SOIL MOISTURE DYNAMICS DURING SNOWMELT

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ABSTRACT

Little research exists examining soil moisture characteristics under a snowpack, especially during the active meltout period. Unlike snow water equivalent (SWE) and snow depth, which has been measured by the Snow Survey Program for 80 years, soil moisture changes during meltout have been difficult to monitor and analyze. Advances in sensor technology, increased deployment of instrumentation, and longer period of records present new opportunities for analysis and a better understanding of soil moisture dynamics under snowmelt. Three characteristic annual soil moisture patterns are discussed. Analysis of hourly soil moisture, SWE, and precipitation data have resulted in the observation of new relationships between daily snowmelt and soil moisture. At most SNOTEL sites, snowpack melt results in diurnal soil moisture fluctuations. At well-drained sites, during periods of rapid melt, fluctuations of up to 10 percent soil moisture by volume are observed. Typically, fluctuations are expressed by all three sensors through the 50 cm measurement zone during the entire meltout period, or until saturation is reached. Diurnal fluctuations in soil moisture scale in magnitude with the SWE loss during the same period. At sites with well-drained soils and no run-in from adjacent areas, the volume of water transmitted through the entire 50 cm zone correlates well with the volume of SWE loss on a daily basis. Four select sites with different soil properties and geographic areas within Utah and California are examined and the correlation between SWE and soil water flux is quantified and found to range from an R^2 of 0.50 to 0.76. Analysis of diurnal soil moisture fluctuation provides a valuable window into the significant water flux occurring during the melt cycle and may assist in making soil moisture a quantitative input in statistical-based streamflow forecasting. (KEYWORDS: soil moisture, snowmelt, active melt, snow, diurnal fluctuation)

INTRODUCTION

Spring snowmelt is an important natural process in the Western United States where a vast majority of culinary and irrigation water is supplied by melting snow. As population grows significantly in the Western States, water becomes an increasingly important resource. Accurately forecasting the timing and extent of water supplies necessitates a full understanding of all aspects of the spring snowmelt process. Snow water equivalent (SWE) and seasonal water supply have been understood to have a strong relationship (SCS, 1970; Zuzel, 1975). Less well understood is the role that soil moisture conditions play in the timing and quantity of water supply. It has been established, however, that soil moisture conditions across a watershed do influence snowmelt dominated water supply (Wetzel and Woodward, 1987).

Work by Julander and Perkins comparing soil moisture and streamflow forecasts found it apparent that soil moisture had an extraordinary impact on streamflow not accounted for in statistical forecast equations (2001). The current role that soil moisture data play in water supply forecasting is limited to being a subjective modifier when abnormal (e.g. extremely dry/wet) conditions are present. Using soil moisture data in forecasts is limited by the complex relationships between soil moisture, groundwater contributions, and runoff (Julander and Perkins, 2001). In addition to these complexities, our understanding is limited by relatively short period of record at some sites (>10 years). At older sites, however, the period of record is approaching 15 years; certainly enough time to allow for meaningful analysis. Despite a very short data record and the complex relationship between soil moisture, runoff, and groundwater contributions, Julander and Perkins concluded that soil moisture is a useful tool as an anecdotal indicator of conditions that could cause a significant deviation in the relationship between SWE and observed streamflow (2001). This is currently the role these data play in statistically-based streamflow forecasts.

Limited research has focused on making soil moisture data more quantitatively useful in streamflow forecasting. In 2001, Julander and Cleary first proposed the use of volumetric soil moisture data to create a relative estimate of the soil moisture deficit. The “deficit” being the capacity of the soil for snowmelt infiltration before pore space is full and runoff occurs. More formally, the soil water deficit (SWD) concept was proposed by Vaughan and

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Julander as a way to quantify how much soil water storage is available at a given point in time (2011). The value of SWD is twofold: 1) to estimate the potential runoff and, 2) to estimate the amount of soil water storage capacity at any given point in time. Both are of value in water supply forecasting, because they provide a quantitative idea of the soil's potential behavior just prior to the commencement of spring snowmelt. Understanding this number can be very useful, since soil moisture conditions in the spring can vary from having virtually no storage capacity (nearly saturated) to almost 50 cm of water storage in the top 100 cm of soil. The latter case assumes a deep organic-rich mollic epipedon, loam textures, and a depth of 100 cm or more, the combination of which is common in soils under Aspen plant communities in Utah.

One limitation of the SWD is that it only gives you a snapshot of something dynamic that changes on both a seasonal and daily basis. Another limitation is that it doesn't give the user any information regarding the relationship of volumetric soil moisture, or volumetric water content (VWC) relative to field capacity for each of the sensors. Field capacity (FC) is the water content at which there is a significant decrease in soil water moving downward through the profile in response to gravity. It roughly corresponds to a tension of -1/3 bars, which is not measured by the instrumentation utilized by the SNOTEL program. The volumetric soil moisture content at -1/3 bars varies by soil and depends on several properties (e.g. texture, organic matter content, bulk density, rock fragment content, particle density), but can be estimated if soil texture and rock fragment content are known. Not all soil water is likely to percolate and contribute to groundwater; it is only when soil moisture content is above field capacity that water moves by gravity. Water movement under soil moisture conditions below FC is dominated by capillarity in response to a concentration gradient.

