Rate in High and Low Snow Years.

Low snowpacks require less total energy to melt than large, deep snowpacks. During low snowpack years, the lack of storms contributes to melt because little SWE is added during the critical accumulation months (or during melting). In addition, fewer storms potentially mean more sunny days and more shortwave energy available to melt the snowpack. Conversely, in high SWE years, melt out is delayed by an average of 19 days with a range of 14 to 28 days. In those years, climatic conditions are such that storms are frequent, adding to the pack even during the melting phase and generally delaying the melt period.

Runoff efficiency (the percentage of snow that can be measured as streamflow) in any given year depends on many factors such as snow melt rate, soil moisture content, rain on snow events, how long or short the melt season is, various losses and the magnitude of that year's snowpack. The more snow and the shorter the time frame for melt, typically the greater runoff tends to be. With low snowpacks there is a potential for a longer duration melt period with greater losses to evapotranspiration and sublimation, lower daily melt rates that lead to less soil saturation, less runoff and lower runoff efficiency.

Larger snowpacks tend to accumulate longer, begin melt processes later, and have substantially higher daily melt rates (Cooley and Palmer, 1997). Consistent higher daily melt rates across the total snowmelt period leads to longer periods of and higher soil saturation which in turn leads to a higher efficiency of runoff. Figure 4 shows the difference in average daily melt rates between low and high snowpack years for Utah watersheds. Because snowmelt in high years is substantially delayed—on average nearly 2 weeks later than average and nearly 4 weeks compared to low years—there is more overall energy, both radiative and thermal, to melt the snow (Cline, 1997).

Daylight is longer, the sun angle is more direct and temperatures are warmer thus these deep snowpacks, on average, melt faster than their counterparts with low snowpack totals.

In this analysis, only average melt out dates of the various classifications (low, average and high) are considered but one could use the proportion of a given year's melt out in the same way, such as 50% melt out. This point is pursued at length for the Weber River Basin as follows: in an average snowpack year on the Weber River (Figure 5) when the lowest elevation SNOTEL site (Smith and Morehouse) melts out (near May 11), about 17% of the average April-July streamflow will have occurred. Chalk Creek #2 melts out next about a week later near May 18 with about 24% of the April-July flow having passed by the gage. Chalk Creek #1 and Trial Lake are the high elevation sites in the basin, melting out last and very close to each other on June 8 and 10. In this average year, peak flow is very nearly coincident to melt out of these two sites and at this time about 56% of the April-July flow has occurred. This means that about 40% or a little more of the total April-July streamflow occurs post melt out of the highest elevation stations in the normal year. A water manager can utilize this information to either hold or spill water depending on management objectives.

