SNOW MELT, ENERGY BALANCE, AND PREDICTION: MORMON MOUNTAIN

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ABSTRACT Management of snow, as a water resource within the arid/semi-arid southwest, requires timely and accurate predictions of snow melt. Using energy balance, regression, and temperature melt factor models predictions were generated from in-situ hydro-meteorological observations. Comparisons were made between model and USDA Soil Conservation Service Snow Telemetry [SNOTEL] snow pillow. Observed days of melt, as reported by the snow pillow, appear to summarize all previous days' worth of melt that were below the snow pillows' sensitivity. Coupling direct observations and model predictions appear necessary for timely and accurate predictions of snow melt.

Snow melt is the single most improvable and manageable water resource available for the unrelenting needs of the arid/semi-arid southwest. Numerous regional studies [Jones and Brazel, 1986; Ffolliott and Rasmussen, 1976], predictive technique studies [Ffolliott, 1985; Jones et al, 1976], and simulation models [Rasmussen and Ffolliott, 1981; Solomon et al, 1976] have been completed. All have indicated differing results due to variables observed, period and frequency of observation, instrument sensitivity, spatial variability, and model type.

The focus of this paper and research is to determine the 'best' model type to predict snow melt. The study site used is one of fourteen permanent USDA Soil Conservation Service Snow Telemetry [SNOTEL] sites situated in Arizona. These sites are located along a northwest to southeast transect anchored to the south by the White Mountains and to the north by the San Francisco Mountains, and parallels the Mogollon Rim. The specific study site used is situated in a saddle just south of Mormon Mountain on the drainage basin dividing line between the Little Colorado and the Verde river at an elevation of 2287 m [7500']. This site is typical for the whole region lying upon a molli eutroboralf soil formed by the residuum of cinders over basalt formed during the Quaternary-Tertiary period [Choric, 1983]. The surface soil is dominated by the montmorillonitic clays which define a limited infiltration rate of only 0.05 cm/min. Snow melt, which can and does occur rapidly in this region, is forced into overland flow. Rapid melt and limited infiltration require immediate identification of melt to preclude flooding and assure maximum water sorage.

Each of the SNOTEL sites is instrument with a thermistor at 2 meters for air temperature, a snow pillow for solid precipitation, and a precipitation gauge for all precipitation. Daily observations are reported to a the western states master station in Ogden, Utah. The data is then forwarded to Portland, Oregon for inclusion into the SCS centralized forecasting system. Beginning in January 1989, a hydro-meteorological platform was erected to measure mass, heat, and energy exchanges between the snow, air, and ground. Measurements included solar radiation [incoming and outgoing], net radiation, wind and air temperature at three levels above the snow surface [50, 100, 150 cm], and relative humidity at 50 cm above the snow. Soil temperatures were collected from the snow-soil interface, and at 5, 10 and 20 centimeters below along with soil moisture probes. Together these instruments allowed for direct measurement or calculation of vertical energy and mass transfer from and between the ground, snow, and air. Readings were collected at 15 minute intervals on five different days [12-13 Jan, 20-21 Jan, 27-28 Jan, 10-11 Feb, 24-25 Feb] before the snow cover was gone. During periods without direct quarter hour observation, hourly data from the Flagstaff Weather Service Office [WSO], - to include wind, temperature, humidity, minutes of sunshine, and cloud cover - were used.

MELT MODELS

Several models for snow melt prediction have been derived. All models can be classified as full energy balance [FEB] considering ground-snow-air interfaces, surface energy balance [SEB] considering snow-air interface only, temperature models [TEMP] which only use air temperature, or regression models [REG] which use whatever data is available and correlates with melt. Energy balance models are the most complex requiring direct observation of all radiation, heat, and mass exchanges [Gray and Male; 1981; Colbeck, 1972].

$$Qm = Qs + Ql + Qh + Qe + Qg + Qp - du/dt \quad [1]$$

Qm = energy flux available for melt
Qs = net short-wave energy absorbed by the snow
Ql = net long-wave radiation absorbed by the snow
Qe = latent heat flux at the snow-air interface
Qh = convective/sensible heat flux at the snow-air interface
Qg = heat conduction at the ground-snow interface
Qp = heat flux from the rain
du/dt = rate of internal snow cover change per unit area