In an effort to improve the use of soil moisture in streamflow forecasting, the Natural Resources Conservation Service (NRCS) snow survey program has been installing soil moisture and temperature sensors at its automated SNOTEL sites. As mentioned earlier, soil moisture's current role in statistical forecasting is as a subjective modifier. With an increase in network size and period of record, soil moisture should soon play a quantitative role in forecast equations

ANALYSIS AND DISCUSSION

Currently, soil moisture sensors are installed at about 420 of the 820 sites in the SNOTEL network. Installation implementation began in Utah in 2005. All sites in Utah, Nevada, and California have at least three soil moisture and temperature sensors at depths of 5, 20, and 50 cm. Data collection and transmission occur on an hourly basis in Utah, Nevada, and California, although collection intervals vary in other states within the network. Program wide, soil moisture and temperatures are measure using the Stevens Hydra Probe. These instruments make in-situ measurements and are left in the ground indefinitely until a malfunction necessitates replacement. The Hydra Probe is used program-wide and utilizes existing Campbell Scientific CR10x datalogger and Meteorcomm 545B radio for data storage and transmission, respectively. The Hydra Probe uses a low frequency (50 MHz) to measure complex dielectric constant, which is converted to VWC using a soil texture-specific calibration equation. Currently, all Hydra Probes deployed in the SNOTEL program use the 'silt" calibration equation. It is the hope of this author that more suitable calibration equations will be employed in the near future as soil sampling proceeds and better soil texture data is obtained. Accuracy, as reported by the manufacturer, can be as good as +/- 0.03% VWC in fine-textured soil using a texture-specific calibration equation. Independent evaluation by Munoz-Carpena, et al. assessed the accuracy of the Hydra Probe to be in the range of +/- 1% VWC, after soil-specific calibration (2006). Hydra Probes also report bulk soil electrical conductivity and measure soil temperature using a built-in thermistor.

Annual Data

In an early effort to categorize and characterize soil probe behavior, three characteristic annual soil moisture shapes have been identified: seesaw, plateau, and flatline. All soil moisture instrumentation at SNOTEL sites in the area administered by the Salt Lake City Office fit into one of these categories. About 60% of these sites can be characterized by having a seesaw pattern. Approximately 30% of the sites are plateau sites, with the remaining 10% being the flatline sites.

Several sets of factors affect soil moisture pattern, including soil physical properties, site hydrologic characteristics, and regional hydrologic characteristics. Site hydrology exerts the greatest influence on soil moisture pattern, because it drives whether the site receives run-in from immediate adjacent areas, due to concave micro-topography, or regionally, due to landform (e.g. floodplain). If the site does not receive run-in, physical soil properties dominate the effect on soil moisture pattern. Shallow depths to bedrock (<100 cm) can cause a site to "plateau" when the soil percolation rate exceeds that of the bedrock, which is likely. Commonly, plateau sites have soil textures that are high in clay, resulting in a percolation rate lower than the melt rate, causing saturation.

Seesaw sites are those where sensors rarely saturate, even during intense snowmelt (>5 cm/d) during the spring. Generally, seesaw sites are in convex or flat landscape positions and do not receive run-in from adjacent areas. Soils at seesaw sites are typically deep to bedrock (>100 cm) and have coarser soil textures. Rocky Basin Settlement SNOTEL, mentioned earlier is a good example of a seesaw site (Figure 1).

