FIVE SNOWMELT MODELS: A COMPARISON OF PREDICTION ACCURACY

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BY

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INTRODUCTION

In much of the Western United States, management of reservoir and canal systems depends on accurate predictions of each season's snowmelt runoff and on the pattern and timing of the runoff season. Snowmelt forecasts may be made using models that range from simple temperature indices to more complex models that incorporate heat and mass flux budgets.

Extensive areas of California's snow zone are managed by the USDA Forest Service. The effect of timber harvests on snow accumulation and melt has received deserved attention over the last 20 years (Harr, 1981; Anderson et al., 1976; Smith, 1974). Although results are not conclusive, harvested areas may sustain more rapid melt and produce runoff hydrographs that peak both earlier in the season and at higher discharge rates than forested areas.

Information on the quantity and timing of water released to the soil due to melt or rain on snow is the goal of a plot-scale snowmelt model. The ideal melt model for management use would contain variables such as cover density, shading, slope, and others that could be included in harvest planning. Most models now in use do not explicitly include such variables, but before development of new models begins, an evaluation of existing models and theory should be made. This paper reports on a comparison of the accuracy of five melt models in predicting hourly or daily snowmelt. The predicted results are compared against outflow data from four meltpans and changes in snow water equivalent (SWE) as measured by an isotopic profiling snow gauge and a snow pillow.

METHODS

The Central Sierra Snow Laboratory (CSSL), located near Soda Springs, California at an altitude of 2100 m, was the data collection site. About 100 cm of precipitation falls annually and about 80 percent of it is snow. Although recent winters have produced a 4.5-m snowpack with a SWE of 250 cm, the 30-year average snow depth on April 1 is 2 m with an SWE of 86 cm. Cool nights and warm, often sunny days create thick melt-freeze crusts of large sintered grains in forest openings. Rain on snow occurs several times per year, and water releases to the ground occur after January due to both rainfall and snowmelt on sunny days.

All data for this test were collected in an irregularly-shaped, 50-m diameter forest clearing. A movable platform and an instrument shelter 1 meter above the snow surface support radiometers, air temperature and dew point sensors, three-vector anemometers, and an infrared thermometer that senses snow surface temperature. Eight adjacent meltpans underlie 25 m^2 of snow, but only four of the meltpans were operating so the areal depths were averaged to yield a single outflow estimate. Snow density and water equivalent are estimated by an isotopic profiling snow gauge (Smith et al., 1972; Kattelmann et al., 1983), and SWE by a snow pillow. During the eight-day interval, four snow gauge and 150 snow pillow measurements were made.

Two temperature index models developed for the CSSL area were tested (U.S. Army Corps of Engineers, 1956):

$$\begin{array}{ll} M = .183\,(T_m + 2.78) & T_m > -2.78 \\ \quad = 0 & T_m \leq -2.78 \end{array} \qquad (1)$$

$$\begin{array}{ll} M = .274\,(T + 4.44) & T > -4.44 \\ \quad = 0 & T \leq -4.44 \end{array} \qquad (2)$$

in which M is melt (cm/day), T_m is the maximum daily temperature, and T is the average of the maximum and minimum temperatures ($^\circ$C). These models incorporate all melt processes in rate and base temperature coefficients.

Since much of clear weather melt is due to insolation, a radiation model was included in the comparison (U.S. Army Corps of Engineers, 1956):

$$Q_m = QSN + QLN \qquad (3)$$

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in which Q_m is the heat of melt (KJ/m2-hr), QSN is the net shortwave insolation (incident minus reflected), and QLN is the net longwave insolation (net allwave minus QSN). Daily melt or freeze "depths" were obtained by summing the hourly heat values and dividing by the product of density, latent heat of fusion, and thermal quality of the snow. A liquid water content of 5 percent was assumed, so the thermal quality was 0.95.

