SOIL TYPE AND SITE LOCATION IMPACTS ON SOIL MOISTURE DATA COLLECTION AT HIGH-ELEVATION SNOTEL SITES

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ABSTRACT

The Natural Resources Conservation Service has recently begun the installation of soil moisture sensors at SNOTEL sites in the western United States in an effort to better characterize watershed hydrology pertaining to snowmelt runoff. Most research in the movement of water through a soil profile has been done in agricultural settings where topography is relatively flat, vegetation is relatively homogenous, and soils are typically fine textured and deep. This paper attempts to document some of the anomalies encountered in soil moisture data from mountainous sites and link them to potential site physical characteristics such as topographic convergence or divergence, distance to bedrock, and elevation, as well as soil type and texture.

INTRODUCTION

The location of soil moisture sensor sites may play a vital role in the correlation of snow water equivalent, soil moisture and runoff. SNOTEL sites were located primarily based on snow courses that had SWE values that were highly correlated to streamflow. The snow courses themselves were located on a trial and error basis and the ones that were most closely correlated to streamflow were the ones that were kept in the system when others were eliminated. Those sites that have high SWE correlations may not necessarily be those that are most representative of predominant soils or subsurface processes of the watershed. Thus, they may not be an accurate depiction of the absolute value of snowmelt loss to infiltration. Even though some sites may not be representative in a general context, if they remain relational to the dominant soil type or hydrologic process, they still might be useful in an empirical or even a modeling situation. The movement of water through a soil matrix can be very complex. There is the ever-present influence of gravity, but there are many other factors as well, such as impervious material, lateral movement, temperature and capillarity. There are the affects of topography; convergence and divergence. Soil physical characteristics such as texture, particle size distribution, organic matter content and pore size distribution play an important role in water movement. Vegetation exerts a critical role in evapotranspiration during the growing season and hence, the residence time capillary water is retained in the soil matrix. A. R. Croft (1946) found that on the Farmington, Utah watershed, (1) practically all water from rains or snowmelt passes through the soil mantle before it becomes available for runoff and (2) the soil mantle has a high capacity to retain water that otherwise would be available for streamflow - 43 to 56 centimeters (17 to 22 inches) of water. From this high elevation watershed study it is apparent that a large soil moisture deficit has the potential to significantly reduce streamflow from snowmelt. Being able to quantify soil moisture in some capacity may lead to a reduction in forecast error. It therefore, becomes important to understand the data being collected and the impacts that various physical characteristics may have on those data.

SENSOR LOCATION AND DATA DISPLAY

Soil moisture sensors are installed at 5, 20 and 50 centimeter depths at current SNOTEL sites. When soils and resources allow, sensors may also be installed at the 10 and 100 centimeter depths. Sensors are typically installed within 5 to 15 meters of the SNOTEL shelter and located and marked to minimize any foot traffic in the area. Soil characterization will be done for each soil but may or may not be done at the time of installation. The current means of analysis is to proportionately weight each sensor according to its position in the vertical soil profile and combine the three sensors into one index trace per site. Thus, the weighting scheme is 19%, 35% and 46% respectively from the 5 centimeter sensor to the 50 centimeter sensor. As more information is gained from each site about the relative role each sensor depth has on water movement, additional index methods may be developed. The index will be applied in an empirical modeling situation to quantify water supply in individual watersheds.

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The temporal domain of data collection varies from area to area, but daily values are always available and in many cases, hourly readings are taken. For the purposes of this study, only daily values taken at midnight are used. In future studies, the hourly data may give an indication of infiltration rates in both the steady and unsteady states, how much (depth) precipitation or snowmelt is required to bring a soil from some known point to saturation and other applications.

Data will typically be displayed as a weighted index of the three soil moisture sensors installed at each site and as a percent of saturation. The weights are proportional to the sensor installation depth relative to the entire measured profile and the weights for each sensor are 19%, 35% and 46% for the 5, 20 and 50 centimeter depths respectively. Individual sensor behavior will be shown when site characteristics have a significant impact on a single sensor. The desired time frame for a predictive index from past observations would be in the fall after the onset of annual snow accumulation, winter or very early spring months (Julander and Cleary, 2001). Soil moisture behavior becomes relatively stable after the onset of snowpack and remains relatively stable through the winter months until snowmelt with the exception of some sites that possess unusual physical characteristics.