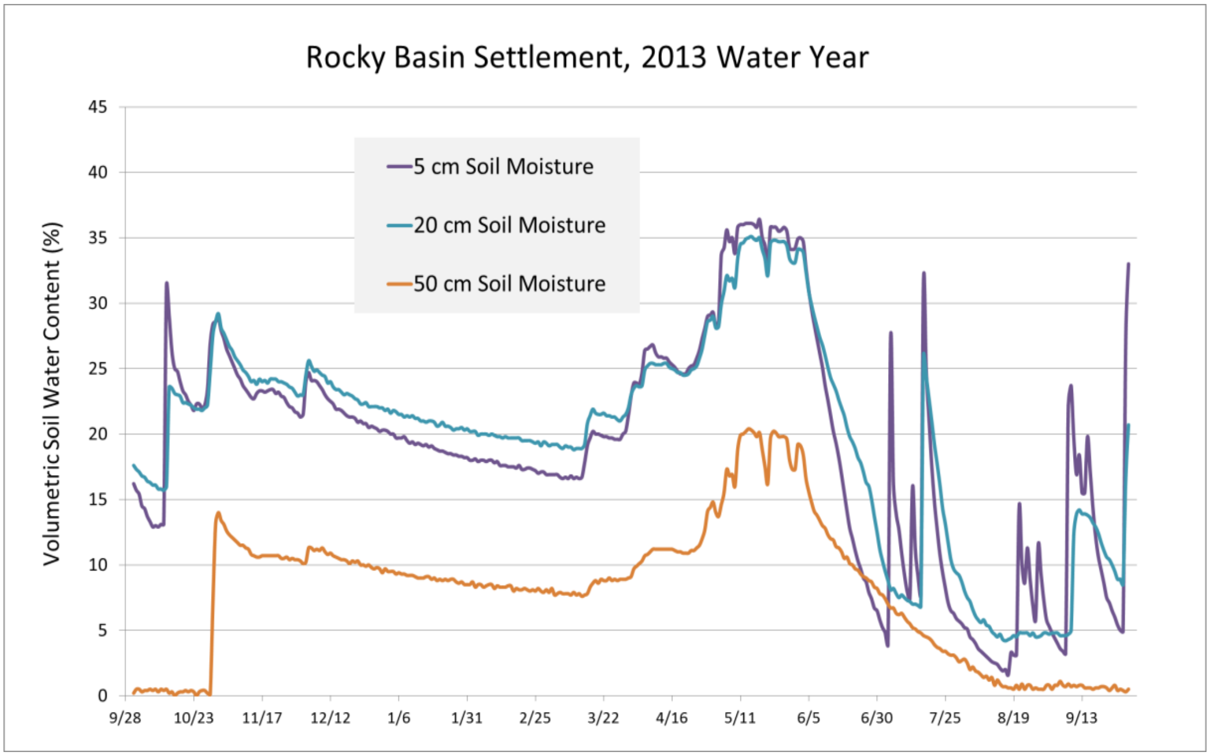

Figure 1. Daily soil moisture (VWC) at 5, 20, and 50 cm depth for the 2013 water year at the Rocky Basin Settlement SNOTEL site

Rocky Basin Settlement is located in the Oquirrh Mountains, at an elevation of 2553 m. Parent material is colluvium and slope alluvium of Pennsylvanian dolomite and limestone from the Butterfield Peaks Formation (Clark et al., 2012). Soil at this site has not been sampled, but based on limited field observation appears to have loamy textures and low coarse fragment content. The "seesaw" name comes from the period of time during the spring when the melt rate is high. In Figure 1, this period is roughly from mid-April to June 1st.

Plateau sites are similar to seesaw sites, except that these sites become saturated during rapid snowmelt; snow melt rate exceeds soil percolation rate. Plateau sites usually have finer soil textures, with lower percolation rates. In a few examples, shallow bedrock causes the saturation. The Gooseberry R.S. Upper SNOTEL site exhibits a classic plateau pattern (Figure 2). Coincidentally, many SNOTEL sites on the Wasatch Plateau of central Utah exhibit the same pattern, because they all have similar landform shapes and parent material. Soils at Gooseberry R.S. Upper are clay loam to clay in texture and are deep to bedrock. The name "plateau" is given because of the pattern exhibited during May, when soil moisture increases to saturation and stays there for the remainder of the melt period.

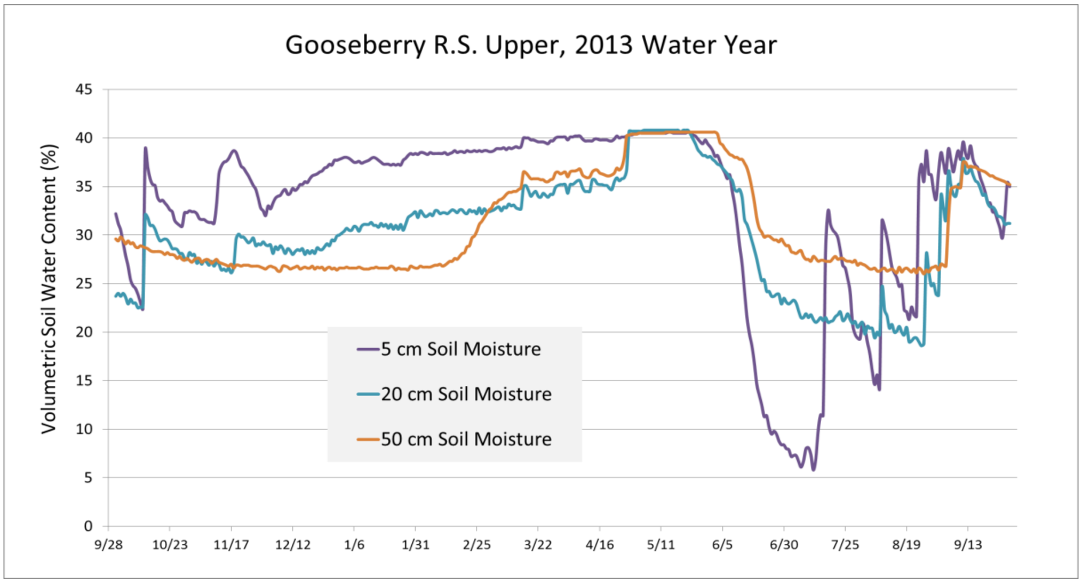

Figure 2. Daily soil moisture (VWC) at 5, 20, and 50 cm depth for the 2013 water year at the Gooseberry R.S. Upper SNOTEL site

