TEMPERATURE INDICES OF SNOWMELT DURING RAINFALL

BY

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Rain-on-snow events require special techniques of estimating snowmelt for both physical and practical reasons. Snowmelt during rainfall results primarily from turbulent exchange processes as opposed to radiation-dominated energy exchange during clear weather. Thus, different factors must be considered during rain-on-snow events than under clear skies. Rain-on-snow events also have much greater potential for generating serious floods than do short periods of radiation-induced snowmelt. Therefore, accurate forecasting of snowmelt is particularly important during rainy conditions.

When solar radiation is largely blocked by thick clouds, the turbulent transfer of latent and sensible heat becomes the principal energy input to the snowpack. Energy exchange between the atmosphere and the snow results from temperature and moisture gradients and air movement in the zone immediately above the snow surface. These energy exchanges have been approximated for operational forecasting of snowmelt during rainfall.

Most streamflow simulation models now in operation use special equations for rainy periods. While these rain-on-snow melt equations are based on reasonably sound theory, little is known about their performance in isolation from other components of the streamflow models. Rain-on-snow melt equations were first evaluated by this author during the development of a snowpack water balance model for a weather modification project (Kattelmann et al., in press). The data set has been expanded and more equations considered in this assessment.

This paper reports an evaluation of the accuracy of several rain-on-snow melt estimation methods. The melt estimation equations considered here depend mainly on air temperature as an index of energy exchange at the snow surface. For typical situations, temperature index approximations often perform as well as more sophisticated energy balance approaches. However, the simpler index methods may fail under certain conditions, such as high humidity and strong winds (Anderson, 1979). Therefore, some of the methods examined here also include windspeed and vapor pressure as inputs.

ESTIMATION EQUATIONS

Seven equations for estimating snowmelt during rain-on-snow events were selected from the literature as being representative of those in use and for which input data were available at the study sites. Other methods of estimating rain-on-snow melt are generally some variation of these equations. A thorough energy balance approach was not included due to lack of adequate input data.

The equations included here are largely based on the work of the Cooperative Snow Investigations of the U.S. Army Corps of Engineers and the then-Weather Bureau. The following assumptions can be made in simplifying more complete theoretical treatments of snowmelt during rainfall (U.S. Army Corps of Engineers, 1956):

1. Shortwave radiation input is minimal and can be represented as a constant.
2. Longwave radiation is linearly related to air temperature.
3. Convection and condensation melt may be approximated as a linear relationship with air temperature and windspeed during the typical high humidity conditions of warm storms.
4. Conduction melt from rain may be represented as a simple function of air temperature and rainfall.

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The following equations were evaluated in the study reported here (some were slightly modified to simplify computation):

$$M = T_a\,(0.133 + 0.086\,u_{15} + 0.0126\,P) + 0.23 \quad (1)$$
(U.S. Army Corps of Engineers, 1956)

$$M = T_a\,(0.142 + 0.051\,u_2 + 0.0125\,P) + 0.25 \quad (2)$$
(Dunne and Leopold, 1978)

$$M = T_6[0.032 + 3.91\mathrm{x}10^{-6}\,B\,u_{0.5} + 0.0126\,P_6] + 0.0514\,u_{0.5}\,(e_a - 6.11) \quad (3)$$
(Anderson, 1973)

$$M = 1.42\mathrm{x}10^{-3}\,T_a u_{10} + 7.34\mathrm{x}10^{-3}\,(e_a - 6.11)\,u_{10} + 0.23 + 0.0126\,P\,T_{wb} \quad (4)$$
(Winston, 1965)

$$M = T_a\,(0.45 + 0.013\,P) + 0.25 \text{ (for light winds, indexed as <400 km/day)} \quad (5a)$$

$$M = T_a\,(0.65 + 0.013\,P) + 0.25 \text{ (for high winds, indexed as >400 km/day)} \quad (5b)$$

