SOIL MOISTURE DATA COLLECTION AND WATER SUPPLY FORECASTING

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ABSTRACT

Extreme deviations in hydroclimatic conditions are a source of considerable error in statistical water supply forecast models. Much attention has been given over the past years to the relationship between snowpack, precipitation and streamflow (Martinec, 1975, Hawley, et al. 1980, McCuen, 1993). These relationships tend to vary in strength, but in large part have been satisfactory for water supply forecasting purposes. Increased demands on water resources have led to crises in water management and ways are being sought to improve water supply forecasting. Many other hydroclimatic variables such as soil moisture are implicit in these statistical relationships. As long as these variables (soil moisture) remain proportional to the independent variables (snowpack, precipitation, etc.) in the forecasting relationship, then the model will be stable. If there is some amount of disproportion, then the model will most likely produce significant error. Such a case in northern Utah is presented with a limited database. The success of this instrumentation has led to a broader scale application with the goal of complete soil moisture and temperature sensor installations at all SNOTEL sites system wide. Currently, soil moisture data are being incorporated into water supply forecasting in an analog method with some success.

INTRODUCTION

The strong relationship between snow water equivalent and seasonal water supply has long since been demonstrated (SCS, 1970, Zuzel, 1975). These statistical relationships vary in strength depending on a host of factors such as latitude, elevation, and others. Forecast error in these statistical models is primarily in three parts: 1) statistical uncertainty in the forecast equation, 2) error associated with the measurement of the data, and 3) uncertainty associated with current or future hydroclimatic conditions. Statistical uncertainty is partly a reflection of the other two error sources. Data measurement error is assumed to be a constant as measuring techniques and sensors have been, for the most part, standardized (Amer et al. 1994). Reducing the error in the quantification of current or future hydroclimatic conditions has the greatest potential for reducing forecast error. It is unlikely that there will ever be sufficient data collection sites to completely quantify hydrologic parameters such as snowpack, precipitation and soil moisture, etc in time and space over every watershed of general interest and thus some

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portion of this error will likely remain as well. Also, unforeseen and radical seasonal fluctuations in hydrologic conditions, such as seen this year, can drastically affect projected water supplies from month to month in the forecast season. Soil moisture conditions across a watershed are generally presumed to influence seasonal water supplies from snowpack (Wetzel and Woodward, 1987). If extremely dry conditions are prevalent in the fall prior to the seasonal snowpack, then it is presumed that these soils have additional capacity to absorb and retain greater than normal amounts of snowmelt. This leaves a reduced amount to generate seasonal streamflow. Conversely, if the soils are saturated prior to the onset of snowmelt, it is presumed that, since the soils have less capacity for infiltration and certainly less storage, the majority of snowmelt should contribute directly to seasonal streamflow. After prolonged periods of dry weather, total potential snowmelt loss to soil moisture recharge can be significant. Assuming a 24 inch soil depth, 8 to 10 inches of snowmelt or more, could be lost to soil moisture recharge depending on soil type and condition. Some portion of this would eventually contribute to runoff and some portion would be lost from the immediate contributing system through either evapotranspiration or to deeper groundwater. In quasi-normal conditions, soil moisture is implicitly accounted for in statistical relationships whereas in extreme conditions, these relationships become unstable. These extreme conditions are often when accurate and reliable water supply information is most critical. In past attempts to quantify the impact of soil moisture on subsequent runoff, various types of surrogate indices have been used such as fall precipitation or base flow conditions with varying degrees of success.

The Natural Resources Conservation Service has installed soil moisture sensors at nearly 50 SNOTEL sites in Utah to determine if the use of such data can reduce the error associated with statistical water supply forecasting and be incorporated into various modeling applications. Some of these sensors, installed at the 2-inch, 8-inch, and 20-inch depths have been in place for 4 years, but most have only one to two years of data, thus only preliminary data are available for analysis. In Figure 1, the April 1 snow water equivalent at Trial Lake, is plotted against the Bear River at Stateline April-July streamflow. It is clear upon examination, that there are years of very high snowpack which result in very low streamflow and conversely, years that have comparatively low snowpack which result in high runoff. The status of soil moisture prior to runoff may be a dominant influence in these anomalies.