Flatline sites are those where soil moisture does not change significantly through the year. These soils begin the spring melt cycle saturated, so no further increase in soil moisture occurs, regardless of melt rate. Soil properties can vary considerably between sites exhibiting a flatline pattern because it is local and regional hydrologic characteristics that drive site hydrology in these settings. Buck Pasture is a good example of a flatline site, shown in Figure 3, below.

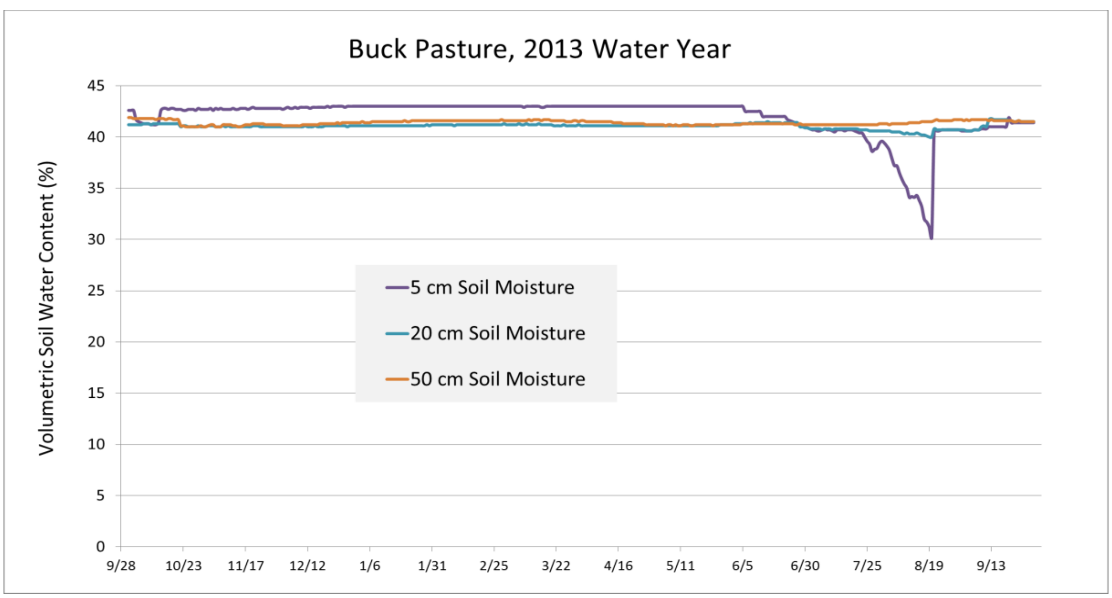

Figure 3. Daily soil moisture (VWC) at 5, 20, and 50 cm depth for the 2013 water year at the Buck Pasture SNOTEL site

Soils at Buck Pasture are low in rock fragments and are clay textured to a depth of about 70 cm, with loam textures deeper. Not surprisingly, these soils exhibit evidence of saturation during the growing season, in the form of redoximorphic features. Buck Pasture is in a flood plain of the West Forks Blacks Fork River and is heavily affected by this water.

Hourly Data

Hourly data editing and analysis has recently commenced, instead of the daily data (midnight value) previously edited and analyzed. Hourly SWE and soil moisture data analysis has yielded the identification of an interesting relationship between the two that had not been previously identified in this dataset. Diurnal fluctuations resulting from the daily snowmelt have been identified at most sites in Utah, Nevada, and the Lake Tahoe Basin of California. These soil moisture fluctuations occur over a 24 hour cycle in response to the daily pulse of melt water from the melting snowpack. Figure 4. shows this phenomenon occurring at the Rocky Basin Settlement SNOTEL site during the spring of the 2012 water year. Diurnal fluctuations in all three sensors are clearly visible (Figure 4). Also evident is the step-wise drop in SWE as a result of the increased melt rate during the day and the slowing or ceased melt during the cold nights. Greater than half of sites in the area administered by the Salt Lake City office exhibit diurnal soil moisture fluctuations

Other researchers have noted the presence of diurnal fluctuations in soil moisture. Flint, et al. noted diurnal fluctuations in soil moisture at three depths (10, 36, and 72 cm) under a melting snowpack in Yosemite National Park (2008). It was concluded that the daily fluctuations were the direct result of diurnal melt cycles of the snowpack (Flint, et al, 2008).

