INCREASING CLIMATE VARIABILITY AND THE CLUES TO UNDERSTANDING WHAT MAKES YOUR BASIN FLOW

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ABSTRACT

An increase in climate variability magnifies the challenges for water users, water managers and water supply forecasters. As the demand for water in the west increases, due to competing uses for this natural resource, so has climatic variability. Presented here is a review and reinforcement of past research on long-term streamflow forecast skill levels, examples of recent climate variability in Idaho, key indicators to monitor, and their relationship to historic snowmelt-streamflow relationships. Understanding these key climatic indicators and the amount of remaining snow in the basin results in a better understanding of your watershed and events that generate an increase in streamflow. Past climatic events are discussed to provide a better context for the relationship between melting snow and how a basin may react when extreme weather occurs. With an increase in climatic variability, our predictive power using historic tools has decreased, forcing us to look deeper at the underlying physical properties to understand snowmelt-streamflow relationships. Each basin is different and the sequence of events that produce rapid runoff is becoming required knowledge for water managers and users to understand what makes your basin flow. (Keywords: Climate variability, snow, streamflow, extreme weather, and snowmelt-streamflow relationship)

INTRODUCTION

Water is a renewable natural resource that is highly variable within the water year and from year to year. In the western US, the majority of the spring and summer streamflow originates from melting mountain snow that has accumulated in the mountains each winter. Numerous reservoirs are managed to store water during times of surplus to provide supplemental storage water during the low flow but high summer demand period.

Historically, the major demands for water supply forecasts were for irrigated agriculture, power generation and flood control. Today, demands for water have increased to include predicting flows for whitewater river running, river and reservoir fishing and boating, fish augmentation flows, water rights curtailment, endangered species, and managed groundwater recharge projects. Because of these increasing and often competing demands for water, there is a need to better understand your basin and the key climatic indicators that produces runoff. Add in an increase in climatic variability and the need for better predictive tools becomes more imperative.

Observed recent trends, current research and studies indicate that climatic variability is increasing, generating more extreme weather events in the west. In the past, knowing how much snow was held in the western US mountains was critical for wise agriculture planning. That simple knowledge of the volume of snow in the mountains is not providing the predictive capability we once had. Now understanding the key climatic variables that contribute to runoff and streamflow timing in your basin is just as important to wisely manager this natural resource for today's competing needs. Managers and agencies should be proactive in understanding what makes your basin flow, and this fundamental knowledge will help provide insight into the impacts when extreme climatological events occur.

Discussion

As the Water Supply Specialist for the Natural Resources Conservation Service (NRCS) Snow Survey Data Collection Office in Boise since 1991, I have observed an increase in climate variability, and current research suggests this trend will continue. Analysis of Long-term Trends in Water Supply Forecast Skills illustrated the average skill over a 20-year moving window in the west peaked around 1985 (Pagano, 2005). This is based on analyzing the April 1 streamflow forecasts from 1960-2002. The skill level started decreasing after 1985. Pagano's research took this a step farther to see if spring precipitation was becoming more irregular, staying typical of the region, or becoming more extreme. Analysis showed precipitation in the Pacific Northwest and Southwest was

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becoming more variable for the 1981-2000 period compared to the 1961-1980 period, matching the timing of the decline in streamflow forecast precision. The important question at the time of the study was if this spring precipitation trend would continue to become more extreme or return to the calm, reliable, near normal spring precipitation pattern that occurred during the 1960-1990 period. Since completion of this study, spring precipitation pattern remains in the more extreme range. This increase in precipitation variability in the Northwest and Southwest US regions is reiterated in the National Climatic Assessment Report online data analysis tools with data through 2011 (NOAA National Climate Data Center http://www.ncdc.noaa.gov/cag/time-series/us).

To provide reinforcement of these observations, the next discussion provides examples of recent climatic variability, and events in Idaho and Wyoming that are causing concerns and challenges for water managers and users. Then, climatic relationships coupled with the resulting runoff, and the lessons learned are described. Understanding the climatic inputs and the resulting water volumes and timing will help to better understand your watershed when these events happen. With increasing variability of hydrologic input and timing, it is better to have several tools available to monitor streamflow to provide predictions. Ideally, if accurate streamflow models were available for all basins, then there is less need to understand these relationships, but these will never be perfected, particularly with a moving input target. Developing additional predictive tools to use as a resource provides another level of understanding for your watershed and what makes it flow.