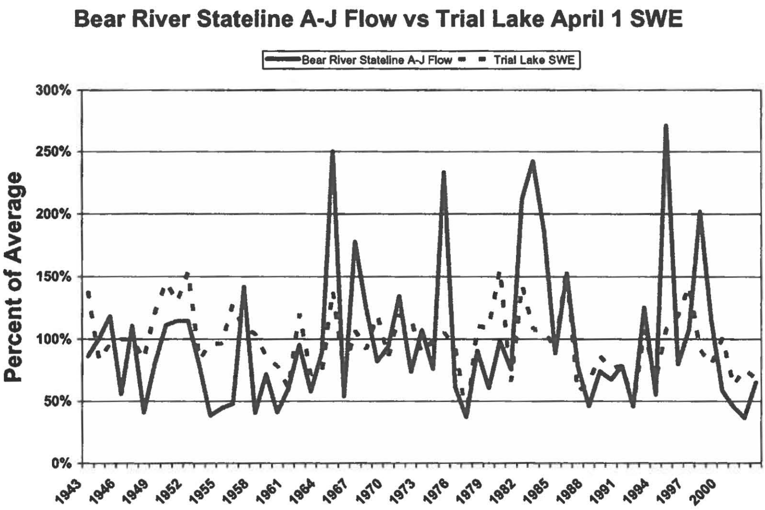

Figure 1. Bear River streamflow and Trial Lake snow water equivalent.

The soil moisture sensor installed is the Vitel Hydra Soil Probe. The operation principle is based on a high frequency complex dielectric constant and measures soil moisture by volume. Both the capacitive and conductive components are measured. A thermistor is used to determine temperature. It is designed for a field life of approximately 15 years and is constructed of stainless steel. It has an accuracy of plus/minus 3 percent in the absence of specific soil calibration and about 0.5 percent if soil analysis is done (Vitel, 1994). With the advent of a sensor with this longevity and anticipated stability, many of the complex problems associated with long term soil moisture monitoring may be avoided. This, in turn, could lead to a relatively accurate soil moisture index with the potential to reduce water supply forecast error.

Soil moisture is highly variable in time and space (Washburne, 1998). It is dependent on the type and depth of soil, slope, aspect, the type and amount of vegetation as well as climatological conditions such as temperature, precipitation and snowmelt (Diestal, 1993). Given this variability, point soil moisture data will need to be processed as an index, in much the same way as snowpack data currently is related to streamflow. The form of this index is currently uncertain because there is insufficient data to be able to make any reasonable quantification. It may simply take the form of average point data in a statistical relationship, i.e. the average value of the three soil moisture sensors at a particular time such as October 1, or March 1 of the forecast year. It could be a more complex formulation weighting various depths or times. There is certainly the potential for calculating a point soil moisture deficit and a potential net loss of snow water content to the soil given the appropriate soil physical data such as bulk density, transmisivity, etc. Even without the appropriate soils data, an index can be referenced to a static point (such as assuming the soil can hold a total of 10.8 inches of water in the upper 24 inches of soil profile) and used in a relational or linear context. In a point fashion, it will be important to eventually know the exact water holding capacity and calculate potential snowpack losses. This soil moisture deficit index might then be extrapolated to larger geographic areas or used in simple statistical water supply forecasting relationships. Given the analogy of soil moisture as a large reservoir (Hanks and Ashcroft 1980), a variation of soil moisture data or index could be a direct input to many of the Hydrologic Tank Models currently in use such as the Sacramento Soil Moisture Model.

Study Area

The watershed of primary analysis is Parrish Creek, in the Wasatch Mountains of Utah. General observations from other sites will be included that will demonstrate the potential for forecast improvement as well as sites that appear to have less value due to physical soil characteristics. The Wasatch Front, where Parrish and Centerville Creeks are located, is marked by a normal fault of large displacement. The west portion has been displaced downward several thousand feet, whereas the eastern Cottonwood uplift was displaced upward. It has many complex structural features such as several major synclines and anticlines as well as major and minor faults. The area is very steep, with the mountain crest in the study area near 9,000 feet and the various gauging stations mostly near 5000 feet MSL. The predominant sedimentary rock formations are sandstones, shales, conglomerates and limestones. Major igneous rocks are granite and quartzite. Major metamorphic rocks are migmatite, pegmatite, granulite, gneiss and hornblende-biotite granite. There is evidence of extensive glacial action in many of the canyons as well as glacial cirques. (Bell, 1952) Soils in the upper regions are generally coarse textured, immature, rocky and shallow; parent material was disintegrated in place by frost action. Many profiles are stony throughout (Olson, 1949).

Parrish Creek has a drainage area of 2.08 square miles above the gage elevation of 4,600-feet. There is historic evidence and records of flood and mud/debris flows in the past. Parrish Creek The watershed vegetation consists mainly of Aspen / Conifer stands at higher elevations with Sage Brush, Gambel Oak and various brushy species at lower elevations. The watershed orientation is westerly (Julander, 1988). The SNOTEL site is located in the center of the watershed at an elevation of 7740 feet MSL. The site aspect is westerly and the vegetation at the site location is primarily Aspen, forbs and grasses.

Centerville Creek is directly adjacent to Parrish Creek and has a streamflow gauging station maintained by the USGS with a fairly long record. It is very analogous to the Parrish Creek watershed in terms of elevation, aspect, geology, vegetation, hypsometric curve and orientation. It is slightly larger at 3.15 square miles. Centerville Creek streamflow will be used to correlate snow and soil moisture.