$$M = T_a\,(DDF) \quad (6)$$

$$M = T_a\,(0.46) + 0.25 \quad (7)$$

where M = daily snowmelt (cm)
$u_{0.5}$, u_2, u_{10}, u_{15} = windspeed at 0.5, 2, 10, and 15 m respectively (m/s)
P = daily rainfall (cm)
P_6 = rainfall for a 6 hour period (cm)
T_a = mean air temperature ([T max + T min]/2) (°C) at 1 m above snow surface
T_6 = mean temperature for 6 hours (°C) at 1 m above snow surface
e_a = vapor pressure (mb) at 1 m above snow surface
B = atmospheric pressure (mb)
T_{wb} = wet bulb temperature (°C)
DDF = degree day factor, which changed monthly and was computed from observed clear weather snowmelt

All of the equations estimate snowmelt as a daily quantity, except for equation 3, which uses a 6-hour time period. Equations 3 and 4 require the most data. Equation 7 was developed during this evaluation by averaging the coefficients and constants of some of the other equations. It has not been calibrated.

STUDY APPROACH

The equations were tested with data from two sites on the western slope of the Sierra Nevada of California: the Central Sierra Snow Laboratory (CSSL) of the Forest Service, U.S. Dept. of Agriculture, at Soda Springs and the National Weather Service station at Blue Canyon. CSSL is located at 2100 m elevation near the crest of the Sierra near Donner Summit. It accumulates deep seasonal snowpacks and receives 1 or 2 major rain-on-snow events in most years. Blue Canyon is at 1600 m elevation in the lower part of the snowpack zone and is often below the storm snowline. These sites are the only locations in the Sierra Nevada with long-term records of both daily snowpack water equivalent (SWE) and the required input data. SWE was measured at CSSL in a 50 m diameter clearing in the forest, and at Blue Canyon, in an open area of several hectares.

All storms with usable record over an 11-year period at CSSL and over a 24-year period at Blue Canyon were included in the test data. Many storms were excluded due to deficiencies in the data or changes in precipitation type. Equation 3 was tested with Blue Canyon data for only a 10-year period due to insufficient data prior to 1974. Inputs to the equations were measured with standard meteorological instruments. Precipitation type was determined by observation. Windspeed was extrapolated from the anemometer level to other heights specified in the equations with a logarithmic windspeed profile (Linsley _et al._, 1975; p. 43). Storm characteristics varied greatly throughout the test period. Selected storms lasted from 2 to 10 days, storm rainfall ranged from 2 to 40 cm, and measured daily change in SWE ranged from 0 to 2 cm at CSSL and from 0 to 6 cm at Blue Canyon.

Changes in measured snowpack water equivalent over the duration of a storm were compared with the sum of the computed daily snowmelt values for each of the equations. The equations were evaluated in terms of objective error: (root-mean-square-error [RMSE] = $[\Sigma(\text{estimated } \Delta \text{SWE} - \text{observed } \Delta \text{SWE})^2 / \text{sample size} - 1]^{.5}$) and bias (Average Error = [estimated Δ SWE - observed Δ SWE] / sample size).

The equations were evaluated for each storm rather than on a daily basis to compensate for day-to-day errors in measurement of snowpack water equivalent. Water equivalent at CSSL was measured at the exact same location with a profiling snow gage, an instrument well-suited for monitoring changes in a portion of the snowpack (Kattelmann et al., 1983). Water equivalent at Blue Canyon was measured with a federal snow sampler at different spots within a small area. This change in sampling location at Blue Canyon and the inherent problems of the federal snow sampler in shallow snow suggest that the measurement and sampling error was greater at Blue Canyon than at CSSL. Although absolute measurement and sampling error cannot be determined, the probable maximum error in the change in water equivalent during a storm was assumed to be 1 cm at CSSL and 2 cm at Blue Canyon. Using changes in SWE for a storm period rather than daily changes also minimized the influence of water retention by the snowpack. Research in progress at CSSL suggests that water generally is detained by fresh snow for only a short time rather than being stored for a long period. Snowpacks at both sites were usually isothermal and any heat deficiency was assumed to be less than the overall measurement error.