CLIMATIC VARIABILITY AND LESSONS LEARNED

Water Year 2011

Ocean and atmospheric El Niño / Southern Oscillation Index indicators set the stage for a strong 2011 La Niña, one of the strongest signals since 1974. Figure 1 illustrates the snowpack at Two Ocean Plateau SNOTEL site, 9,240 feet, in Yellowstone National Park was tracking the 1971-2000 snow water equivalent (SWE) averages though March. Then, abundant spring storms added moisture to the snowpack allowing the SWE to continue accumulating until June 1, well after the snow usually starts melting. According to the April 1, 2011 Idaho Water Supply Report, 26 SNOTEL stations across the state set new records for the most precipitation received in March and 18 stations received double digit precipitation amounts that month. Spring precipitation, May, June and July, in the upper Snake River basin was record high, 175 percent of average, based on a 17 station SNOTEL precipitation index. This precipitation index starts in 1990 while most individual daily SNOTEL data starts in the early 1980s.

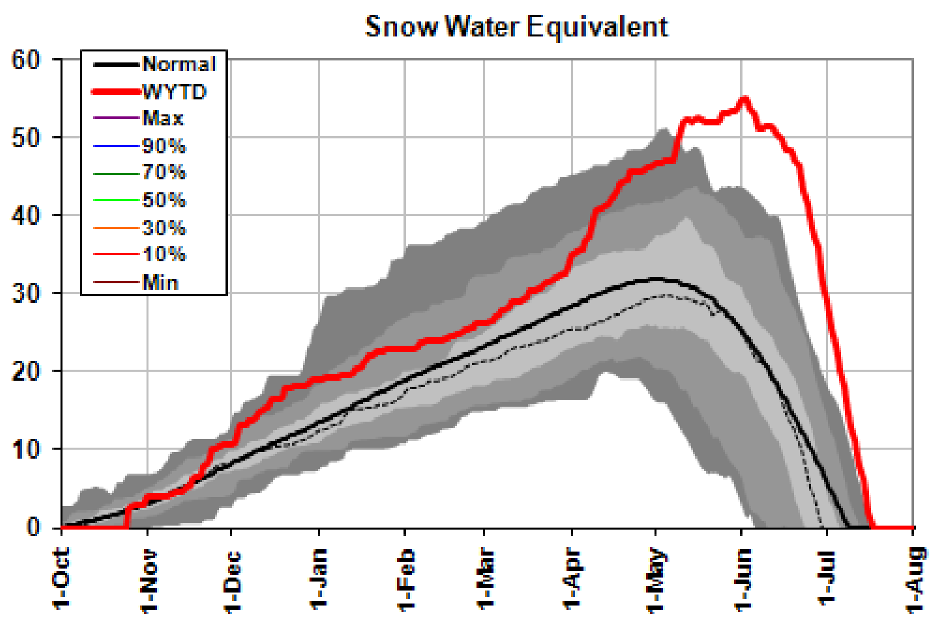


Figure 1. 2011 Two Ocean Plateau snow water equivalent (thick line) peaking June 1 from the delayed melt and wet weather compared to historic averages (thick black line) and different exceedance levels (shaded bands of grey).

Figure 2 shows the daily NRCS volumetric streamflow forecast for the Snake River near Heise, Idaho mirrored the wet trend with the forecast increasing from 110 percent of average on Mach 1 to an observed runoff volume of 149 percent for the April-July period, near record high. The delayed and abundant runoff was a challenge for water managers to manage and mitigate floods by not filling the reservoirs too soon. However, just over the Snake River divide in Montana, abundant and record high spring rainfall pushed the Yellowstone and Missouri rivers to near record high levels. The 2011 irrigation season came to a close with another record being set, near record low reservoir storage water was used because of the extremely high natural flow levels. The abundant reservoir carryover storage set the stage for the 2012 season, but also raised concerns if another wet year were to occur. Other positive and negative impacts include delayed recreational access to the summer high country, flooded county and forest roads, extended rafting season, excess hydropower, and few forest fires.