Analysis

In a fortuitous set of circumstances, peak snow water equivalent at the Parrish Creek SNOTEL site was essentially equal for three of the four years of data analysis, which gives more or less a constant in a mass balance context with regard to snowmelt input. Soil moisture and streamflows were, over that same period, highly variable giving a very good correlation and highly promising results from this small watershed. Figure 2 shows streamflow for Centerville Creek, SWE and a weighted soil moisture index for the Parrish Creek Watershed. For the first three years of data collection, the peak SWE was essentially equal at 26.8, 25.5 and 26.6 inches for the water years of 2000, 2001 and 2002. The total streamflow for the period of April through July for those years was highly variable at 841, 1199 and 1105 acre-feet respectively. The seasonal average for the period of record is 1,452 acre-feet. The range in flow for the study time period is 353 acre-feet which is 24% of the long term average, a significant deviation from what is ostensibly equal snowpacks or water inputs to a watershed mass balance. The question now being, can this variability be directly correlated to some kind of soil moisture index or is it insignificant when coupled with other snowpack losses such as sublimation or evapotranspiration? Other questions would be what kind of soil moisture index might explain the most variability? What time frame is most important - fall or spring moisture? What kinds of factors may influence soil moisture over time? In looking at the weighted soil moisture index, there are some complex processes occurring. With extremely warm, dry summers and falls over these years, the depletion of soil moisture over this time frame is readily apparent. However, during the winter months, soil moisture appears to rebound to some extent except the 2004 water year. At first, it was thought that this could be due to some soil surface melt from the snowpack but this was discounted when the total amount of water necessary to bring soil moisture from an index of 13% to 27% was compared to precipitation events and snow water equivalent records from the site.

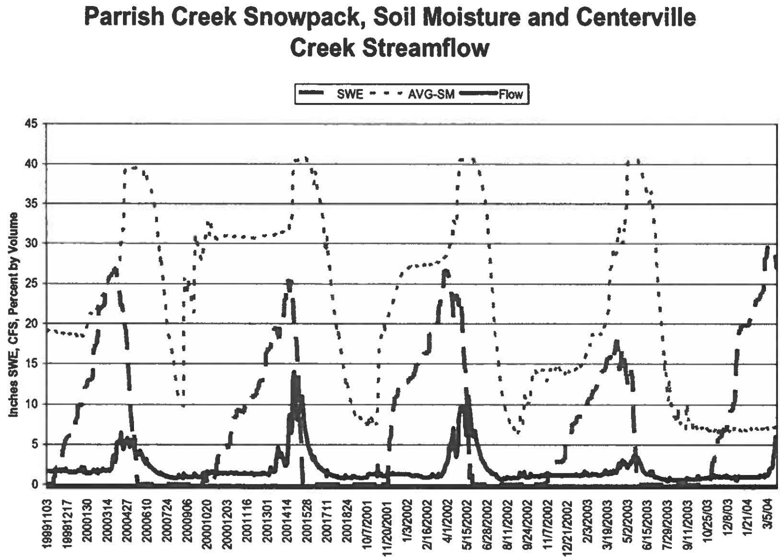

Figure 2. Snowpack, Streamflow and Soil Moisture.

The rebound in soil moisture may be due to the topographical convergence features of the site. It is in the very bottom of a small cirque on the watershed and potentially moisture from the surrounding slopes could migrate downward to the sensors over the winter period where it essentially remains till the beginning of ablation. Of particular note in Figure 2 is the fact that during the current 2004 water year, this phenomenon has not occurred and could be due to the longevity and intensity of drought in this area leaving very little moisture to migrate this year. With regard to the response in streamflow, the higher the soil moisture index in the three equal snowpack years, the higher the response in flow and conversely, low soil moisture severely limits flow. In the 2003 water year, note that soil moisture had less rebound in the winter months and thus going into the melt season, was able to take significant more snowmelt. This combined with 30% less snowpack yielded an extremely poor runoff season of only 494 acre-feet. If snowpack and streamflow had a strictly linear relationship, 30% less snowpack would have yielded runoff in the 750 to 800 acre-foot range, essentially double the observed flow. Given the fact that the March soil moisture index was near 15%, the lowest value of all years of data up to the current year, indicates that losses to soil moisture could easily account for the loss in flow and that the incorporation of soil moisture as a forecast variable could explain significant variability in current equations.