Convective or sensible heat absorbed from the air can affect melt quantities, as can the latent heat flux due to evaporation or condensation. Because data on temperature, humidity, and wind speed at multiple heights were not available, simplified expressions were used (Male and Gray, 1981; p. 390):

$$Q_m = QSN + QLN + D_h U_z (T_a - T_s) + D_e U_z (e_a - e_s) \qquad (4)$$

in which D_h and D_e are bulk transfer coefficients for convective and latent heat (0.00168 $KJ/m^3\text{-}^{\circ}C$ and 0.008 $KJ/m^3\text{-}mb$), respectively; T_a and T_s are air and snow surface temperatures (°C); U_z is wind speed at 1 m (m/s); and e_a and e_s are air and saturation pressures (mb). The fourth model includes the convective and latent heat fluxes.

The final model is similar to equation 4 except that the up and down longwave fluxes were explicitly calculated based on snow surface, air, and dewpoint temperatures:

$$\begin{aligned} LWU &= E \sigma T_A^4 \\ LWD &= (E_a \sigma T_A^4)\, VF + (E_v \sigma T_v^4)(1 - VF) \\ E_a &= 1.24\, (e_a/T_a)^{1/7}\, (P/P_o) \end{aligned} \qquad (5)$$

in which E, E_a, and E_v are snow, atmospheric, and vegetative emissivities, and T_A and T_v are air and vegetation temperatures (°K), σ is the Stefan-Boltzman constant (2.0411×10^{-7} $KJ/m^2\text{-}hr\text{-}K^4$), VF is the view factor of CSSL's forest clearing (0.80), and P and P_o are atmospheric pressures at the site and at sea level (mb). E and E_v were assumed to be 0.98 and 0.96, respectively. Atmospheric emissivity was calculated using Brutsaert's formula (1975) corrected for the reduced density of the mountain atmosphere.

RESULTS AND DISCUSSION

The study interval, April 20-27, 1984, contained both sunny and cloudy periods and followed a storm that deposited 4.8 cm of SWE. Albedo declined during the interval from 0.72 to 0.58, and an increase in net shortwave and net allwave is evident (Table 1). Net longwave became less negative during this time, indicating that less heat was being released from the snowpack. Average daily wind speeds ranged from 0.30 to 0.76 m/s, and both wind speeds and temperatures were lower during the cloudy period. Insolation levels were lower and more variable during April 25-26, and the depressed air temperatures reflect the decrease in energy input (Figure 1). Air temperature patterns are similar to snow surface temperatures under cloudy conditions, but the two were consistently different under clear skies. Snow surface temperatures were slightly in excess of 0°C under full sun.

Predictions by the two index models differed by 3.6 cm, but the melt predicted by model 2 for the cloudy days was 0 because T fell below the base temperature of -4.44°C (Table 2). The other three models produced higher melt estimates than the second model, and the melt amount decreased as additional variables were introduced. The effect of adding sensible and latent heat fluxes (model 4) was to reduce the melt quantities calculated by model 3, but the pattern of daily melts remained similar. The total sensible heat melt for the study interval was 0.6 cm, but the calculated latent heat loss due to evaporation was 2.8 cm. These values are small, however, compared to the net shortwave-induced melt of 28.8 cm and the net longwave heat loss of 14.7 cm.

The daily average outflow depths of the four operating meltpans corresponded with predictions by models 3 and 4 (Table 2), but the unreasonably large daily depths cast doubt on the meltpan record. Three of the four pans produced similar total depths, but the fourth had a much lower total. Water from the inoperative pans may have contributed to the flow in the operating pans, or the excess water may be due to lateral inflow along ice lenses.