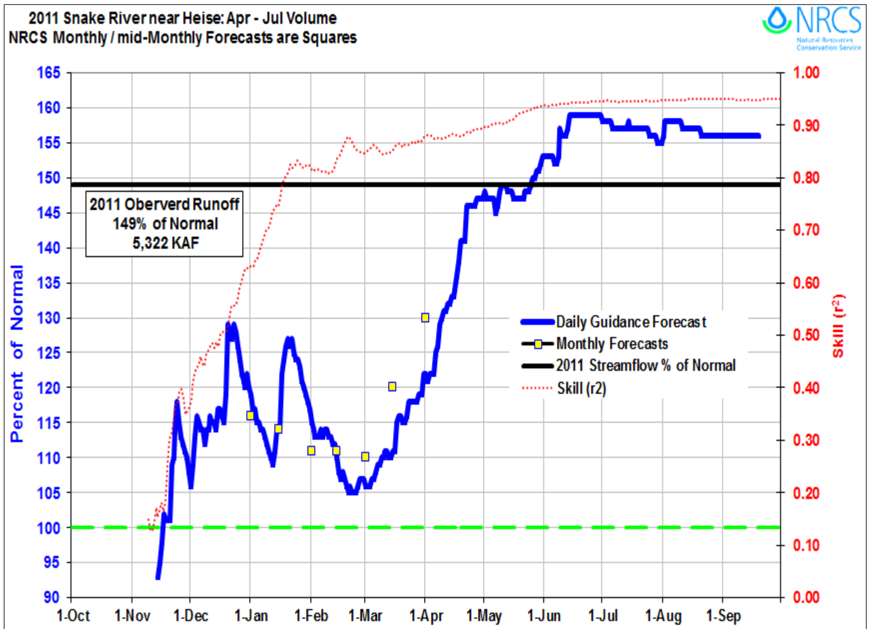


Figure 2. 2011 Daily water supply forecast volume (thick line) and skill level for the Snake River near Heise illustrating the rapid increase in expected volume from the delayed snowmelt and wet spring.

Water Year 2012

Water year 2011 ended with above normal baseflows across most of the state. The downside was water year 2012 started with few fall storms and minimal snowfall across the west as illustrated in Figures 3 and 4. Lack of snow prevented many ski areas from opening until mid-January and made it a challenge for winter recreationists and business which rely on winter snowfall and tourists that support many western communities. Idaho's Bogus Basin Mountain Recreation Area had its latest opening ever on January 19, 2012.

By mid- January, a major storm was predicted for most of the West. The storm brought several feet of snow and joy to winter recreationists and business that rely on snow. The snowpack in the low elevation drainage of the Owyhee basin in southwest Idaho was at record low SWE levels in mid-January 2012; daily data starts in the early 1980s. This series of storms brought over four inches of snow water in a two week period and provided more than half the total snow water content for the season (Figure 5).

This precipitation pattern of larger storms providing more of the annual total snowfall amounts appears to be more common. It is observed by looking for the stair step increase in snow water content observed in recent years and as seen in Figure 5. This pattern of more extreme precipitation events also supports the research by Kumar et. al. (2012) who concluded that more of the annual snow water is coming from more intense but less frequent storms and the work of Magney et. al. (2012) that illustrated spatial and seasonal increases in the maximum daily precipitation events in Idaho.

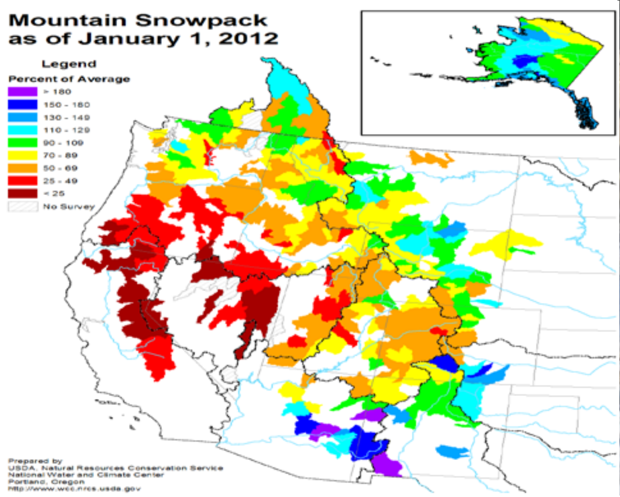


Figure 3. January 1, 2012 snowpack map as a percent of 1971-2000 average with amounts ranging from less than 25 percent in California to nearly 90 percent for most of the west.

Figure 4. Future Snow Surveyors sampling manmade snow January 13, 2012 at the 62nd NRCS West Wide Snow Survey Training School in Tahoe City, California.