SITE DESCRIPTION – COARSE SOILS

We will start with sites that have extremely coarse soil textures such as Mosby Mountain. The site is located on the southeast end of the Uintah Mountains at an elevation of 2900 meters. The soil is sandy with a high proportion of rock and cobbles and is very well drained. There are few fine particles or organic matter in this soil. Vegetation consists mainly of Lodgepole Pine with little under-story vegetation. Snowmelt and precipitation moisture moves through the profile so quickly because of the large number of macropores that the site rarely reaches complete saturation, and as soon as the moisture source is removed the soil drains to a nearly bone dry condition. In this case, a predictive index would be of little to no use at any point in time prior to runoff since the soils will be nearly dry with little variability year after year. Figure 1 shows the weighted soil moisture index for Mosby Mountain.

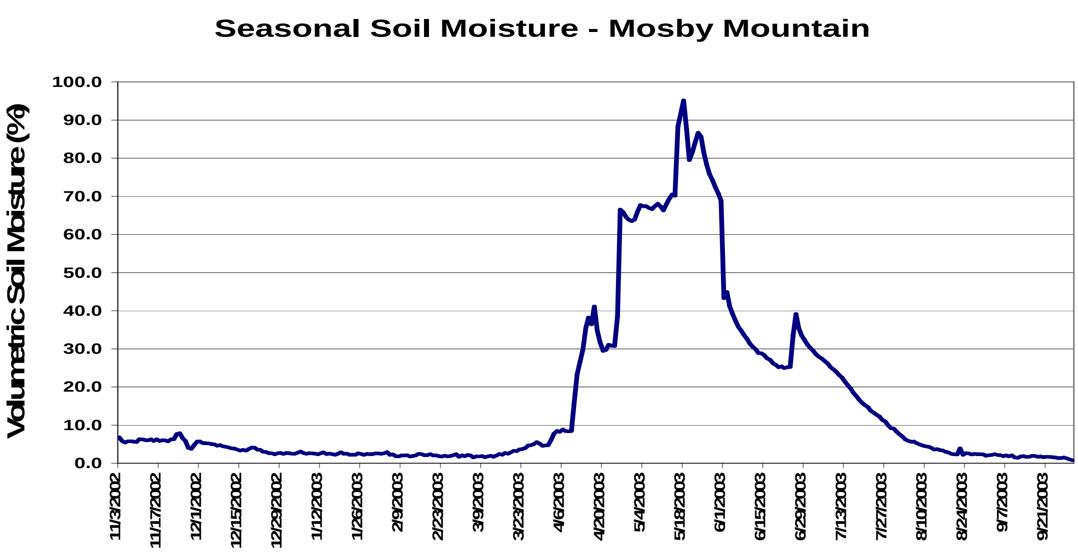

Figure 1. Mosby Mountain weighted soil moisture index for 2003.

Notice in this figure that the only time that significant moisture exists in the soil profile is April through July during active snowmelt. Even precipitation events such as the one on August 21, do not raise the index significantly. August received 3.5 centimeters of precipitation and there was 4 centimeters in September with essentially no response in soil moisture. Between April and the end of May, this site moved 26.5 centimeters of snowmelt and 10.1 centimeters of precipitation through the profile and it only crossed 80% saturation for a short period of time. In order for a soil moisture index to be useful in the prediction of water supply, there has to be a stable relationship between the magnitude of the soil moisture content or deficit to the total snow water equivalent and runoff. Runoff is a residual. In other words, it is the surface water available for streamflow that is left after evaporation, transpiration, sublimation and the soil moisture recharge processes have been satisfied. Obviously, there has to be variability in the soil moisture parameter in order to have predictability. The higher the soil moisture content, the less snowmelt is required to fill the profile and the greater the efficiency of runoff. Conversely, the drier the soil profile or the greater the soil moisture deficit, more snowmelt is required to satisfy that deficit and less snowmelt will be available for streamflow. The soil moisture sensors at Mosby Mountain do not have any predictive capability regarding water supply forecasting. In this case, installing a second or potentially a third set of sensors at different locations with finer textured soils may have the relational variability necessary to serve as forecast components.

