Improved Water Supply Forecasts Using Soil Moisture Data

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Abstract

Much of the water in the Western United States used for irrigation, municipal supplies and hydro-electric production originates as winter snow pack at higher elevations. Since the early 1900s, the correlation between stream flow and the snow water equivalent (SWE) has been used to forecast the available water for beneficial uses and assess flood potential. Currently the US Department of Agriculture, Natural Resources Conservation Service (NRCS) maintains a network of nearly 850 high elevation stations called SNOTEL to collect snow and climate data in addition to over 1100 manually measured snow courses used in the statistical based forecasting of streamflow. Because the soil under the snowpack represents a significant storage reservoir for snow melt water, soil sensors began to be installed at SNOTEL sites starting in the late 1990s. In this network, some of the longest records of soil moisture are at three Idaho SNOTEL sites. This study is to determine if 14 years of soil moisture data at 3 SNOTEL sites measured with the Stevens Hydra Probe could statistically improve the stream flow forecasts at a river gage operated by the US Geological Survey (USGS). A parameter call the Soil Moisture Deficit Index (θ_{di}) was calculated from the average soil moisture and the soil's water content at 333 hPa, was used as an attenuation coefficient in the stream flow forecasts. The forecasted stream flow was compared to the actual stream flow recorded by the USGS and a correlation faction (R) was developed to compare the accuracy of the forecasts. Preliminary work shows that soil moisture data improved the water supply forecast and showed a positive correlation between stream flow and soil moisture deficit index. The impetus for an improved forecast are many, as water resources continue to be limited, especially in light of increasing demand in an environment where there is evidence that climate change is changing seasonal snowpack and snowmelt timing.

Introduction

Water in the Western United States

Most of the water in the arid part of Western United States originates from as snowpack at higher elevations (Folliott, et al., 1989). The streamflow in most streams in the western US are fed from the springtime melting of the seasonal snowpack or fed from aquifers that are recharged by snowpack melt. In the western United State, about 80% of the water consumed is for irrigation (Kenny, 2005) since many crops grown in the west require irrigation. Another major use for water in the western United States is hydroelectric power. More than half of the electricity in the States of Oregon and Washington come from hydroelectric (US EIA). In recent years, climate change has been identified as a factor that could affect the snowpack in terms of the amount of available water and the timing of the runoff, and thus affect the availability of water. Monthly forecasts of the seasonal water supply from the snow pack are critical for water management decisions for irrigation, hydroelectric, and other water uses (emergencies, such as for flood mitigation).

SNOTEL and Snow Survey

The relationship between the snowpack characteristics and the available water throughout the year for specific watershed basins was first scientifically studied in the early 1900s by setting up snowpack observation reference points called snow courses (SNOTEL). The snow water equivalent (SWE) which is the amount of water the snowpack would yield if it were to melt was correlated statistically to volumetric streamflow at monitoring stations in the watershed (SNOTEL). The SNOTEL program emerged from the snow courses in the 1970s, when the snow courses were suplimented or replaced with a new automated station. Today, the US Department of Agriculture National Resources Conservation Service (NRCS) operates about 900 SNOTEL sites in 12 western States and provides seasonal streamflow forecasts for water management and decision making for many federal, state and local water users, and the general public (SNOTEL).

Streamflow Forecast Modeling

Statistical models are used to forecast water supplies using a spreadsheet approach developed by the NRCS. This model is based on a statistical principle component regression between the antecedent snow data from the SNOTEL network and the historical streamflow data measured at US Geological Survey measurement points. This regression analysis is a statistical technique restructuring a set of weighted inter-correlated variables to generate a new variable (principle component). The weights of inter-correlated variables used in the linear combinations are from eigenvectors of the correlation matrix. The output variable, principle component, is an eigenvalue represented by a percentage of a total variance (Garen, 1992). This allows the modeler to use several interrelated variables to produce a robust regression equation. The input variables in the water supply forecast, using the model, are parameters such as snow water equivalent (SWE), antecedent precipitation, and observed streamflow. The statistical measure used to determine the accuracy of the forecast is correlation coefficient, R, (sometimes called the skill of the forecast) between the actual stream flow and the model produced forecasted streamflow values. The closer the R value is to 1, the stronger the correlation between the predicted and measured data and the better the accuracy of the forecast.