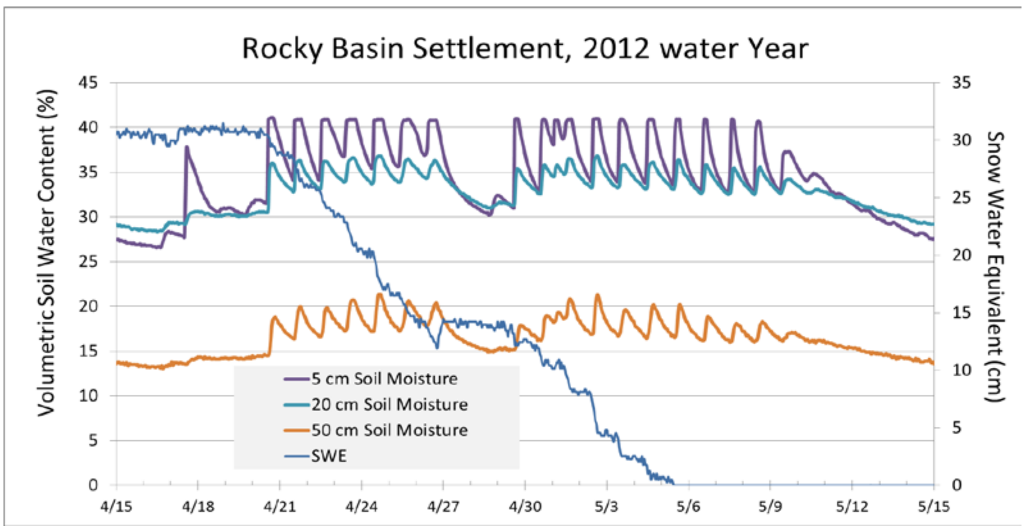

Figure 4. Hourly soil moisture (VWC) at 5, 20, and 50 cm and SWE at Rocky Basin Settlement SNOTEL mid-April to mid-May, 2012

In order to verify this relationship in our dataset, the difference between daily minimum and maximum soil moisture was correlated against the daily SWE loss at four SNOTEL sites for water years (WY) 2011 - 2013. This period of time was chosen because it covered a wide range of snowpack conditions, with one very wet and two dry years. Four sites were selected for hourly data analysis during meltout. These sites have different geographic characteristics and geology, but exhibit diurnal soil moisture fluctuations and have relatively stable SWE data. Rocky Basin Settlement, Kimberly Mine, and Little Bear were selected from Utah; the Truckee #2 site was selected from California. All four sites are part of the SNOTEL network and are administered by the Salt Lake City Data Collection Office. The correlation was calculated by comparing the daily difference in SWE to the difference in soil moisture (maximum-minimum) multiplied by 50 cm, to get a volume. Results from this analysis are discussed for each site.

Rocky Basin Settlement

Rocky Basin Settlement is situated at an elevation of 2553 m, in the Oquirrh Mountains. Parent material is colluvium and slope alluvium from Pennsylvanian dolomite and limestone from the Butterfield Peaks Formation (Clark et al., 2012). Soil at this site has not been sampled, but based on limited field observation appears to have loamy textures and low coarse fragment content.

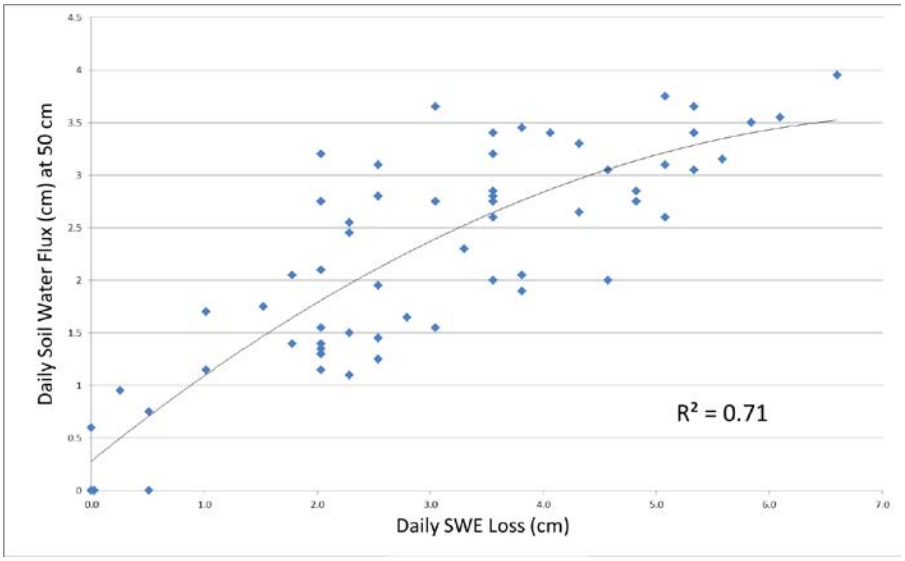

Figure 5. Daily SWE loss (cm) and daily soil water flux (cm) at 50 cm, Rocky Basin Settlement SNOTEL, select days during meltout, 2011-2013