SITE DESCRIPTION – ORGANIC LAYER SOILS

Some sites contain unique layered soil structures such that organics reside in the upper layer(s) and coarse textured soils lie below. These sites have a different response than that of Mosby Mountain where the soil is coarse throughout. A case in point is Trial Lake, which is situated on the west slope of the Uintah Mountains at an elevation of 3036 meters. This site has coarse textured soils derived from decomposing Gneiss. The distance to bedrock is typically moderately deep, on the order of 50 to 80 centimeters. This site is located on the edge of a small meadow that has shallow ponds and drainage through the middle with coniferous over-story and significant shading. The soil moisture sensors were installed a few meters up the adjacent slope to avoid the saturated conditions near the center of the drainage. Figure 2 shows all sensors for the Trial Lake site. The upper sensors have far greater soil moisture retention than does the 50 centimeter sensor. The coarser material at the lower depth moves water efficiently through the system whereas the upper layers retain moisture through the year.

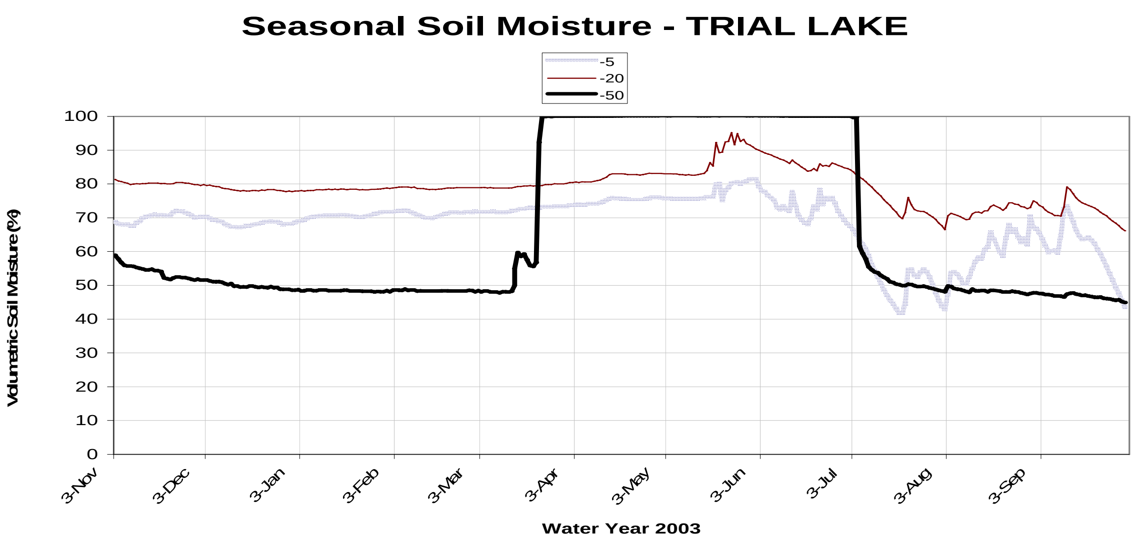

Figure 2. Trial Lake Soil Moisture at the 5, 20 and 50 Centimeter Levels.

The 50 centimeter sensor, which is only a short distance from bedrock goes to complete saturation for an extended period of time indicating that this site is in a bit of a "bathtub" which certainly fills to the lower sensor even in very dry years and could potentially fill to the upper sensors for extended periods in wet years. The moisture source for the 50 centimeter sensor is likely from water moving upward, filling the bathtub so to speak, and not from the downward infiltration of snowmelt. This physical process is evidenced by the fact that the 5 and 20 centimeter sensors do not start increasing till a month later in the snowmelt season. Given this behavior, moving the sensors farther up the adjacent slope may be sufficient to get the sensor out of the "bathtub". The decline of moisture at this sensor is as dramatic and precipitous as the rise, simply confirming that the source of moisture is likely accumulating from the bottom up and not infiltrating from the top down. There might also be value in knowing when the "bathtub" is full regardless of the source of moisture. Owing to the sufficient soil moisture content at the 50 centimeter level, this layer remains at a very steady value for months when not saturated and does not respond to the summer drying cycles. Even with the limitation on depth to bedrock, this site has sufficient variability in the upper two sensors to serve as a predictive indicator of water supply. Moving the entire sensor set further up the adjacent slope may improve the overall index by increasing the variability in the 50 centimeter level soil moisture data.