Soil Moisture Deficit Index

The soil under the snow pack represents a large reservoir capable of holding large amounts of water in a watershed and the soil moisture is an important factor in forecasting streamflow. Preliminary work (Lea and Harms, 2011) suggests that soil moisture data could significantly improve streamflow forecast. They indicated that the use of the data was provisionally an important parameter in improving water supply forecasts. With the additional years of data and using the full soil moisture deficit of the soil column, there is an improved correlation to streamflow, and the accuracy of streamflow forecasts is also improved. Soil moisture historically has not been used in the water supply forecasts because soil moisture data were not available, and hydraulic properties of the soil were scarce. Monthly precipitation has been used as a surrogate of soil moisture, as well as groundwater well data, when available. Starting in the late 1990s, SNOTEL stations began to include the Stevens Hydra Probe Soil Sensor and now many SNOTEL stations have been equipped with Hydra Probe Soil Sensors. The Hydra Probe soil sensors are installed at standard depths of 5, 10, 20.3, 51 and 102 cm. Sensors at multiple depths capture the distribution and the variation of water content gradient throughout the soil column as it changes throughout the year. At some SNOTEL sites, the deeper probes may not be installed if there is shallow bedrock. The SNOTEL station evaluated here, Bogus Basis, Jackson Peak, and Atlanta Summit, have the four soils sensors at the standard depths but do not have a soil sensors at 102 inches.

The available water held in the soil at a given point in time is the difference between the field capacity, θ_{fc} and the soil moisture at that point in time, θ (m^3m^{-3}). The available water holding capacity of the soil is defined as the soil moisture deficit index, $\theta_{di:}$

$$\theta_{di} = \overline{\theta} - \theta_{fc} \qquad [1]$$

where $\overline{\theta}$ is the average soil moisture throughout the column for a time step. The field capacity, θ_{fc} , is the upper limit of soil moisture where the soil's capillary forces can no longer suspend water. If the soil moisture is above field capacity, the soil is near saturation and water can be pulled downward by gravity or run off. If the soil moisture is below field capacity, the water is held in the soil by capillary forces. In this study, the soil moisture deficit index is a parameter that describes how much more water the soil can retain during the spring melting period and theoretically is positively correlated to stream flow. It will be a negative value if the moisture content is below field capacity, equal to zero at field capacity and a positive number above field capacity.

The purpose of this work is to quantify the improvements to the streamflow forecasts by incorporating the soil moisture deficit index on monthly time steps into the principle component statistical model along with the SWE and precipitation data.

Methods

Site Descriptions

Three SNOTEL sites in Idaho, namely, Bogus Basin, Atlanta Summit, and Jackson Peak were used in this study to forecast the streamflow at the USGS monitoring point on the Boise River near Twin Springs site ID 13185000. Each of these SNOTEL sites contains the standard complements of sensors, such as snow pillows for measuring SWE, a large cumulative "rocket gage" for measuring total precipitation, as well as meteorological sensors to measure parameters such as wind speed and direction, air temperature, relative humidity, and barometric pressure. In addition to the standard sensors, these SNOTEL sites also have four to five Hydra Probe Soil Sensors at 5, 10, 20.3, and 51cm and are among the first soil probes installed in the SNOTEL network. Hourly data are reported and transmitted via Meteor-burst telemetry to telemetry ground receive sites and stored on an NRCS server. The data are available from the NRCS web site http://www.wcc.nrcs.usda.gov/snow/.

Soil Moisture Sensors

The soil sensors used are the Stevens Hydra Probe Soil Sensor. The Hydra Probe is an impedance based dielectric sensor that contains a fractal model that separates out the real from the imaginary dielectric permittivity (Campbell, 1990, Logsdon, 2005). Dielectric permittivity is a complex number containing both a real and imaginary component and is dependent on the frequency, temperature, and the properties of the material. This can be expressed by,

$$\kappa^* = \varepsilon_r - j\varepsilon_i \qquad [2]$$

where К* is complex dialectic permittivity, ε_r is the real dielectric permittivity, ε_i is the imaginary dielectric permittivity and $j = \sqrt{-1}$ (et al. Topp, 1980). The soil moisture is determined from the real component due to the strong rotational dipole moment that water has in relation to soil from 1 to 1000 MHZ. A general calibration based on a dielectric mixing model was used and is expressed in equation [3] (et al. Seyfried, 2005).

$$\theta = A\sqrt{\varepsilon_r} + B \qquad [3]$$

where "A" and "B" are empirical coefficients fitted from 20 different soil samples representing a variety of soil textures and morphologies (et al. Seyfried, 2005).