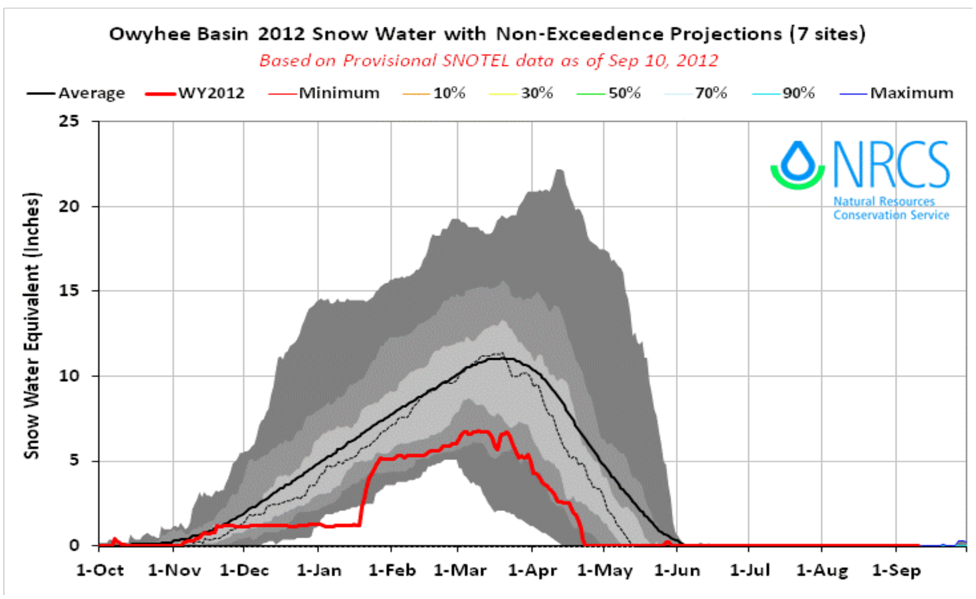


Figure 5. Seven station snow water equivalent index for the Owyhee Basin comparing the bold 2012 levels to historic averages and exceedance levels.

March 2012 continued this trend with more extreme weather across Idaho, especially in Idaho's central and western mountains, namely the Boise River basin. According to the April 1, 2012 Idaho Water Supply Report, warm storms set precipitation records at 25 SNOTEL sites, started melting the snow two weeks earlier than normal and initiated snowmelt in the mid-elevation stations across the state. This is key information for water managers – the snowpack is ripe and melting at higher elevations than usual for this time of year.

The May 1, 2012 Idaho Water Supply Report stated that the back to back 91 degree temperatures on April 22 and 23 at the Boise Airport were record highs. This is another combination of key conditions that water managers should look for in Idaho: unusually high temperatures for time of year with good snow coverage still in the mountains. This hot spell produced 70 degree mountain temperatures at SNOTEL sites and continued melting the snowpack in the low and mid-elevations. Using long term Boise weather station data as a gauge, this heat wave was likely the hottest in April since 1875 when records began. The temperatures fell just one degree shy of the all-time April temperature record of 92 degrees. Then, on April 26, 1 to 2 inches of rain fell up to 8,500 feet in Idaho's central mountains. Figure 6 illustrates how streams responded in this region. The Boise River near Twin Springs increased to record high levels for this time of year – another key for water managers. This station's record dates back over 100 years and also supports this unique climate event's ability to produce record high flows.

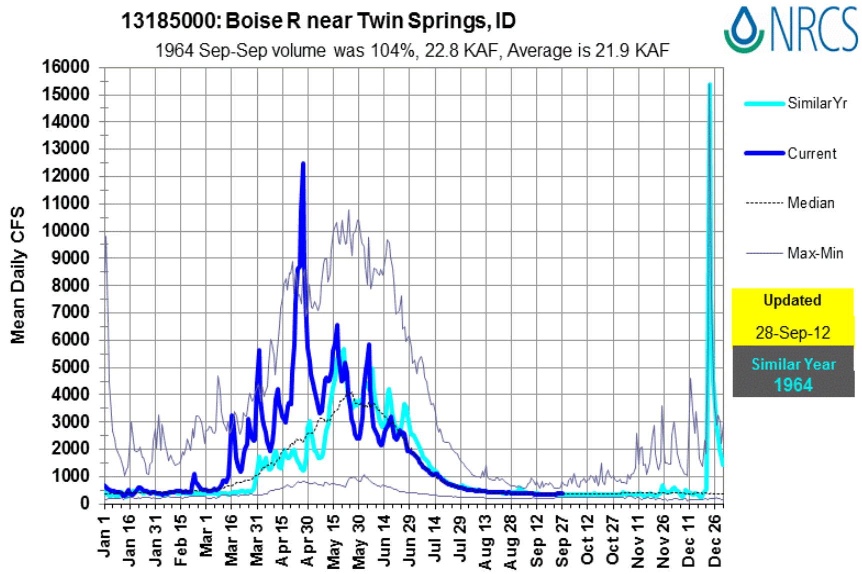


Figure 6. 2012 Boise River near Twin Springs illustrating the spring rain-on-snow event compared to the 1964 winter rain-on-snow event.