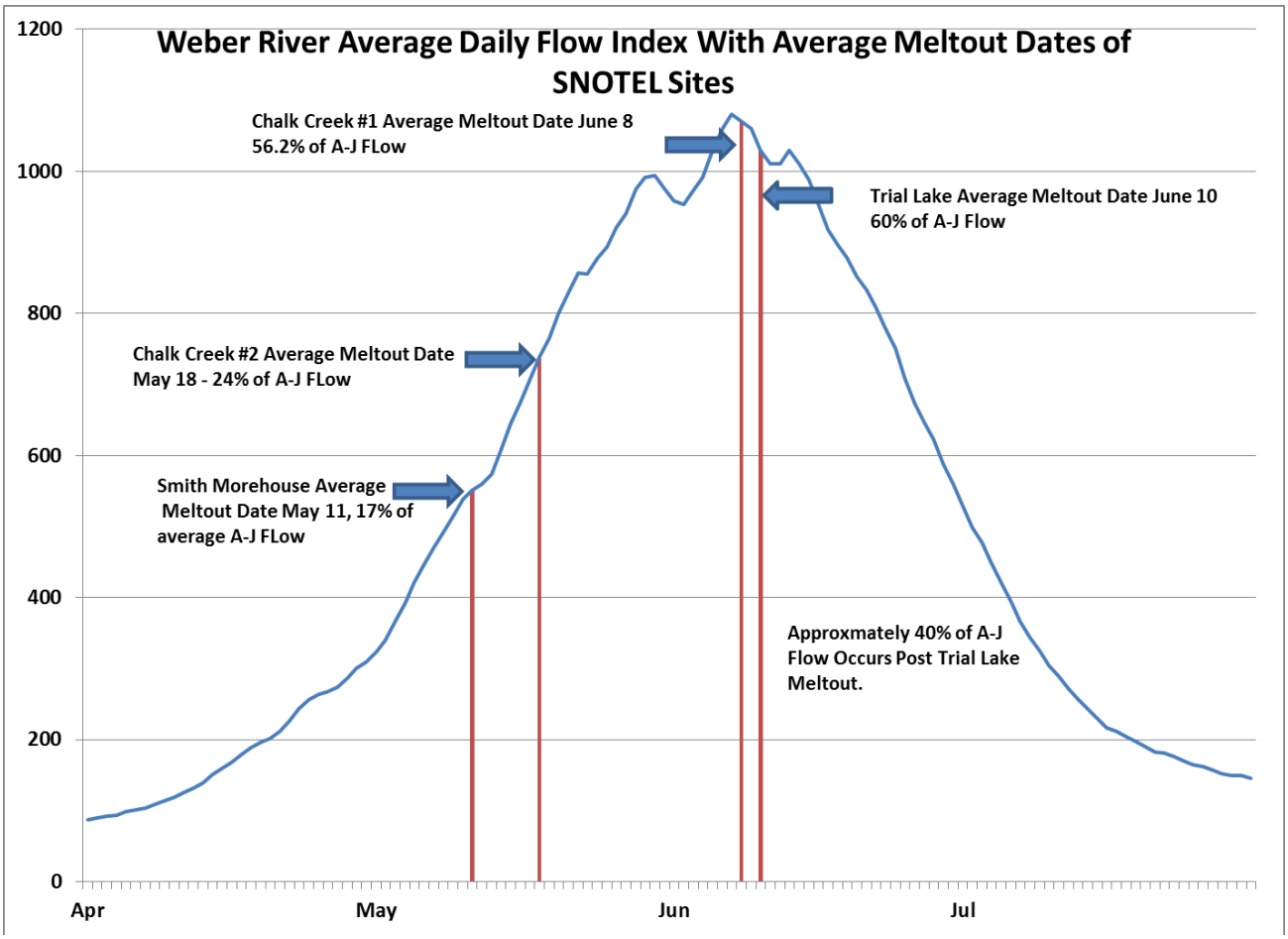

Figure 5. Weber River average year snowpack average daily flow and melt out dates of SNOTEL sites with Percent of total April-July streamflow (A-J).