Using the soil moisture percent by volume data, one can calculate a relative estimate of the soil moisture deficit, or the potential amount of snowpack that, given the correct ablation circumstances, could be infiltrated to the soil and lost from direct surface flow to the stream. (Julander and Cleary, 2001) Using this deficit index, a simple multiple linear regression model was constructed using all five years of data available and compared to a regression model using snow water equivalent alone. The soil moisture deficit index used was a November as well as a March index to determine how far in advance soil moisture could reasonably portend an impact on runoff. Using snow water equivalent alone produced an R-square of only 0.40, extremely poor results considering that there were only 5 data points available for analysis. When the November soil moisture deficit was added to the April 1 snow water equivalent, the R-Square improved to 0.74. And finally, when using the March soil moisture deficit instead of the November, the R-square improved to 0.88, a significant improvement. The standard error was reduced from 718 down to 412 acre feet, also a significant improvement. This analysis appears to show that point soil moisture data has the potential to significantly improve snow melt based water supply forecasting at some locations.

In a broader geographic scale covering northern Utah, the past 5 years have shown tendencies at many sites towards less efficient runoff. That is to say, snowpacks seem to have had greater losses and have generated proportionately less streamflow during these mainly below normal snowpack years. Summers have been very hot and dry, depleting soil moisture which, in turn seems to be impacting runoff. Figure 3 shows just such a case for the Weber River Watershed. In 1999, a basin average snowpack of 82% produced streamflow of 100% to 120% of average on two watersheds within the basin. We do not know what the soil moisture condition across the basin was during that year, but the assumption is that it was sufficient for a very efficient runoff, since the seasonal runoff during the previous four years was above average. The very next year, 2000, snowpack was actually higher at about 90% of average but produced far less flow on the two basins, 30% to 60% of average. In the year 2001, with a far smaller snowpack, (62%) runoff is essentially the same, 30 to 55% of average. In the 2002 water-year, snowpack is again higher at nearly 82%, but runoff remains static at the 30% to 55% range. Finally in 2003, snowpacks are similar to the 2001 water year yet streamflow is markedly lower at just 15% to 20% of average.

If we correlate to just the Parrish Creek soil moisture site (the only site with sufficient data), the 2000 water year had a fairly dry March index of 18, fairly dry and the streamflow compared to the previous year was much lower. In the 2001 water year, the March Soil Moisture index rebounded to 31 and streamflow remained the same as the previous year but with nearly 20% less snowpack. In 2002, the soil moisture index decrease to 27%, not a great deal but again, streamflows are nearly the same as in 2001. However, the snowpack was nearly 20% higher, maintaining a solid relationship between flow, SWE and the March Soil Moisture index. During the 2003 water year, the snowpack was similar to

2001, but the watershed produced only 40% as much flow. The March Soil Moisture index during this time had fallen to its lowest point of 15, thus accounting for the difference in flow.

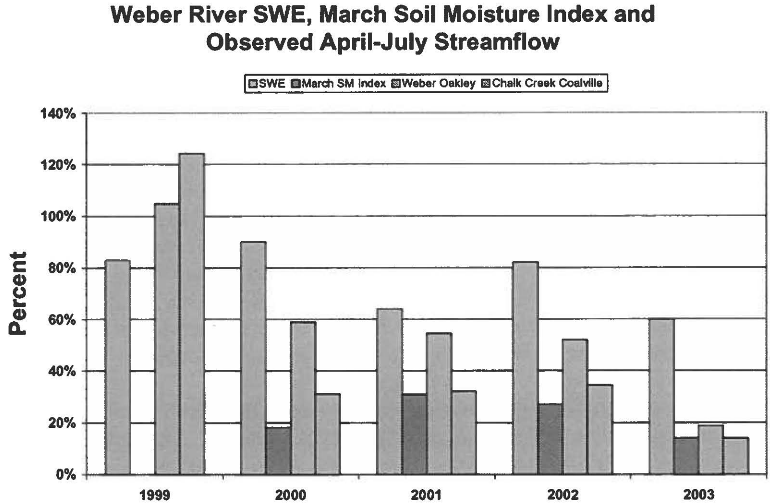

Figure 3. Weber Basin Average SWE, March Soil Moisture Index and Observed April-July Streamflow.

CONCLUSION

Preliminary results of soil moisture data seem to explain some of the wide error discrepancy between computer generated forecasts from SWE data and observed streamflow on Parrish Creek/Centerville Creek in northern Utah. The anecdotal use of soil moisture data as an indicator of abnormal conditions that could cause a significant deviation in the empirical relationship between SWE and observed streamflow is gaining acceptance and forecasts are being subjectively modified to include these conditions. In a more quantifiable context, previous year's data for streamflow, SWE and soil moisture can be used to proportionally modify current year's forecasts. The complex relationships between soil moisture, ground water contributions and runoff preclude more definitive analysis or a precise accounting of the total water balance of the basins. It is apparent that extreme deviations in soil moisture, such as those encountered in the past few years in northern Utah can have an extraordinary impact on streamflow, not explicitly accounted for in statistical forecast equations. Certainly long-term soil moisture data will give a much clearer picture of these complex interactions and hopefully, a reduction in forecast error.

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