The tree community consists of Aspen, Engelmann Spruce, and Subalpine Fir. Figure 5 shows the results of this analysis for the Rocky Basin Settlement Site; fairly good relationship between diurnal soil moisture fluctuations and SWE. Soil and site characteristics at this site are ideal for supporting this relationship; the soils never saturate, even during rapid snow melt, but percolation rate is slow enough that diurnal fluctuations are expressed in the data. Also contributing to this relationship is the stable behavior of the snow pillow, with little noise due to diurnal temperature cycling.

Little Bear

The Little Bear SNOTEL site is in Northern Utah, near Powder Mountain ski resort. At 1986 m, it is one of the lowest-elevation SNOTEL sites in Utah. The site is in a small valley at the base of James Peak in Tertiary-aged Salt Lake Formation, which contains a wide variety of lithologies (King and Coogan, 2001).

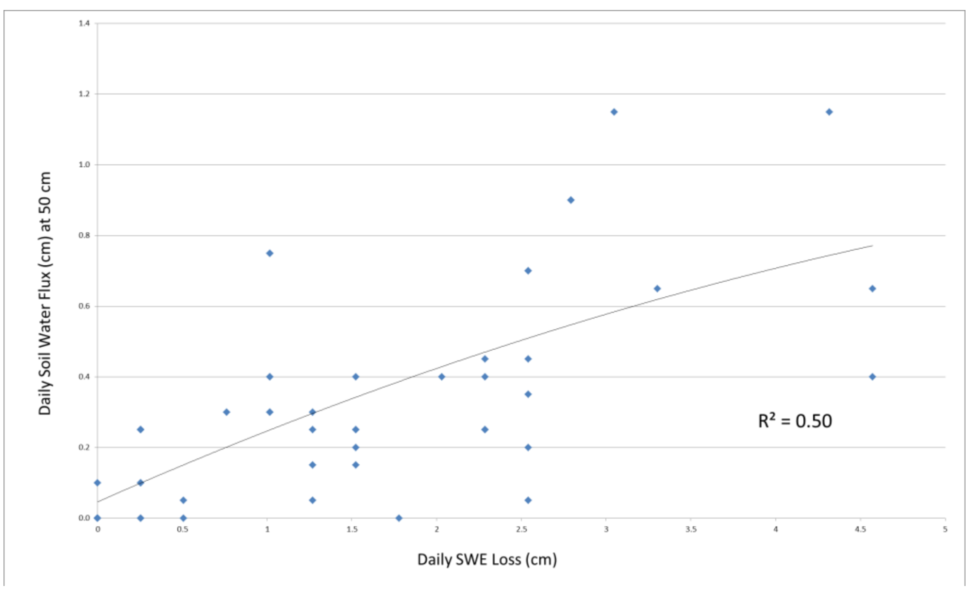

Figure 6. Daily SWE loss (cm) and daily soil water flux (cm) at 50 cm, Little Bear SNOTEL, select days during meltout, 2011-2013

Soils at the site classify as Fine-loamy, mixed, active, Pachic Haplocryolls. Soil texture is clay loam from the surface to a depth of 66 cm. From 66 to 138 cm, silt loam and loam textures dominate; at 138 cm the texture changes markedly to coarse-sandy loam, with low clay content (8%). Rock fragment content is low, averaging 3% in the profile. An Aspen tree community dominates the site; the understory consists primarily of Western Coneflower. The correlation (Figure 6.) was not as strong at Little Bear as at the others. Soil properties and geographic setting appeared to be favorable for this relationship, so it is a little surprising the correlation is not stronger. The answer may lie in the elevation. As one of the lowest SNOTEL sites in Utah, the site does not experience daily minimum temperatures as low as the higher elevation sites. Although diurnal soil moisture fluctuations are still evident, there is significant loss of SWE during the night, as melt continues. This effects the correlation in two ways: 1) there is a higher percolation rate through the night in the soil, and 2) estimating the cyclical SWE loss becomes more difficult.

Kimberly Mine

The Kimberly Mine site is situated at an elevation of 2773 m in the Tushar Mountians, east of Beaver, Utah. Parent material is colluvium and slope alluvium from the Joe Lott Tuff Member of the Mount Belknap Volcanics Group (Rowley et al., 2005). Soil textures are loam in the surface and coarsen to coarse sandy loam at a depth of about 40 cm. Coarse fragments in the soil profile are high; averaging about 55% in the upper 100 cm.