Regression Modeling

The inputs to the model in monthly time steps from October 1997 to March 2014 are snowpack SWE value on the first of the month and total accumulated monthly precipitation (snow and rain) are used every month. The hourly soil moisture values collected at each depth were averaged across depth for the whole month. The field capacity was physically measured and determined by the volumetric water content at a potential of 333 hPa (1/3 bar). The soils data is exhibited in table [1] and the soil moisture deficit was calculated using equation [1].

Table 1, Soil survey data including the water content at 333 hPa (Lea and Harms 2011)

SNOTEL Site	Horizon	Top depth (cm)	Bottom Depth (cm)	Water content at 333 hPa
Atlanta Summit	A	2.00	5.00	12.79
	Bw1	5.00	23.00	24.24
	Bw2	23.00	36.00	21.44
	C	36.00	58.00	20.45
Bogus	A1	0.00	5.00	21.62
	A2	5.00	18.00	21.11
	A3	18.00	38.00	25.60
	Bw1	38.00	63.00	12.59
	Bw2	63.00	91.00	14.50
	Bw3	91.00	119.00	16.42
Jackson	A	0.00	13.00	28.36
	B1	13.00	25.00	24.53
	B2	25.00	43.00	19.00

Figure 1. Soil moisture deficit index and average soil moisture from October 1997 through March of 2014.

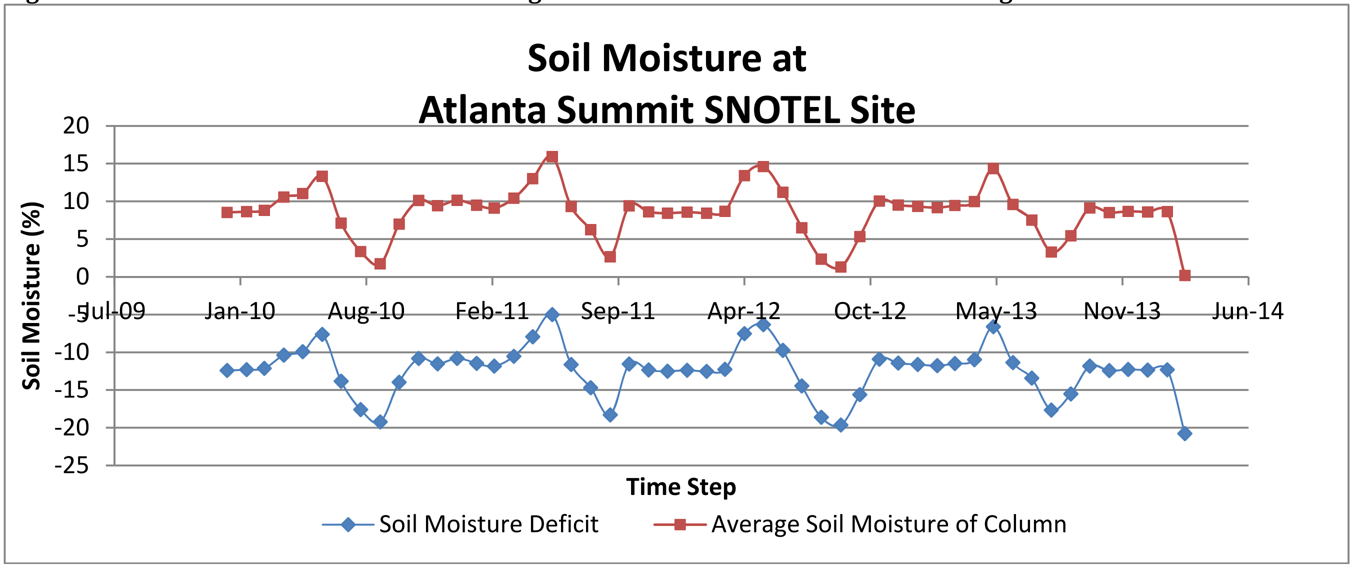


Figure 1 shows that there is strong correlation between the average soil moisture and the soil moisture deficit. Distinct seasonal trends can be observed. Both the soil moisture and the deficit index reach a low point in late summer when the soil is the driest and reach a maximum in spring when the snow begins to melt. The monthly seasonal soil moisture pattern is consistant with seasonal precipitation in this region with higher values in the spring during the melting period and lower values in the summer during the drier parts of the year. Soil moisture deficit index will theoretically be a better predictor of streamflow than the average soil moisture because it takes into consideration the soil textural differences in the ability to hold and retain water.