The presence of springs at sites such as Parleys Summit and Farmington Lower presents a challenge in the collection of soil moisture data. Parleys Summit (2290 meters) has soils that are derived from limestone and shale substrate, they are fine in texture and have high clay content (Coon, King, Knowlton el al., 1982). Observe that at the Parleys Summit site in figure 3, the 50 centimeter sensor is at complete saturation all the time and that the 20 centimeter sensor is nearly saturated all the time. Only the 5 centimeter sensor shows any variability throughout the various seasons. The sensors obviously do well in quantifying the soil moisture at each level but are certainly not representative of more general watershed conditions, which is the objective in collecting these data for use in water supply forecasting. Water flows on both sides of the pillow and exists in the drainage provided for the snow pillow at various times, which indicates the presence of a spring. While this is an excellent site for the observation of snow and precipitation data, saturated conditions present a deficiency with regard to the measurement of soil moisture.

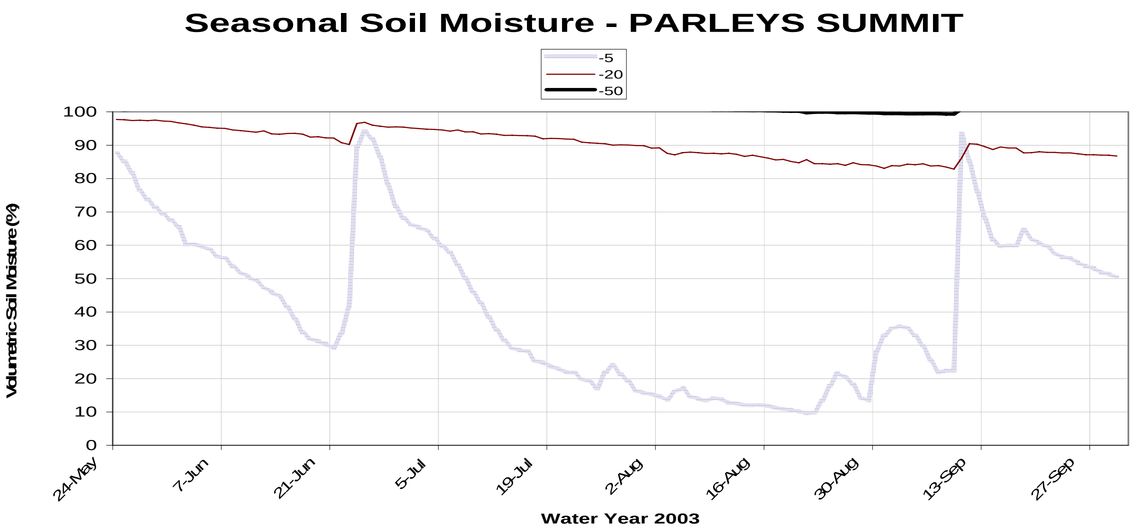

Figure 3. Parleys Summit Soil Moisture at 5, 20 and 50 centimeter depths

Because of the widespread nature of the springs in this area, the only recourse would be to move the soil moisture sensors to a location several hundred feet or more from the current installation. NRCS is currently researching ways of transmitting data from soil moisture installations remotely located from SNOTEL sites in order to obtain soil moisture data that are more representative of general watershed conditions. Because there is no variability in soil moisture at this site, it will have no predictive capability associated with water supply forecasting and the sensors will need to be installed in another more suitable location.

The site at Farmington Lower (2066 meters) was installed in the middle of a large scale snow event in November in order to have snow, precipitation and soil moisture data on a burned area of Farmington Canyon. The town of Farmington is at the mouth of this canyon and has a history of devastating floods, mud and debris flows. Installing soil moisture monitoring sensors with 3 feet of snow on the ground is challenging to say the least and one has no good idea of exactly what kinds of conditions may be lurking underneath. In this case, they were installed in a location that had significant subsurface water movement, and in fact, where there was surface water flowing during active snowmelt. Figure 4 shows the saturated conditions at this site.