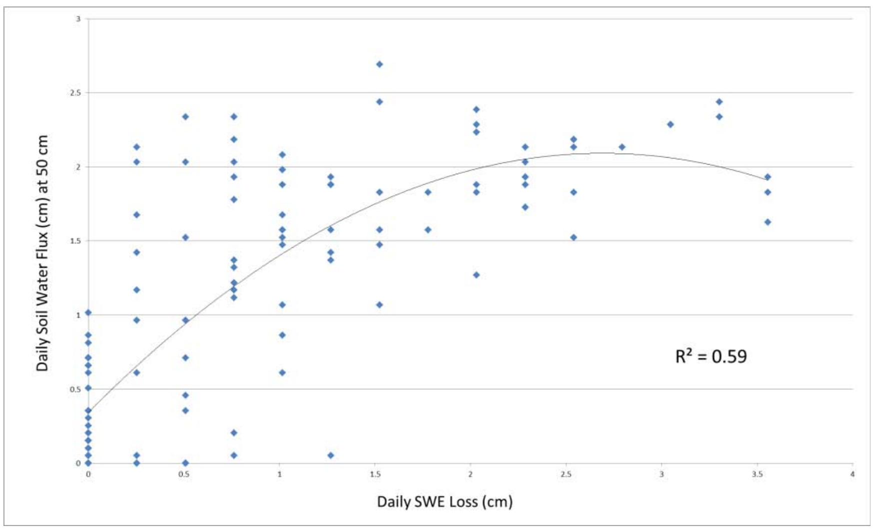

Figure 7. Daily SWE loss (cm) and daily soil water flux (cm) at 50 cm, Kimberly Mine SNOTEL, select days during meltout, 2011-2013

Soils at the Kimberly Mine SNOTEL classify as Loamy-skeletal mixed superactive Pachic Argicryolls. The tree community consists of Aspen, Engelmann Spruce, and Subalpine Fir. The correlation at Kimberly mine was reasonable at .59 (Figure 7.). Coarser textured soils at the site are well suited, with an assumed percolation rate just lower than the melt rate, allowing the diurnal change in soil moisture data. Limitations at the site were related to temperature-induced noise in the SWE data, which were significant here.

Truckee #2

In California, the Truckee #2 SNOTEL site is situated at an elevation of 1981 m, just south of the town of Truckee, CA. Parent material at the site is volcanic residuum from Pleistocene volcanic rock (California Geological Survey, 2014). The tree community at the site is a mix of White Fir and Jeffery Pine, with an understory composed primarily of Currant and Greenleaf Manzanita. Soils have been sampled at the Truckee #2 site, but analysis has not been completed. Preliminary data indicate a sandy loam surface, but clay content increases quickly with depth. Soil texture at the 50 cm sensor is clay. Truckee #2 had the strongest correlation between diurnal soil moisture fluctuations and SWE (Figure 8.). It also had the most linear relationship of sites studied. This was a bit of a surprise, as this site also had the most clay-rich subsoil of the sites. Partial explanation may come in the form of the low rock fragment content, which aids percolation rate and water holding capacity.

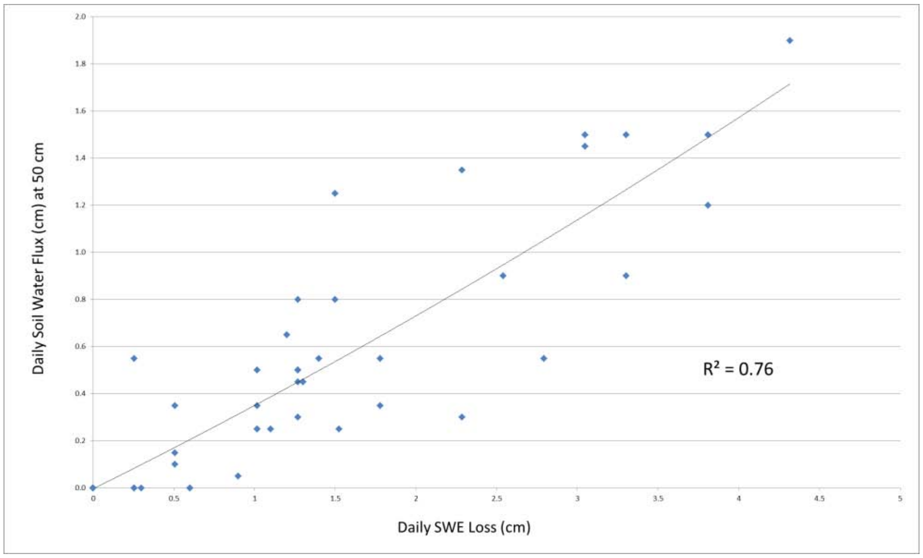

Figure 8. Daily SWE loss (cm) and daily soil water flux (cm) at 50 cm, Truckee #2 SNOTEL, select days during meltout, 2011-2013

Soil Water Flux

In addition to confirming SWE melt behavior, analysis of diurnal soil moisture fluctuation provides a valuable picture of what happens below ground. By looking at the top 50 cm of soil as its own system that is wetting and drying on a daily basis, we can infer a minimum flux volume through that system and a percolation rate. Soil water is moving in these systems all the time, but these fluctuations provide a snapshot of the maximum and minimum where the difference represents the minimum volume of water transferred through the system.