RESULTS AND DISCUSSION

On the basis of computed errors (Table 1), the equations better estimated the measured snowmelt at the CSSL site than that at the Blue Canyon site. In addition to the measurement error discussed earlier and differences in sample size, this discrepancy may have resulted from the greater energy input and consequent greater snowmelt at the lower elevation Blue Canyon site. For example, air temperature during rainfall rarely exceeded 2°C at CSSL while it was commonly above 4°C at Blue Canyon. Values for the inputs and the measured snowmelt were small at CSSL. Therefore, there was less opportunity to generate large errors at CSSL than at Blue Canyon. Additionally, the Blue Canyon site is exposed directly to storm winds, whereas wind at the open site at CSSL is moderated by the surrounding forest and is probably more turbulent than at Blue Canyon.

The equations that performed best had RMSE values of 1.5 cm or less at the CSSL and 4 cm or less at Blue Canyon over the duration of a storm. Occasionally, the errors for a particular storm were much greater. An attempt was made to isolate troublesome properties of storms; however, there was no consistent pattern that related large errors and storm characteristics. The largest errors produced by the widely used U.S. Army Corps of Engineers equation (equation 1) occurred during long lasting storms with periods of intense rainfall or high vapor pressure or both. However, at other times, such conditions produced an accurate estimate.

TABLE 1. Computed errors in snowpack water equivalent (cm) estimated by eight equations and compared with values measured at the Central Sierra Snow Laboratory (CSSL) and Blue Canyon for all storms.

EQUATION	1	2	3	4	5	6	7
CSSL (n = 10)							
RMSE[1]	1.4	1.0	1.7	1.3	1.4	1.6	1.0
Average error	+.8	-.5	-.5	-1.0	+.2	-1.3	+.3
Blue Canyon (n = 26)							
RMSE[1]	6	3	3(n=10)	8	6	7	4
Average error	+4	+.3	+1	-6	+4	-5	+1

[1]RMSE = root mean square error

For this data set, equation 2 (Dunne and Leopold, 1978; p. 479-480) and equation 7 had the lowest RMSE values. The relatively low RMSE values of equation 7 were surprising because it was the simplest equation and required the least data--air temperature only. Equation 3 was the most sophisticated approach, requiring four separate computations per day. It also required the most input data. Equation 1 (U.S. Army Corps of Engineers, 1956) and its offspring, equation 5 (Kattelmann *et al.*, in press), performed adequately but appeared to suffer from an overly large coefficient in the wind term. This coefficient is essentially the only difference between equation 1 and equation 2. Equation 2 generates less melt out of the wind term than does equation 1 and was more accurate as a result. Equation 4 (Winston 1965) underestimated snowmelt in almost all cases and appears to suffer from excessively small coefficients in its convection and condensation melt terms. Equation 6 (the simple degree method based on clear weather degree-day factors) also underestimated melt in almost all cases and demonstrated that rain-on-snow situations do require special melt estimation techniques.

CONCLUSIONS

Simple equations requiring air temperature, precipitation, and windspeed estimated point snowmelt during rain storms within a few centimeters of observed change in snowpack water equivalent. In this comparison, equation 2 (Dunne and Leopold 1978, p. 479-480) had the lowest combined RMSE values for both sites and a simple temperature-only index (equation 7) had the next lowest. The temperature index method, where daily snowmelt = 0.46 cm per degree Celcius + 0.25 cm/day, may be of use where wind data are unavailable or judged too difficult to extrapolate. A more rigorous evaluation of these snowmelt estimation methods may be possible in a few years, when an adequate amount of precise snowpack outflow data from several locations under a variety of conditions are available.

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