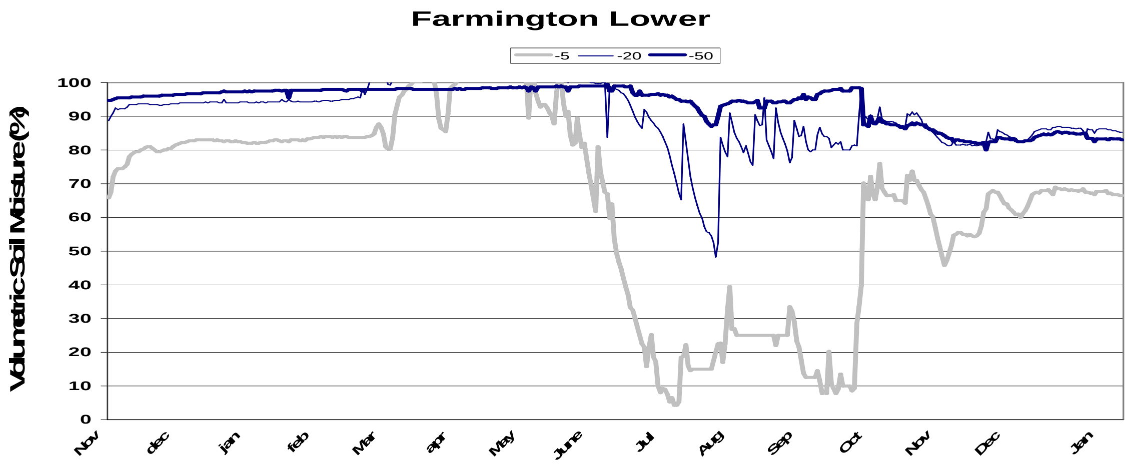

Figure 4. Farmington Lower Soil Moisture at 5, 20 and 50 centimeter depths

The 20 and 50 centimeter sensors are near complete saturation most of the time, similar to the Parleys Summit site. In this case, the sensors were moved from their original installation location to a location further up the slope and away from the spring. This relocation was accomplished in mid October during a 6.5 centimeter precipitation event. The 50 centimeter sensor dropped from nearly 100% saturation to the 80% level but the 5 and 20 centimeter sensors responded quickly to the precipitation event and rose commensurately. Time will tell if the relocation of these sensors will provide soil moisture data reflective of overall watershed conditions. Simply being removed from active subsurface flow is an improvement. The summer of 2005 should provide an opportunity to see if the 20 and 50 centimeter sensors display sufficient variability to be used in a predictive context.

ELEVATION AND SOIL EFFECTS

Site elevation may play a role in determining the temporal domain of a soil moisture index that can be related to streamflow. Similarities exist, as would be intuitively expected, between the temporal and elevational domain of the snowpack and that of soil moisture, as snowmelt is the main factor in bringing soil moisture to a saturated state at high elevation SNOTEL sites in Utah. As shown in Figure 6, two sites on the same watershed, Chalk Creek 1 (2775 meters MSL) and Chalk Creek 2 (2500 meters MSL), have markedly different soil moisture responses to both snowmelt and precipitation. Much of the amplitude and magnitude of the soil moisture response is due to vastly different soil characteristics as well as the total amount of precipitation received at these two sites. The temporal differences can be attributed to elevation and the onset of melt at the two sites. Thus, elevation and its influence on the timing of saturation would be another factor to consider when calculating an index suitable for empirical equations. Note that at the lower elevation Chalk Creek 2 site, there is a significant moisture movement even in early February and then a steady increase during March. At the higher elevation Chalk Creek 1 site, increases in soil moisture do not commence until late April. For an index to be relationally stable it needs to quantify the potential loss of snow to bring soils to a saturated point where infiltration is lowest and the melt to flow ratio is highest. At some lower elevation sites, the index could be calculated during the February to March time frame and at higher elevations it could be calculated later in the season.

In the summer of 2003, when Mosby Mountain and other sites with coarser soils had extremely low weighted indices, Buck Flat most likely also got as dry as it probably could, but that value was much greater than most, in the 50% range, when others were far less than 10%. Buck Flat is located on the Wasatch Plateau at an elevation of 2990 meters. The parent material for the soil is shale, and mudstone leading to a very fine textured soil dominated by clay. The soil is difficult to excavate for purposes of installing a soil moisture sensor since it is extremely heavy and holds moisture extremely well. When wet, it is thoroughly obnoxious to drive or walk across. In figure 6 we see the weighted soil moisture index at Buck Flat. The index between October and April is most notable for