The average monthly soil moisture deficit was used as a parameter in the regression equation to assess if it could be correlated enough to be used in the water supply forecast. Each station's soil moisture deficit index was an input as a monthly time step and the best fit for the forecast was the soil moisture deficit from the previous summer. This is logical assuming that the winter precipitation and snowpack would melt filling the soil pores combining with the residual soil water from the previous summer before the streamflow runoff would occur.

Results and Discussion

Adding the average monthly soil moisture deficit for each station into the regression model produced the following correlation results:

Table 2. Regression correlation for each station soil moisture deficit to the Boise River at Twin Springs April-July 2013 streamflow.

	Atlanta Summit SNOTEL	Bogus Basin SNOTEL	Jackson Peak SNOTEL	3 Stations
	Previous May-September	Previous Mar-September	Previous Mar-September	
Correlation coefficient(r)	0.361	0.429	0.405	0.484
Years of data	14	13	15	13

When the soil moisture deficits for all stations are combined in a variable in the forecast model, the correlation is 0.484. Using it as the sole predictor in the model of streamflow produces relatively good results that roughly follow the streamflow volumes of high and low years [Figure 2]. When θ_{di} was used in conjunction with the traditional snow and precipitation parameters, the forecast showed significant improvement over the model based on snow and precipitation alone. As shown in Figure 2, the flow simulation is closer to the actual flows for the model that included the soil data with the precipitation parameter than the simulation that include the precipitation parameter alone (Historical Forecast) from 2001 to 2013.

Figure 2. Boise River Flow vs. year. Historical forecast, modeled with soil moisture deficit only, and modeled with snow and soil moisture deficit.