These hot temperatures and high levels of rainfall produced snowmelt rates of one inch per day, record high melt rates for this time of year – another key for water managers. Figure 7 illustrates normal melt rates in mid-April of 0.3 inches per day at Jackson Peak SNOTEL site. This climate event pushed the melt rates to record high levels for mid-April, the magnitude of melt rates normally seen in mid-June. In order to fully understand the influence these rates have in producing runoff during extreme events, knowledge can be gained by closer monitoring of snowmelt rates in your basin just like we monitor and talk about daily precipitation amounts.

Research by Bond (2012) also showed the frequency and occurrence of 3-day maximum and minimum temperatures are becoming more common. This level of persistence of more extreme temperature events is another key for snow watchers and water managers. Lessons learned show that 1-day of record high day or night time temperatures may not be enough to influence or change the snowmelt pattern much. However, several days of record high temperatures on a snow covered basin is enough to significantly influence the melt and increase streamflow levels. Timing of these climatic events is critical. If record high temperatures or rain events occur outside the critical snow melt season, it may become a non-runoff event and is not a major concern of water managers, but becomes a concern of others, such as irrigators and power providers. This timing needs to be coupled with the amount of snow, both in magnitude and extent. These coupled parameters form a pattern of "if **this** happens **when** this is present" that may be unique to each basin.

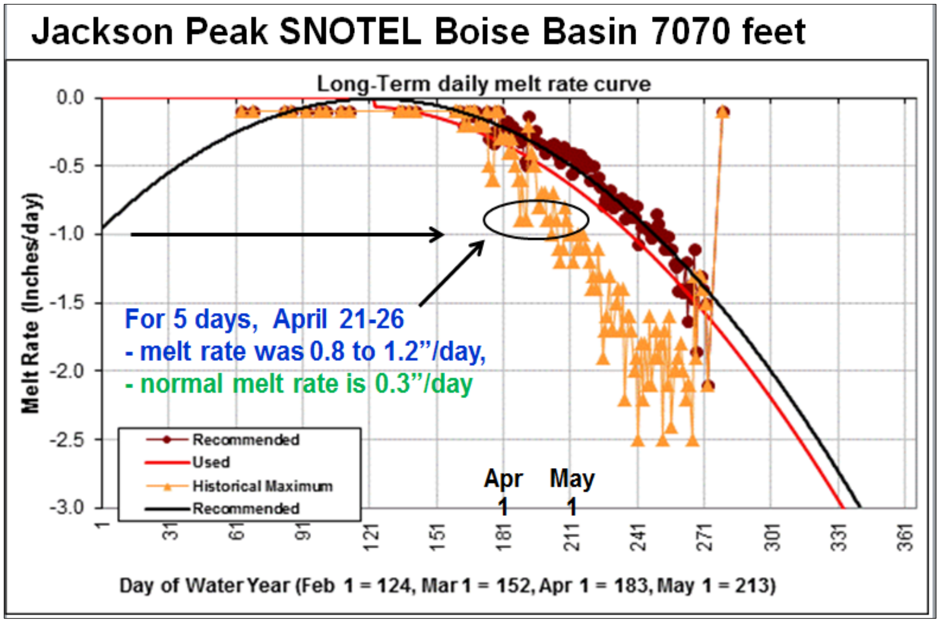


Figure 7. Comparison of April 21-26, 2012 daily snowmelt rates to normal and historic maximum melt rates at Jackson Peak SNOTEL site.

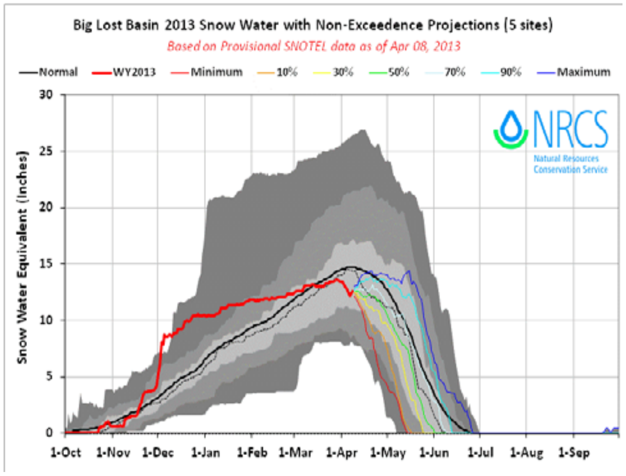
The key for water managers is not just knowing about these climatic events that accelerate snowmelt rates but understanding the impacts they have on a snow covered basin or partially snow covered basin. Knowing the elevation of the snow covered area in the basin is the key to understanding the impacts these climate events have on the remaining snow. Without this snow covered area in the watershed, or a much higher snowline that is more typical of late May or early June, the runoff associated with these events would be different or a non-event.