Several hours elapsed between the estimated occurrence of surface melt and pan outflow (Figure 2). Since the heat deficit contained in the night freeze crust must first be overcome, actual melt would be delayed from when the model predicted melt. The models predicted that the heat flux would be positive by 0800 and that the crust would be near 0°C by about 1100 hours. Meltpan outflow typically began just after noon, peaked rapidly, and then receded in a manner analogous to streamflow recession. While water movement velocities of 3 cm/min would account for this lag, field observations revealed that the crust typically melted by 0930 or 1000. This velocity range of 1 - 3 cm/min is at the slow end of the range reported by Male and Gray (1981).

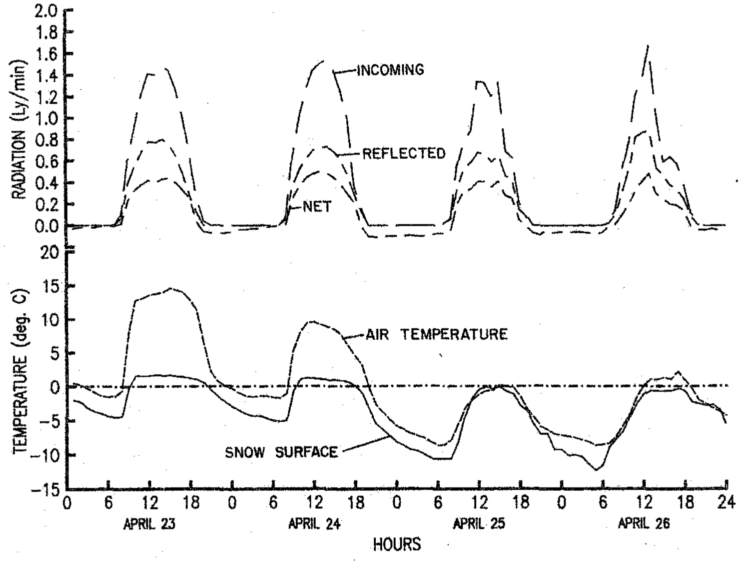

Figure 1. Meteorological variables at the Central Sierra Snow Laboratory, California, April 20-27, 1984.

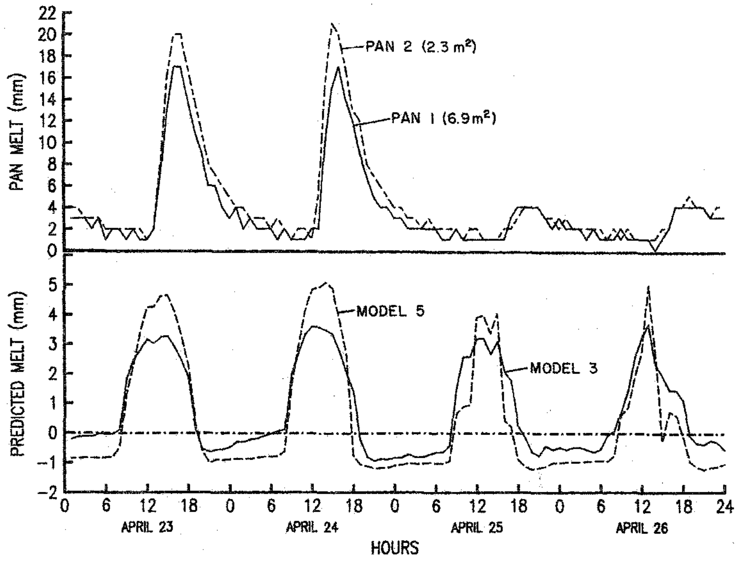

Figure 2. Predicted and observed melt at the Central Sierra Snow Laboratory, California, April 20-27, 1984.

Table 1. Cloud cover, radiation, and average temperatures at the Central Sierra Snow Laboratory, Soda Springs, California, April 20-27, 1984.