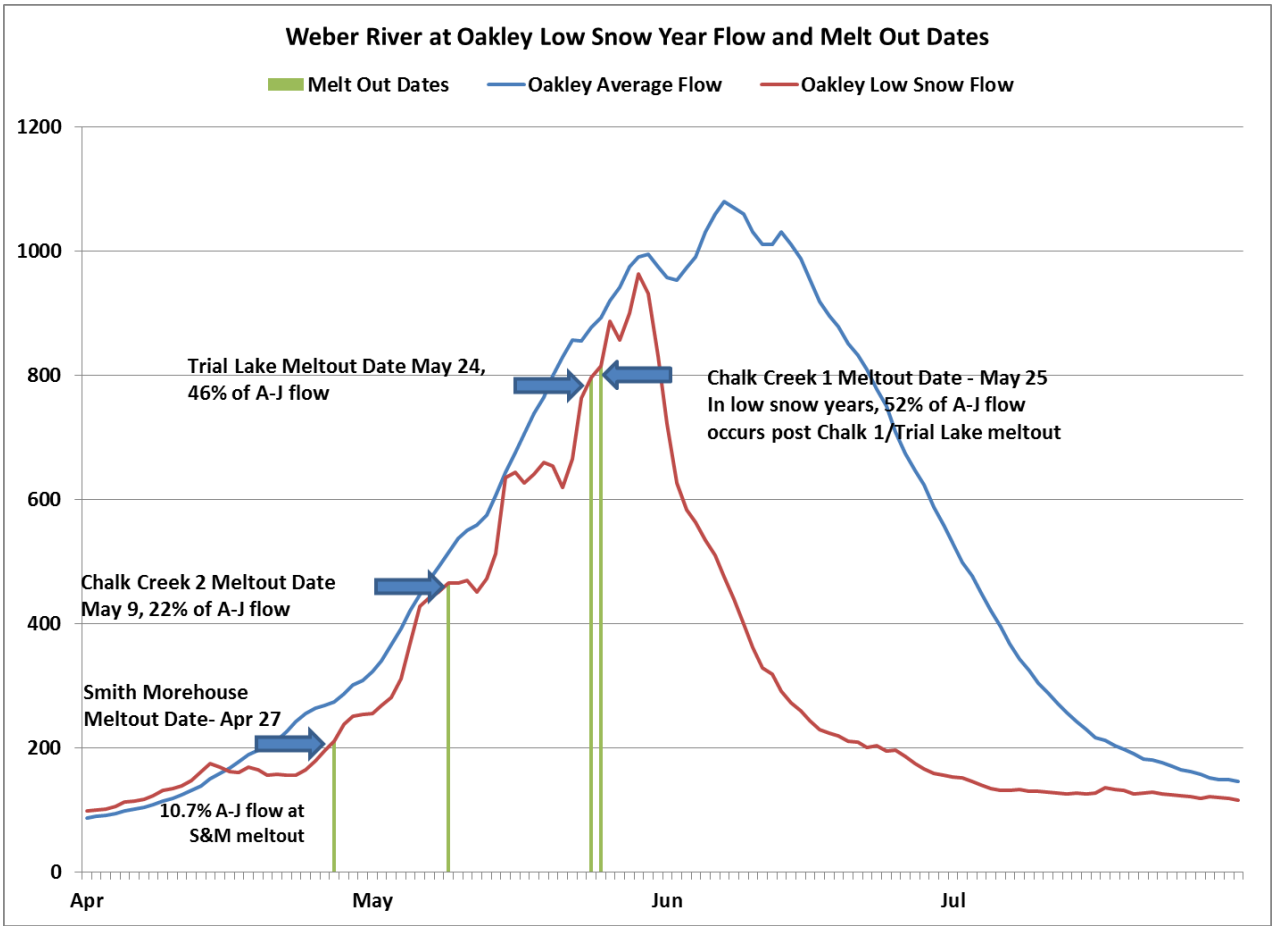

Figure 6. Weber River low snow year average daily flow index and average melt out dates of SNOTEL sites with Percent of April-July Streamflow (A-J).

In low snowpack years for the Weber Basin (Figure 6), the hydrograph and peak discharge are moved substantially earlier in time, as are the snow melt out dates. However, the percentage of overall flow on the melt out of specific sites is much lower. This is a critical observation – proportionally there is more streamflow after melt out than in either average or high flow years, in this case slightly more than 50% of the annual April-July flow occurs post melt out of all sites. Smith and Morehouse SNOTEL melts out in late April with about 11% of the April-July flow, about 6% less than in the average year. Chalk Creek 2 melts out near May 9 with 22% of seasonal flow. Chalk Creek 1 and Trial Lake again melt out concurrently – May 24 with 46% of flow having occurred; instead of being coincident to peak flow, melt out now precedes the peak by a week or so. This means that at the time of melt-out of the higher elevation sites, there is still about 50% to 60% of seasonal streamflow to come (as opposed to roughly 40% for average snowpack years), and peak flow normally occurs within about a week or so post melt out. This distinct forward shift of snow melt out dates in relation to the proportion of April-July total streamflow conveys important information to a water manager. In a water management context, knowing that there is still substantial flow to come after the time of melt out, and having a rough idea of when peak flow will occur, may improve a manager's ability to anticipate critical flow information even if management is a simple fill and spill operation.