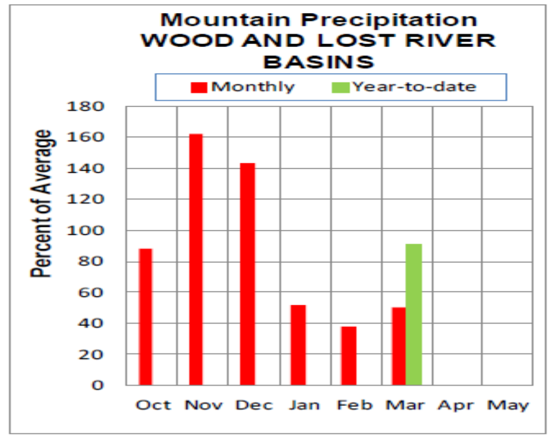
Water years 2011 and 2012 were polar opposites in terms of how the snow fell and runoff occurred. Late snowfall in 2011 produced late runoff volumes and high streamflow levels well into summer and fall. Record high April temperatures in 2012 combined with abundant spring rain resulted in early peak flows, and low streamflows by summer's end across southern Idaho, setting the stage for forest fire potential and more wild weather in 2013.

Water Year 2013

October moisture finally put a damper on Idaho's 2012 fires season. These fall storms continued to strengthen in November and December and brought valley rains and a distinct snowline elevation of 6,500 feet in Idaho's central mountains. This resulted in record high SWE in the higher elevations of central Idaho by mid-December with snowpacks at 130-160 percent of average. This storm pattern was unique with 2-4 feet of snow falling above 7,000 feet and rain falling below 6,500 feet. This weather pattern allowed a handful of SNOTEL sites below 6,500 feet to be at record low SWE while higher elevation sites were simultaneously at record highs. This distinct elevation gradient with higher SWE amounts in the higher elevations remained into the spring and provided increased runoff during snowmelt. Thus, the sequence of events is important. Some of these sequences persist through the accumulation and runoff phases, and some occur, and do not impact the final runoff outcome at all. Sequence is a very difficult factor to determine ahead of time, it is most often observed after the runoff season or by local observers, avalanche forecasts, or water managers working or recreating in the mountains with a keen eye and understanding of the impacts on their local water supply and peak flows. Much of my knowledge about the current year's snowfall patterns is acquired from locals that live, work, play or recreate in their watershed.

The October-December precipitation was the second wettest in the last 30 years at three central Idaho SNOTEL sites and made this one of the best starts to winter accumulation since daily SNOTEL records. However, the climatic spigot turned off for the rest of season, with these same central Idaho basins receiving record low amounts, only 2-4 inches of snow water between January 1 and April 1. Across Idaho, 11 SNOTEL sites were record dry for this mid-winter period, and another 24 had their second or third driest mid-winter snowfall since records start in the early 1980s. Figures 8 and 9 illustrate the record high snow water amounts and historic exceedance levels for an index of five sites in the Big Lost basin, and the record high monthly precipitation in early water year 2013, followed by record low monthly precipitation amounts in mid-winter.





Figures 8 and 9. Water year 2013 record high snow water amounts in the early season, compared to historic exceedance levels that were followed by record low monthly precipitation amounts in January, February and March.

THE OPERATIONAL PHASE AND KEY CLIMATC INDICATORS

The planning phase for water managers is when the January through April monthly volumetric streamflow forecasts are used in conjunction with reservoir operating curves to determine appropriate storage levels. The planning stage is when many decisions concerning the amount of water available for the coming season are made and sets the stage for operational phase. The operational phase is when the snow starts melting in the lower elevations and the annual runoff starts. These different phases require water managers to emphasize different metrics about their basin. While high day or night temperature may be of interest in May, these high temperatures may play only a small role in runoff generation in late July.

In the past, volumetric streamflow forecasts provided the key to wise water management, and crop selection and planning. The increase in climatic variability and variable spring weather, along with increasing water demands makes it challenging for those in the water business to make multi-faceted decisions using monthly volume forecasts alone. This has increased requests for additional tools that better predict the magnitude and timing of snowmelt runoff. Each spring, when the snow starts melting, our office receives numerous inquiries about peak flows, asking if the peaks have occurred, and what is the potential for another peak.