Date	Cloud Cover	Net Allwave	Net Shortwave	Net Longwave	Hourly Average Temperature Maximum (°C)	Hourly Average Temperature Minimum (°C)
		------(KJ/m^2-day x 10^{-3})------				
4/20/84	clear	68.1	676.9	-608.8	6.3	-7.5
4/21/84	clear	105.1	708.9	-603.8	14.6	-2.8
4/22/84	clear	148.9	711.3	-562.4	17.2	-3.9
4/23/84	clear	192.9	713.7	-520.8	14.6	-1.5
4/24/84	clear	192.3	704.0	-511.7	9.6	-5.8
4/25/84	cloudy	120.6	551.5	-430.9	0.3	-8.6
4/26/84	cloudy	117.5	544.9	-427.4	2.3	-8.6
4/27/84	cloudy	120.6	598.6	-478.0	3.7	-6.2

Table 2. Melt depths predicted by five snowmelt models, 4-pan average outflow, and changes in total water measured by a snow pillow at the Central Sierra Snow Laboratory, California, April 20-27, 1984.

Date	Index 1	Index 2	Model 3	Model 4	Model 5	Pan	Pillow[1]
	------------	------------	------------	cm	------------	------------	------------
4/20/84	1.0	.3	.9	.8	.2	.4	-1.1
4/21/84	2.3	1.8	1.4	1.0	1.2	1.5	.0
4/22/84	2.8	2.5	2.0	1.6	1.9	3.8	-0.8
4/23/84	2.3	2.1	2.5	2.4	3.4	5.9	1.5
4/24/84	1.7	1.0	2.5	2.2	2.1	6.2	2.5
4/25/84	.1	.0	1.6	1.4	.3	2.4	3.0
4/26/84	.4	.0	1.6	1.4	.0	2.4	1.5
4/27/84	.6	.0	1.5	1.5	1.3	3.0	0.8
TOTAL	11.2	7.7	14.0	12.3	10.4	25.6	7.4

[1] Negative values indicate delayed increase in water content due to storm ending on April 19, 1984.

Meltpan outflow decreased during the cloudy days, but the model predictions were not consistent. The index and the calculated longwave models showed curtailed melt, but the two radiation model (models 3 and 4) predictions did not diminish markedly.

During the 8-day study, the snow depth decreased from 205 to 161 cm, and average density increased from 396 to 436 kg/m^3. SWE decreased by 9.8 cm (79.4 to 69.9 cm), a loss that included melt water released to the ground and any surface losses due to evaporation. This loss is close to the melt calculated by the radiation and longwave model and midway between the two index model values.

The snow pillow data were confounded by the delayed settling that resulted from the April 20 storm (Table 2). Losses that may have occurred during the first 3 days are masked by the settling. If the negative values are ignored, the SWE change is 9.3 cm--close to estimates by the snow gauge and the longwave model.

CONCLUSIONS

Due to the lack of reliable meltpan and snow pillow records, it is impossible to determine which of the five melt models is closest to the true snowmelt value. The two index models produced reasonable results, but since they were calibrated for the CSSL area, that is not surprising. The radiation model that combines shortwave, sensible and latent, and calculated longwave heats matches the observed meltpan record the best, but it requires far more costly equipment than the index techniques. There is, however, the troubling disparity between the predicted and measured meltpan outflows.

While it may be convenient to assume that snow surface temperature is equal to air temperature when air temperature is below 0°C, these data show that this assumption is untrue. Under cloudy conditions, air and snow may be close to the same temperature.

In deep Maritime province snowpacks, data from the relatively small meltpans (<10 m^2) are not of adequate quality to be useful in tests of melt models. The problem of lateral transmission of melt water prevents the exact knowledge of the source area and hence the actual melt depth cannot be determined. Possible solutions to this problem include very large pans (>20 m^2), small pans with manually-cut grooves, or very small pans installed near the surface from below and used for short-term experiments.

The difficulty in obtaining reliable melt water outflow data illustrates the nature of the field-oriented technical barriers in snow hydrology. While snow science theory has advanced greatly in the last decade, validation and application of the theory has been slow due to the difficulties and expense inherent in the data collection process.

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