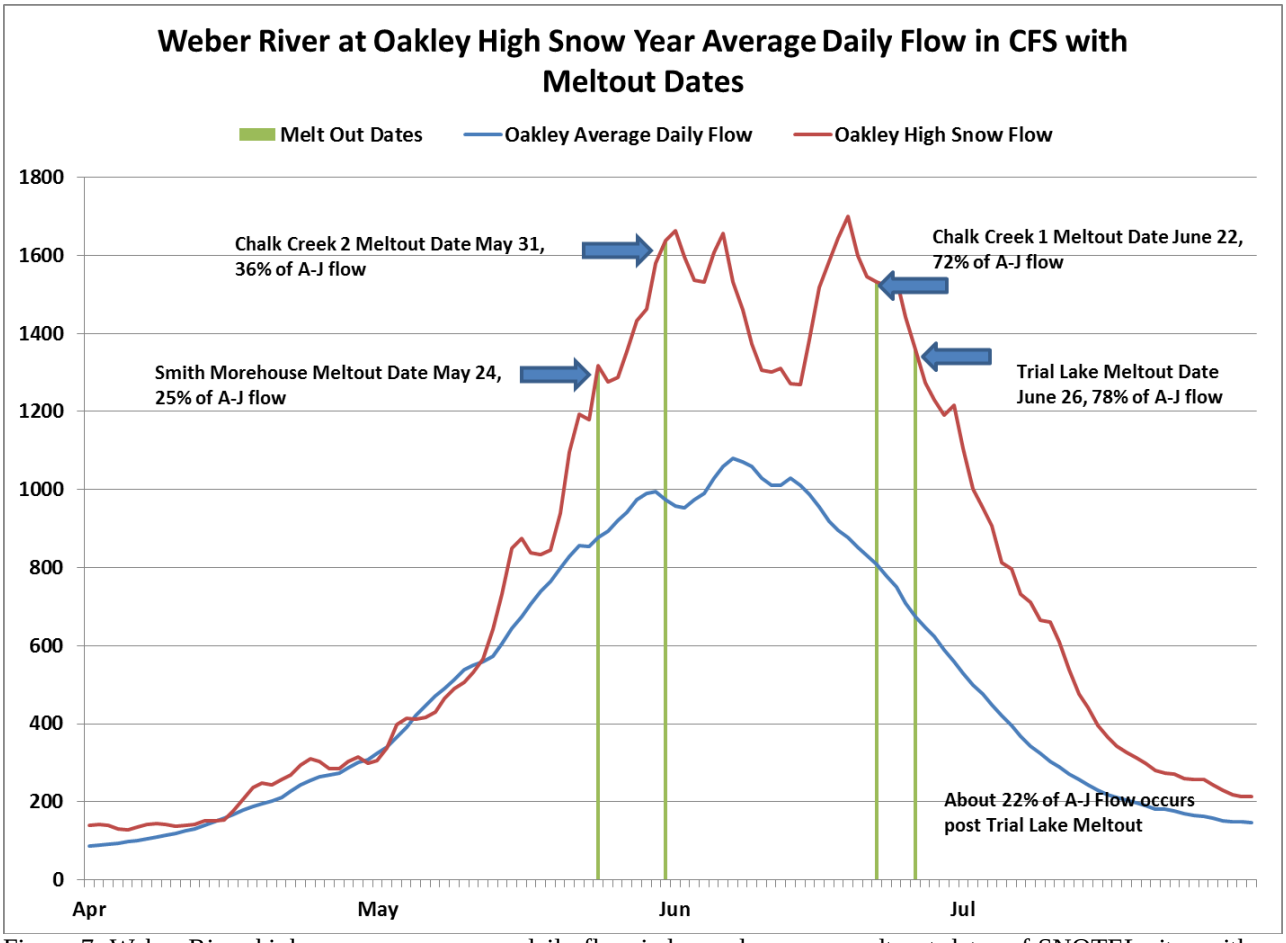

Figure 7. Weber River high snow year average daily flow index and average melt out dates of SNOTEL sites with Percent of April-July Streamflow (A-J). w (A-J).