Melt is therefore a function of external affects and internal conditions.

$$M = Qm/[p*hf*B] \quad [2]$$

M = melt in water equivalent [cm/d]
Qm = energy flux available for melt [kj/m2]
p = density of water [1000 kg/m3]
hf = latent heat of fusion [333.5 kj/kg]
B = fraction of ice in wet snow [estimated from .95 to .97]

For surface energy models the conductive heat exchange from the ground [Qg] is ignored. Ignoring Qg significantly reduces the difficulty of observing and recording mass and heat transfer from and to the ground as well as reducing the instrument set up costs. The strength of these models are in their ability to be applied anywhere for varying frequencies of observation. The weaknesses of these models are their large instrument requirements and high operational maintenance.

Temperature models, also referred to as degree days [Kuusisto, 1984; Male and Granger, 1978], require only air temperature to estimate melt. Much research has identified the strength of using this one variable for predicting melt [Morris, 1985; USACE, 1956].

$$M = MF\ [Ta - Tref] \quad [3]$$

M = melt in water equivalent [cm/d]
MF = melt factor [locally derived]
Ta = air temperature [Celsius]
Tref = reference temperature [minimum temperature for melt]

Each location requires a calibration period during which the melt factor and reference temperature are determined. The strength of this model is its' limited observation data - melt and air temperature - and set up costs. The weakness of this model is that local variations such as slope, aspect, canopy cover, elevation, and snow cover require new coefficients and are not universally applicable.

Regressive models use whatever data is available and correlates with the observed melt. Instrumentation, the heart of this type of research, is the blessing and bane of the researcher. This method allows the use of all data observed.

$$M = a + b1[wyd] + b2[swe] - b3[Ta] \quad [4]$$

M = melt in water equivalent [cm/d]
a = y intercept [variable]
b = slope relating melt and independent [variable]
wyd = water year date [day number beginning 1 Oct]
swe = snow water equivalent [inches of water]
Ta = air temperature [Celsius]

This specific model was calculated for this study site on Mormon Mountain. Note that the variables used are those provided directly from the SNOTEL system. The strengths of this model type is its' ability to use available data. The weakness of this model is that the results are not comparable with melt processes at other locations, and are not universally applicable.

MODEL COMPARISONS

Comparisons were then made with the four model types. The FEB model is limited to the five days of direct energy balance observations. The SEB, TEMP, and REG models could be calculated for the full snow season using the SNOTEL and Flagstaff WSO data. The following table portrays the basic data and period.

Table 1. Snow Melt Model Comparisons

Model	Size [n]	Mean [x]	SD	r2	Estimate
FEB	5	.144	.164	.55	Over
SEB	124	.002	.007	.06	Under
TEMP	124	.055	.053	.11	Under
REG	124	.295	.357	.46	Over
OBS	124	.244	.565	-	-
OBS'	5	.204	.408	-	-

Two observed data sets are used for comparison. The full 124 day set for SEB, TEMP, and REG, and the 5 day set for FEB. The regression and full energy balance models overestimated cumulative melt. Temperature and surface energy balance models underestimated total melt.

All but the regression model underestimated the mean melt size. All models underestimated the standard deviation [SD] of the melt sizes. The coefficient of determination [r2] identifies both FEB and REG as very different from the other models, but with neither being very strong. All of these differences between the models and the observed variables appear to relate to melt days and size of melt. There is a need to compare their identification of melt days.

Table 2. Model Melt Day Predictions

Model	Correct NonMelt	Correct Melt	Correct Total	% Corr. NonMelt	% Corr. Melt	% Corr. Total
FEB	2	1	3	50	100	60
SEB	80	9	89	89	27	72
TEMP	9	21	30	10	64	24
REG	3	32	35	3	97	28
OBS	91	33	124	-	-	-
OBS'	4	1	5	-	-	-

Initial melt day identification shows SEB and FEB as 'best' however for different reasons. SEB is 'best' at identifying non-melt days - which are the majority. The FEB is 'best' at correctly identifying melt days. Interesting to note is the efficiency of REG at identifying melt days also. REG, however, is not very good at predicting non-melt days. TEMP models fail to identify melt and non-melt days very well.