During the operational phase, reservoir operators are watching inflows and delicately balancing storage levels by following operating curves to ensure refill while still mitigating flooding. Snowmelt is in full swing, streamflows are increasing and water managers are using all current available data. This includes streamflow models, correlation tools, short and mid-length weather forecasts, analog years based on current El Niño / Southern Oscillation Index / Pacific Decadal Oscillation conditions, and more. These are used to wisely manage water supplies while trying to outguess nature and the spring weather that drives mountain snowmelt.

Today, with greater uncertainty in the weather, there is a need for more operational tools to assist managers with short lead time tools to provide a better understanding of what may happen. The following analyses are examples of the tools that have been developed and used over the years in different basins to help answer these questions posed when the snow starts to melt.

Key Precipitation Thresholds

In Idaho, we have learned that one or two months of below normal precipitation does not impact the water supply too much, but two or more consecutive months with *below* normal precipitation can significantly impact the annual water supply. This is often an early indicator of the onset of a drought in the winter or summer months.

Brundage Reservoir SNOTEL Site has received more than three inches of rain in 24 hours when snow was on the ground: January 1, 1997 and June 3, 2010. Each event resulted in major flooding in the area. However, receiving over two inches of moisture as snow or as rain with *no snow* on the ground resulted in non-runoff events. In the Henrys Fork, a May 2010 spring rain event *with snow* on the ground resulted in low elevation flooding from 1.5 inches of rain in 24 hours.

The use of precipitation runoff curve numbers in a snowmelt runoff model provides valuable information about spring rainfall intensity rates and volumes needed to produce runoff in the Big Wood River basin. Using these curve number models, we have learned it takes about three-quarters of an inch the first day followed by about a third of an inch the next day to produce runoff, when snow is on the ground.

Each basin is unique and knowledge learned in one basin about precipitation intensities can be generally applied to a nearby basin, until a more robust analysis can be completed. Analysis and documentation of past events provides a better understanding of the conditions that produce a peak runoff. These are infrequent events; applying them to adjacent basins must be done with appropriate caveats.

Snowmelt-Streamflow Relationships

The key is snow falls, accumulates and melts consistent from year to year and decade to decade. Relationships have been around a long time. On June 17, 1806 Lewis and Clark was forced to retreat back to Weippe Prairie in Idaho because of the numerous storms that deposited 10-18 feet of snow in the Lola Pass mountains (Preston, 2006). The party had to request assistance from Nez Perce guides and was unable to continue their return trip home until June 24, after the rivers came up for several weeks which meant the snow melted over Lola Pass.

Since the mid-1990s, Idaho has used several snowmelt relationships as a guide to provide insight on snowmelt streamflow peaks for numerous managers (Sarantitis and Palmer, 1988). The timing of Banner Summit's half-melt is a popular relationship as it reliably predicts the snowmelt peak flow for the Middle Fork Salmon River. This relationship performs well in wet years and dry snow years and still holds true after many recent large forest fires in the basin. Half-melt is when half the annual or peak snow water content has melted.

With just three years of data, a similar relationship is appearing on the recently installed Grand Targhee SNOTEL site. This site was used to accurately predict the peak flow date on the Teton River several weeks in advance during the big 2011 runoff year. Snowmelt rates were projected based on average daily SNOTEL temperatures to determine the when 45 percent of the snow would be melted. This is when the Teton River reaches its snowmelt streamflow peak.

The Big Lost River in central Idaho peaks four days after Lost-Wood Divide SNOTEL site melts out on average. This is also consistent with the locally known snowmelt pattern of the 'Big Lost White Stallion' appearing on a mountain side when the snowmelt peak flow has occurred.

The US Army Corps of Engineers uses receding snow covered area data to assist with final fill of Dworshak and Boise basin reservoirs. Additional research is needed to investigate the use of daily satellite images to determine the snow covered area and assist with final fill of these reservoirs. Knowledge gained from tracking the retreat of snow covered area in your basin also provides a better understanding of the snow line elevation and potential impacts when extreme precipitation or temperature events occur during the critical snowmelt season. A simple hypsometric curve of elevation versus area can be applied when the approximate snowline elevation is known.

To assist water managers in the Big Wood basins, knowing there is still snow at Dollarhide Summit SNOTEL site is a key indicator, and means the potential for another streamflow increase or even a peak flow still exists. To reduce flood worries, this analysis was taken a step further to assist local emergency managers concerned about flooding on the Big Wood River. The Big Wood River at Hailey, Idaho has never been at flood stage unless there is snow on the Galena Summit SNOTEL snow pillow. In one year, the river receded below flood stage the day before Galena Summit melted out. This is a simple relationship to determine, but a very helpful piece of information when you are fighting a flood.