In high snowpack years for the Weber Basin (Figure 7), the hydrograph and peak discharge are moved substantially later in time, as are the melt out dates. However, the percentage of overall flow on the melt out of specific sites is much higher. The Smith and Morehouse SNOTEL site melts out in late May, near May 24th with about 25% of the April-July flow, about 15% more than in the low year. Chalk Creek 2 melts out near May 31 with 36% of seasonal flow. Chalk Creek 1 and Trial Lake are a few days apart on melt out – June 22 and 26 with 20% to 30% of seasonal flow occurring post melt out (compared with around 40% during normal snowpack years and 50% to 60% in low years). Peak flow can occur anywhere post Chalk 2 melt out but is very likely to precede the melt out of Chalk 1 and Trial Lake. As is common in high snowpack years, mid and late season storm events can dramatically reduce streamflows and melt rates for short periods of time, with cooler temperatures and blocked solar radiation decreasing melt (Clow, 2010). Double peak flows are fairly common in these higher snow years. The shifting of streamflow later in the season may provide additional time for management decisions regarding the timing and volume of water that may need to be discharged from reservoirs to provide flood mitigation.

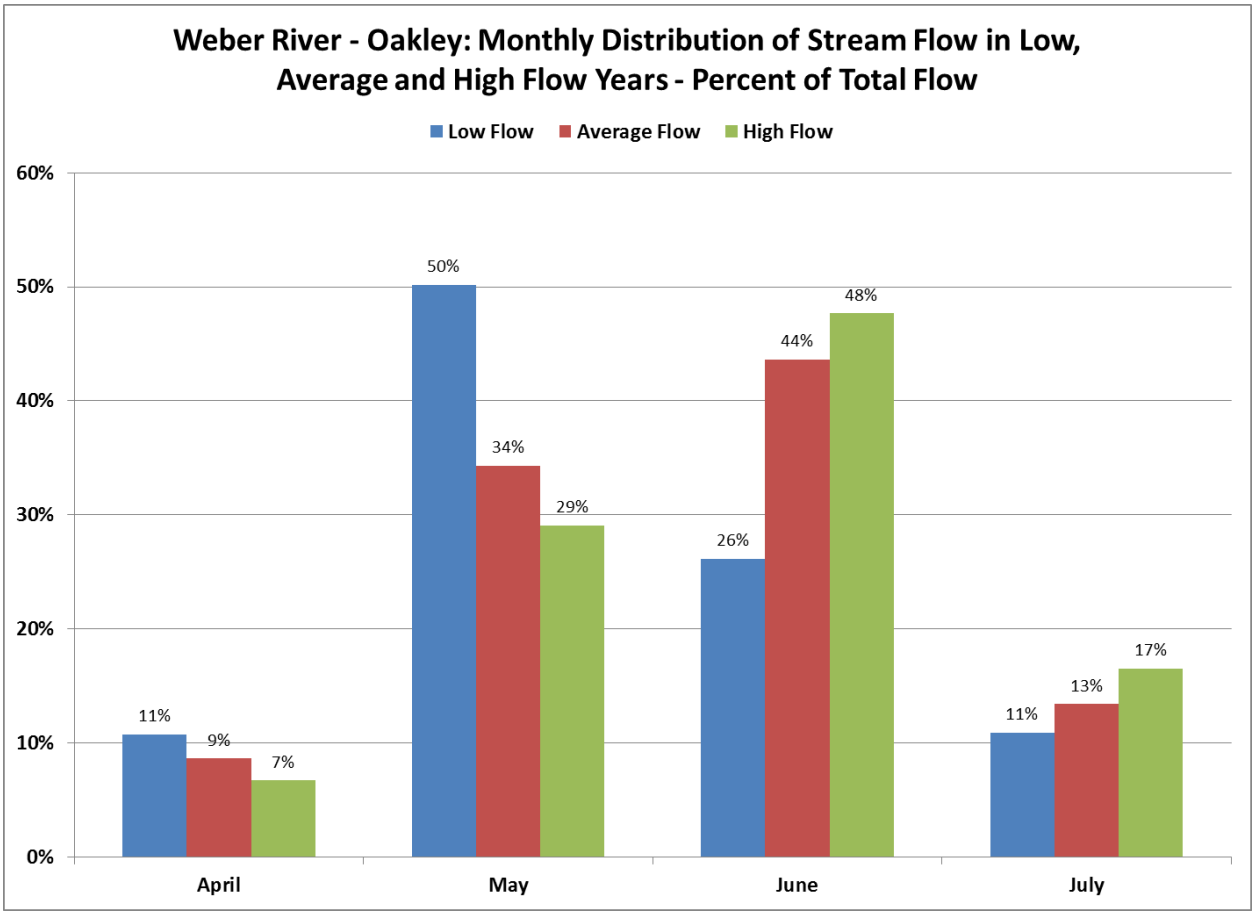

Figure 8. Weber River at Oakley, Utah – Monthly Distribution of April-July Streamflow in low, average and high snow/flow years.

As shown in Figure 8, in low snow years, streamflow is proportionally shifted earlier in the season with 50% of the total April-July flow occurring in May and 26% in June. Compared with high snowpack years—where streamflow is proportionally shifted later in the runoff season—the proportion of flow for low snowpack years is essentially inverted: 29% of April-July flow occurs in May and 48% in June. In all cases, April is the runoff start with a range of flow between 7% in the high years and 11% in the low years. July is also a relatively small month in all cases ranging between 11% in the low snow years and 17% in the high years.