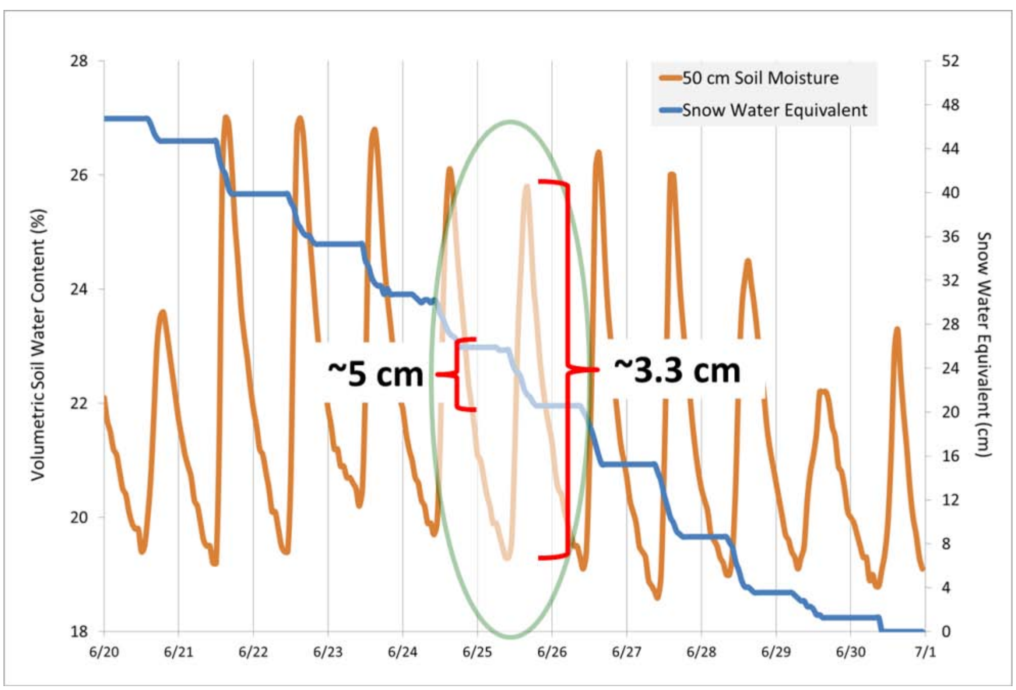

Figure 9. Hourly soil moisture (VWC) at 50 cm and SWE at Rocky Basin Settlement SNOTEL, Late June, 2011

While we don't know the entire percolation volume, it is still valuable to be able to bracket the value. For example, Rocky Basin Settlement, during meltout in 2011, recorded a 5 cm SWE loss, resulting in 3.3 cm of water moving through the soil system to at least a depth of 50 cm (Figure 9). This is snowmelt that did not sublimate, evaporate, or runoff, but snowmelt that went into the ground at the site to contribute to streamflow or groundwater.

SUMMARY

It is hoped that the use of soil moisture data can further improve statistical streamflow forecasts beyond being used as a subject modifier. In an effort to do this, NRCS has built and continues to build a large network of soil moisture sensors at SNOTEL sites. Additionally, hourly data editing and analysis is now occurring in support of this effort. Analysis of soil moisture and SWE data have resulted in the identification of three characteristic annual soil moisture patterns: seesaw, plateau, and flatline. Annual soil moisture patterns are the result of a combination of factors, including local and regional hydrologic characteristics, site topography, and soil properties.

Analysis of hourly soil moisture data has resulted in the observation of new relationships between daily snowmelt and soil moisture. At most SNOTEL sites in Utah, Nevada, and the Tahoe Basin Area of California, the daily snowpack melt cycle results in significant diurnal soil moisture fluctuations. At well-drained sites, during periods of rapid melt, fluctuation of up to 10 percent soil moisture by volume are observed. Typically, fluctuations are expressed by all three sensors through the 50 cm measurement zone during the entire meltout period, or until saturation is reached. Daily soil moisture fluctuations and SWE loss generally scale well and are generally well correlated. All four sites examined in this effort exhibited the daily seesaw pattern; correlation with SWE ranged from an R^2 of 0.50 to 0.76. Understanding diurnal soil moisture fluctuations is important, because they document the minimum water flux through the upper 50cm of the soil system. In combination with the soil water deficit, they have the potential to help unravel the complex relationship between soil moisture, runoff, and groundwater contributions and provide the next step in using soil moisture quantitatively in streamflow forecasting.

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