Having different tools to predict peak flows provides a range of dates and is useful to better understand why one technique works better than another in a given year. Similarly it is better to use several SNOTEL sites at different elevations rather than just one site to examine peak flow timing. If streamflow models are available, this information can be used to verify the potential for another streamflow increase from snowmelt. The different ways of looking at the same question provide an envelope of dates or flows and help managers understand the variability of the information.

Critical Streamflow Thresholds

Threshold forecasts are used to provide additional information about a stream regarding when it may reach a certain level. These analysis tools are useful under normal runoff years but can also provide information and benefits to end users during extreme climate periods.

In the upper Snake basin in Wyoming, equations to predict the number of days of inflow to Jackson Lake above 5,000 cfs were developed to assist water management professionals. The 5,000 cfs level is used as a threshold as it becomes more challenging to mitigate downstream flooding when the lake is full and downstream tributaries are flowing high from snowmelt. In the Boise River basin, if the Boise reservoir system is approaching full, knowing when inflows will decrease below approximately 9,000 cfs is useful as a threshold forecast. This is the outflow level water managers can move through the canals while keeping the Boise River below the 7,000 cfs flood stage level.

Low flow forecast are beneficial to irrigators to determine water right cut off dates, and to river runners to know when low flow boating levels will occur. In the Boise basin, knowing when the natural inflow to the dams decreases to 1,800 cfs is critical as it signals that irrigators must switch from natural flow to their 'banked' reservoir storage rights. A forecast of the timing of this low flow tells irrigators when their storage water may run out and encourages water conservation and wise crop selection in low runoff seasons such as 2013.

Peak flow forecasts are not needed in all basins. The Little Lost River water users are less concerned about peak flows because there is no reservoir to store water in this basin. However, there is a need for recession flow forecasts to predict water right cut-off dates for irrigators. A low flow forecast of 800 cfs, approximately 2.0 feet on the stream gage, for the Middle Fork Salmon River is useful as this is the level when river runners and outfitters start to fly passengers and gear to downstream put-ins to extend the limited river running season, a decision that also increases the cost of river trips. Peak and low flow forecasts are also used by the Nez Perce tribe to monitor employee safety regarding when to install fish traps, or remove them to prevent damage from high flows.

Washington Water Power, now called Avista, had a tool they used to provide guidance in filling Coeur d'Alene Lake each spring. Analysis of past years had showed the lake should be full when the Sunset SNOTEL site decreased to 13 inches of snow water, otherwise, without rain, there was not enough runoff to fill the lake and maintain required outflows. Unfortunately, site characterization around the Sunset SNOTEL site changed due to nearby logging and this in turn changed the key snowmelt-baseflow relationship.

Critical Temperature Thresholds and Influence on Snowmelt Rates

Advancements in extreme weather forecasting seem to be on the increase as record high temperatures are now forecast several days to a week in advance. These improved forecasts are key indicators for water managers to use during the critical snowmelt season and associated impacts from rapidly melting the remaining snow, especially if streams are already full. Just as important, but often not in the news until after the event, is extended period of record high night time temperatures, or extended periods when mountain temperatures do not drop below freezing at night, allowing the snow to melt 24 hours a day.

Tracking the receding snow cover area in a basin is critical during the snowmelt season especially with an increase in climate variability. Use of daily MODIS satellite images to monitor receding snow cover area is a data set that is not fully used at this time and can even help fill the void where SNOTEL sites do not exist in lower elevations and remote higher elevations. Understanding the amount of snow covered area in your basin and the influence of extreme weather on snowmelt rates is critical to understanding your basin and what makes it flow.

SUMMARY

Each basin is unique. The type of water supply timing runoff tools needed in a basin depends on water use, basin size, and precipitation zone along with other watershed characteristics such as elevation and aspect. Understanding key climatic relationships provides additional insight on how melt and streamflow may respond when extreme weather occurs. This knowledge gained is cumulative and can provide increasingly better management decisions despite changing weather variability.

Obtaining information about a watershed, past significant runoff events, and how it behaves and reactions from past weather events is key to understanding your watershed. Additional watershed information can be obtained from past research conducted by different agencies. Much of my information about how watersheds function and key indicators to watch was obtained from local water users and managers, and by participating on NRCS basin wide planning projects.

Once these relationships are understood, much can be learned when the next, similar event happens. This analysis takes time to determine the key relationships, but once learned is useful in answering many of the questions asked each spring when the snow starts melting and the operational phase starts. Once the relationships are determined, they provide a better understanding what makes your basin flow as well as the impacts when extreme weather returns.

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