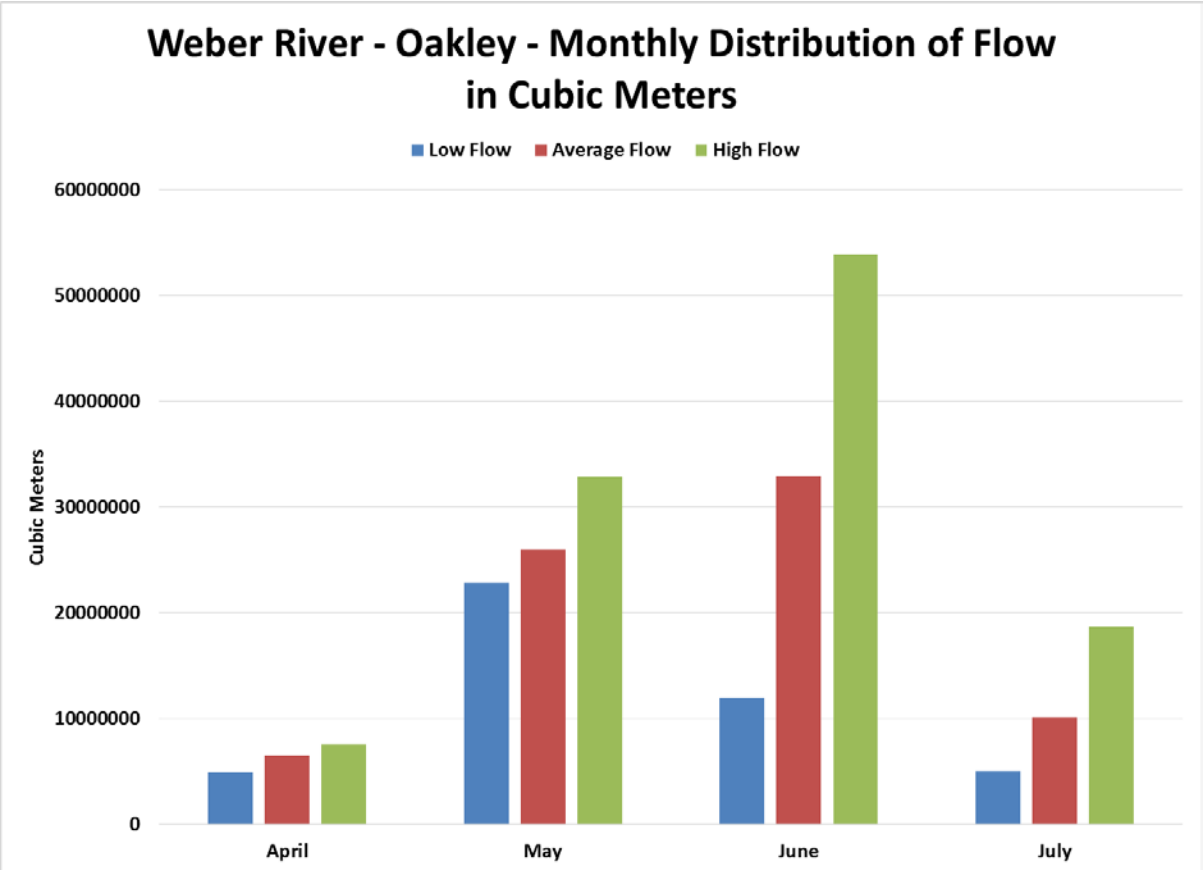

Figure 9. Weber River - Oakley: Monthly Distribution of Stream Flow in Low, Average and High Flow Years – Cubic Meters

While Figure 8 presented the proportion of April-July flow, Figure 9 illustrates the total flow volume for low, normal, and high snowpack years in the Weber Basin. This further emphasizes the shift forward in time for flow in low snow years compared with the delayed response in flow for high flow years. Whereas April flow volume is about the same for all snowpack magnitudes, large differences in flow volume are apparent for May and June, and for all months the flow volume is greatest for the high snowpack years. Hydrograph recession in low snowpack years is well underway in June, whereas during average and high snowpack years this occurs in July.

Importantly, from a water management context, this distribution of flow was similar for most Utah watersheds (although differences in magnitude and hydrograph character were observed). Watersheds of similar elevation, orientation and aspect tend to show similar flow patterns and characteristics (such as the Weber and Bear basins, Manti Creek and Fish Creek). Lower elevation watersheds, such as Blacksmiths Fork, tend to have earlier flow than higher elevation or predominantly north facing watersheds (such as the Bear River Basin at the Stateline USGS gage). Water managers can utilize these patterns during in high snowpack years to make decisions about when and how much water to release to minimize flood potential. In low years, management is oriented towards maximizing storage, and it will obviously be beneficial to be able to predict when the proportion of that year's snowmelt is likely to pass by a given stream gage.

SUMMARY

Considering whether the snowpack is low, average, or above-normal in any given year, this paper has demonstrated that water managers can utilize previous patterns for SNOTEL melt out dates to reasonably predict and quantify that year's forthcoming streamflow hydrograph characteristics in relation to the timing, proportion, and distribution of flow over the April-July runoff period. This method may be refined such that a numerical April-July water supply forecast percent average value may be used to reasonably accurately predict the monthly flow distribution (without the cost of a hydrologic simulation model). More generally, by simply knowing the category –

low, average or high snowpack year, water managers can reasonably predict the timing and distribution of flow. Beyond the clear benefits for water managers in well-instrumented basins, this procedure may be particularly beneficial for areas without active stream gages. Additionally, statistical models could be developed to predict streamflow timing and distribution based on peak SWE and melt out date. They could give forecasts with error bounds, to account for the variability in the relationship.

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