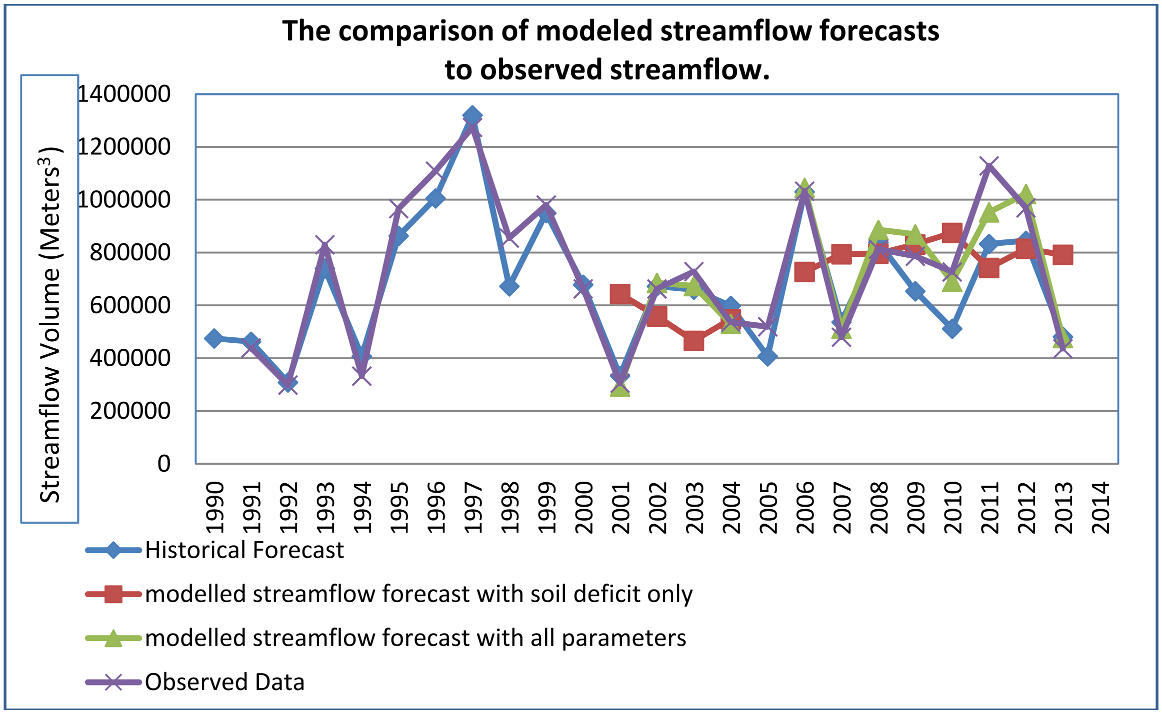
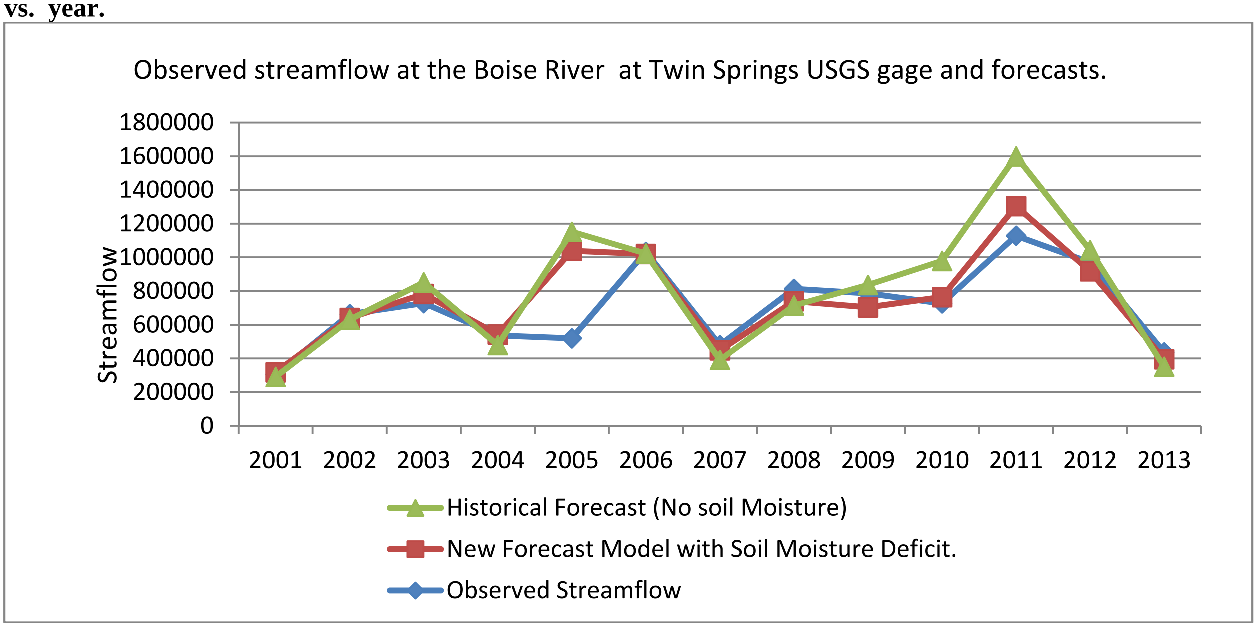


Figure 3 indicates the absolute errors from 2001 to 2013 between the model simulations and the actual stream flow. Streamflow forecasts that include the soil moisture deficit index have less absolute error than those forecasts that is used as a parameter in the forecast.

Figure 3. Historical Forecast, the new model with soil moisture and the observed streamflow, Volume/year vs. year.



Each of the parameters in the forecast provides a percentage of the total to provide the best statistical model of the streamflow volume. The average monthly soil moisture deficit accounts for 13% of the total forecast model. Each station accounts for a portion of the total (table 3.). All the April 1 snow (SWE) combines to a weighted value of 59%, while the combined weighted march precipitation accounts for 28% of the forecast total.

Table 3. The monthly average soil moisture deficit accounts for a percentage of the total modeled forecast equation for the Boise River at Twin Springs Idaho April-July volume.

	Atlanta Summit SNOTEL	Bogus Basin SNOTEL	Jackson Peak SNOTEL	3 Station total
Percentage of the total forecast accounted for by the soil moisture deficit for each station.	3%	5%	5%	13%

Conclusion

Using soil moisture measurements directly can improve the water supply forecasts to provide a more accurate model and assessment of water supplies. The soil moisture deficit also provides early information before the winter season about the water needed to fill the deficit and its effect on the snowmelt streamflow runoff. As the years of data increase for the soil moisture sensors at the NRCS stations, the data will be able to be used in more models across the West. The NRCS SCAN (Soil Climate Analysis Network) also has soil moisture sensors and that data can be used in other applications across the country.

Disclaimer:

The USDA NRCS does not endorse any source or product in our climate and snowpack measurement system.

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