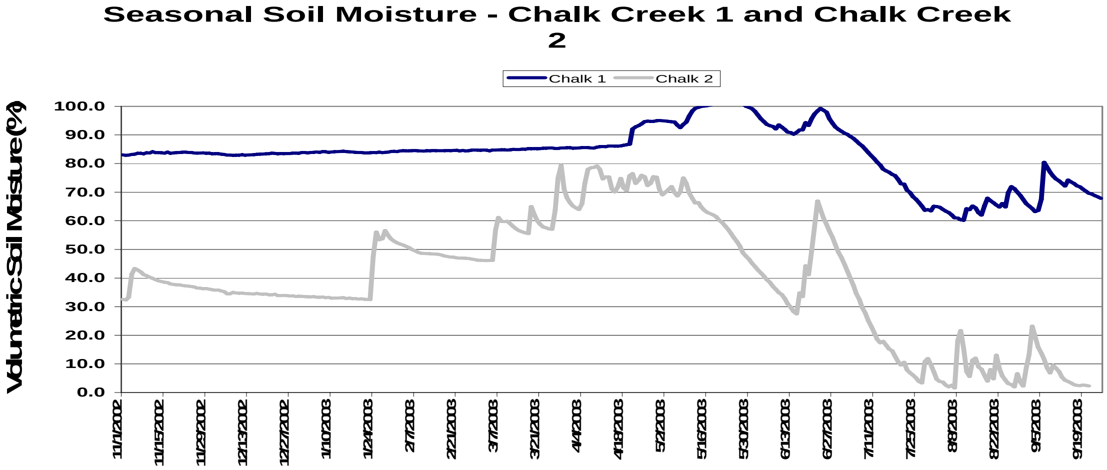

Figure 5. Chalk Creek 1 and Chalk Creek 2 weighted soil moisture index for 2003.

being even and flat. The index goes to saturation quickly at the beginning of snowmelt and then gradually declines into the summer months. At the end of this season, it is near 50% saturation, much higher than many other sites but considerably lower than the previous fall. Even though the total range of index values could be small at this site, the index will most likely be better suited for improving the predictability of streamflow because there will likely be greater variability in that index reflecting abnormally wet or dry conditions in the target time frame, October through March. We could reasonably expect values between 50% and as high as 90%.

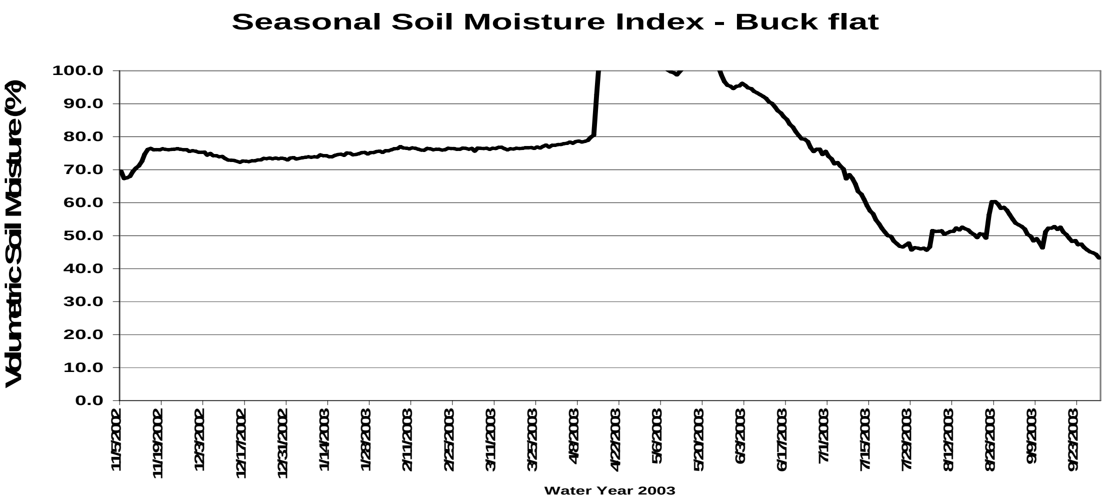

Figure 6. Buck Flat Soil Moisture Index

TOPOGRAPHIC AND SOIL EFFECTS

There are also topographical features such as convergence and divergence that could have an impact on soil moisture and the Parrish Creek site may be a case in point. Parrish Creek is located in the bottom of a small cirque near the top of the watershed. The location is a prime area for lateral soil moisture flow from 3 of 4 cardinal directions with the fourth, being essentially flat, reducing the gradient potential for moving subsurface water down the watershed. Further inspection of the soil moisture curve in Figure 7 reveals that in most years, soil moisture conditions increase during the winter months which could be due to lateral water movement from upslope locations. Note also that during the winter of 2004, this increase failed to materialize, which could easily be due to lack of lateral water movement. In essence, the watershed completely dried out over the continuous years of drought in northern Utah. If this is indeed the case, then a flat line soil moisture index through the winter months would indicate extremely dry futuristic conditions at this site. This situation also re-emphasizes the fact that each soil moisture site may have specific characteristics that may enhance or degrade the data with respect to improved water supply forecast ability. It also indicates that the method of determining which sites will have the most benefit will likely be a trial and error process. Only after many years of data are collected and correlated could the full range of application be known.