It would appear that a combination of models to identify melt and non-melt days is necessary. With the SEB identifying non-melt days and REG predicting melt days a total percent correct of 81% would result. This combination is higher then any single model. A critical question lies in melt size prediction. The SEB model primarily predicted zero size melts even on the 24 days during which melt was observed. REG correctly identified only three of 91 non-melt days assigning very small melts to these days. Melt size predictions therefore become a concern.

Using the observed melt data - mean and standard deviation - a comparison with each model is made. Critical to this portion of the analysis is the ability of each model to predict the correct melt size.

Table 3. Melt Size Prediction.

Model	0	<x-sd	<x	<x+sd	>x+sd	% Corr.
FEB	50%	-	-	-	100%	60%
SEB	89%	-	25%	-	-	66%
TEMP	9%	23%	50%	-	-	13%
REG	4%	31%	38%	33%	83%	14%
OBS	91	13	8	6	6	124
OBS'	4	-	-	-	1	5

SEB only identified non-melt days well; missing all but 2 average size melts. FEB predicted two small melts that were not recorded but were below the snow pillows' sensitivity of one-tenth of an inch of snow water equivalent. The TEMP model missed almost all of the melt and non-melt days by always predicting very small melts thus indicating a need to raise the melt factor coefficient and the reference temperature to reduce the number of melts predicted. REG also over predicted melts - all under the snow pillow sensitivity - but appears the have done the best at predicting melts of all sizes. REG correctly predicted melts from the largest down to the mean melt minus the standard deviation. Once again by combining SEB and REG it appears possible, without adjusting the coefficients, to correctly identify non-melt days using SEB, and the melt days and sizes using REG.

Melts below the mean minus the standard deviation lie below the snow pillow's sensitivity. The snow pillow introduces a problem with infiltration. Melt, as recorded by the pillow, really measures runoff since the pillow is impermeable. Impermeable soil conditions, although often valid for very cold conditions, do not represent the average conditions along the Mogollon Rim. A secondary problem is forced storage of melt water within a snow pack. Because the melt water cannot infiltrate into the soil it is appears to be artificially retained within the snow pack. There exists a need therefore to either design the snow pillows to simulate infiltration using a porous outflow or to directly measure soil moisture changes.

SUMMARY

Model selection for snow melt along the Mogollon Rim needs to identify melt days from non-melt days, to estimate amount of melt, and finally be accomplished at a minimal cost in instruments and operation. Four model types were reviewed ranging from full energy balance with observation of numerous variables, to surface energy balance ignoring ground to snow exchanges, to temperature index models requiring only air temperature and spatially derived coefficients, and finally to regression models using routinely available data. The surface energy balance model was best at estimating non-melt days. Full energy balance was 'best' for melt days but was only applied a limited sample period due to highinsrument cost odf setup. The regression model effectively identified almost all of the melt days for the whole study period. A combination of SEB and REG appear to hold the 'best' potential for identifying melt and non-melt days.

Melt size estimates varied greatly. The full energy balance model accurately predicted the melt size on the one melt day observed but also predicted two melts below the snow pillow's sensitivity on two other days. Melts of these size could easily be retained within the snow pack itself. The surface energy balance and temperature models identified only small and average melts. The regression model was able to identify almost all of the large melts and a portion of the other three melt sizes. One problem with all the models appears to be the use of melt size as observed by the snow pillows. The pillow cannot identify melts below one tenth of an inch of snow water. It is possible that the snow pillow denies small melts and subsequently reports artificially larger melts. There exists a need to observe smaller melts to validate their existence and provide more accurate melt day determination and melt size estimate.

With the instrumentation and data currently available the combination of surface energy balance and regression models provide the 'best' means of determining melt days from non-melt. Having determined on which days melt occurs the regression model provides the 'best' agreement with recorded snow pillow melt sizes. Finally, a means of verifying the existence of small melts is necessary to effectively predict how much and when melt occurs for flood and water resource management along the Mogollon Rim to support the continuing growth in the arid/semi-arid southwest.

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