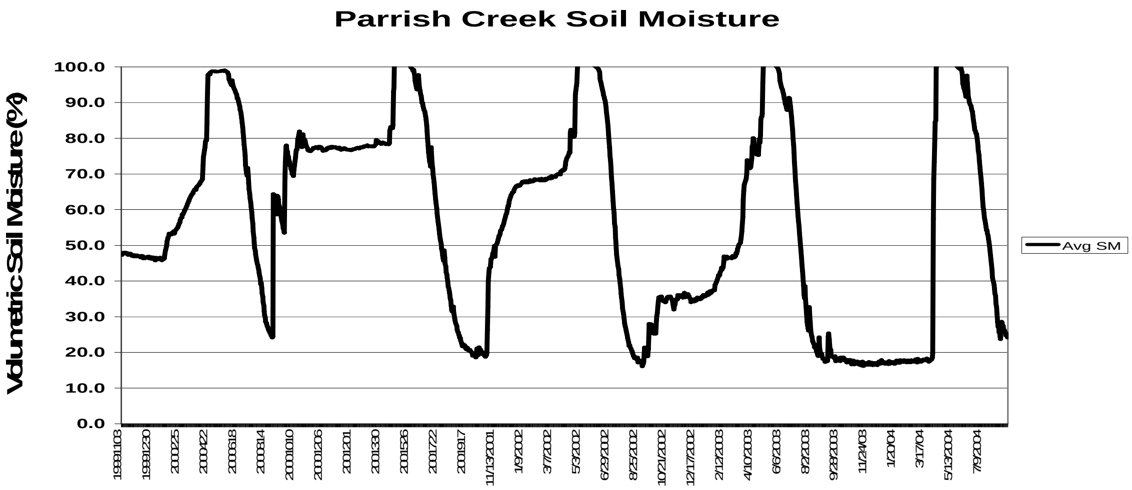

Figure 7. Parrish Creek Soil Moisture

The Ben Lomond Peak SNOTEL site is located on the Wasatch Front northeast of Ogden, Utah on a ridgeline at the 2440 meter elevation. There are downward slopes in three of the 4 cardinal directions and the ridgeline is fairly narrow, on the order of 10 meters. This site accumulates a large annual snowpack for this region, on the average order of 100 to 110 centimeters of snow water equivalent. What soils exist, have a large organic component and are generally categorized as loamy but have a significant rock component and the depth to bedrock is very shallow. Near the site are rocky outcroppings and cliffs. Vegetation consists of large spruce and fir with various shrubs, bushes and grasses. All sensors are displayed in figure 8 to show what seems to an unusual set of

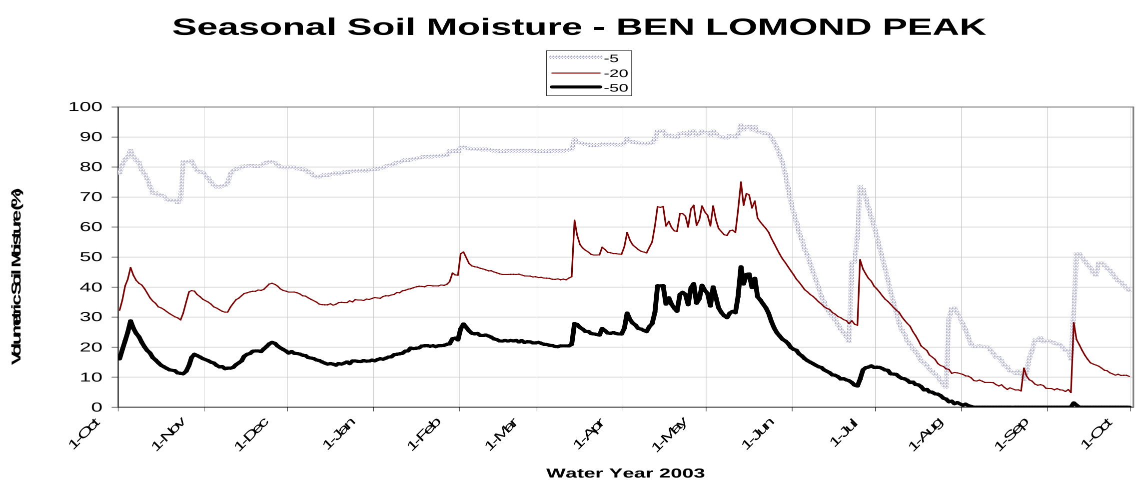

Figure 8. Ben Lomond Peak Seasonal Soil Moisture

circumstances that might be related to topographic divergence. In a normal context, the upper 5 centimeter sensor displays huge variability as it is first to wet in a precipitation event and also the first to dry. The 50 centimeter sensor typically displays less variability and typically doesn't get as dry as the 5 centimeter sensor. In this case, all sensors seem to mirror each other in magnitude as well as in a temporal domain. The pattern is simply not replicated at other sites. There may be other physical reasons for this anomaly but are simply not quantified at this time. This may be an anomaly relative to the majority of landscape positions, but may be representative of the vegetated, topographically divergent and shallow to bedrock sites. While water year 2003 was not an outstanding snow year, this site did accumulate nearly 64 centimeters of snow water equivalent and yet none of the sensors reached saturation with the 50 centimeter sensor only getting to the 40% level. Oddly, during the summer, it was the deep sensor that went to a zero reading and not the upper sensor. This upper sensor responds to precipitation events in a normal fashion showing spikes with significant magnitude and the 50 centimeter sensor responds appropriately with a shallower magnitude and a day or two after the upper sensors respond. Certainly, this site will bear further scrutiny. Given topographic divergence explanation, one could reasonably expect soil moisture to move laterally away from the sensors in several directions in addition to the normal downward movement found in level terrain. In theory, moisture would drain faster from the soils than other circumstances. In this case, it is unclear whether the unusual moisture pattern is due to soil characteristics or to topographic divergence. It is clear that this site has soil moisture data unlike other sites.

CONCLUSIONS

Soil moisture data from sensors installed at SNOTEL sites display various behaviors that can be attributed to site physical characteristics. Recognizing and identifying these data characteristics can lead to more suitable locations for soil moisture data sensing. The most obvious characteristics that would lead to unsuitable data fall into two categories: 1) soils that have extremely coarse textures and 2) soils that are completely saturated for a majority of the time. In these two cases, a predictive index would not be possible because there is too little variability in the data within the target time frame for such an index. In these cases, sensor relocation is the only viable option. There are other factors that can potentially affect soil moisture data collection in a negative fashion. These include the impacts that shallow bedrock may have, especially in creating a “bathtub” affect on the lower sensors where the soil moisture source is coming from the “tub” filling as opposed to the source being snowmelt. The overall impact of this situation is unknown at this time as it may simply quantify a natural stream response in the area but is generally construed as a negative for index purposes at this point. Other sites may demonstrate the impacts of soil moisture movement from lateral inputs such as topographic convergence. It is also unknown at this point if these kinds of situations are positive, benign or negative. Given the data from Parrish Creek, which correlates extremely well with streamflow, it is felt that this seems to be a good characterization of conditions. The opposite of topographic convergence is topographic divergence. In convergence, soil moisture may flow laterally from up-slopes to the impacted sensors whereas with divergence, the site would be located in such a fashion that moisture flow is down-slope away from the sensors. This movement would be the case if a site were on a narrow ridge with downward slopes in two or more directions. These kinds of locations do not typically make good snow measuring sites and thus the problem should be limited to some degree system wide. The soil moisture data from Ben Lomond Peak is very unusual that might be related to topographic divergence. Further soils analysis as well as data analysis will be required to make a definitive conclusion at this site. However, it is conceivable that at many sites that display primarily vertical soil moisture movement, such as Buck Flat and Chalk Creek 1, a good index could be known by November or December or at such time that precipitation events recharging soil moisture are over and seasonal snowpack has been established. Such a time frame could allow for the immediate adjustment of forecast values, giving water managers greater lead time for planning seasonal operations.

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