A PRELIMINARY COMPARISON OF SNOWMELT MODELS FOR EROSION PREDICTION

by

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INTRODUCTION

The United States Department of Agriculture, Water Erosion Prediction Project (WEPP) is developing a process-oriented prediction technology based on hydrologic and erosion sciences (Rawls et al., 1987). The major components of this are: climate and precipitation, snow accumulation and melt, infiltration, runoff, channel routing, erosion, soil moisture, crop growth, plant residue and tillage. Here we describe the work we have done on the modeling of snow melt in the application of WEPP which is being developed by the Forest Service. So far, this is basically a re-evaluation and combination of existing snowmelt models, in particular the Utah State University (USU) model (Riley et al., 1966), Systeme Hydrologique Europeen (SHE) snow components (Morris, 1982) and Precipitation Runoff Modeling System (PRMS) snow components (Leavesley et al., 1983).

Snowpack builds up during the winter then, with the warmer temperatures and increased radiative energy available in spring, it melts, resulting in runoff and possibly erosion. The melt rate is controlled by fluxes of energy into the snowpack. Meltwater trickles down through the snowpack and is delivered at the top of the soil. The rate of delivery of meltwater and its spatial distribution is critical for the prediction of erosion. During the melt phase the melt rate varies with the diurnal cycle of temperature and solar radiation. In many instances, erosion is due to short duration high intensity flows. Therefore, the modeling of erosion for snowmelt must be simulated with short time steps. In this study, we have used one hour and six hour time steps. To capture the spatial distribution of snowmelt delivery, models that are capable of calculating snowmelt at each point on a hillside or small basin are necessary. Models that may have provided good estimates of catchment wide average runoff will not necessarily work well at the point scale required for the estimation of erosion. Here we first present the components of a physically-based energy balance snowmelt model, describing the processes modeled and variables used. We then highlight important aspects of the specific models implemented. We developed our own computer code based on published descriptions of the models so as to ensure uniform programming style and the flexibility to interchange components of the different models. This approach also avoids the overhead involved when running a model in which snowmelt is just one component. In some places inconsistencies or unclear aspects in the model descriptions were resolved using our best judgement. The models are therefore not exact replicas of the original models and any peculiarities or errors in the results are ours, not the original authors. Hopefully some of our changes have been improvements. We are working with smaller time steps than the models were originally constructed for, so some adaptation was necessary in any event. Data from the Central Sierra Snow Laboratory and a SNOTEL site were used to illustrate and compare various aspects of the models. In particular, the focus was on the short term delivery rate of meltwater to the soil surface, which is critical for erosion.

THE COMPONENTS OF A PHYSICALLY BASED SNOWMELT MODEL

Variables

The essential state variables necessary to characterize the condition of a snowpack are: water equivalent, W; Depth, D; Temperature, T; and liquid or free water content, F. Other variables may also be used, for example, density, ρ, calculated as W/D, could be used with W instead of D, or with D instead of W. Albedo, A, the fraction of incoming radiation reflected can be regarded as a state variable varying with age of the snow surface, or may be a function of other state variables, such as ρ. Variation of the state variables with depth within the snowpack is represented, to varying degrees by different models, with different values for various layers. For example, $T_1, T_2, \ldots$ for the temperature at different levels in the snowpack. Complete characterization of the snowpack also consists of several constitutive relationships that determine properties from these state variables. $\rho = W/D$ is one example. Thermal diffusivity $K_v = f(\rho)$ is another.

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Models are driven by three sets of input variables: (1) site variables: these characterize the site and consist of slope, aspect, elevation, latitude, and vegetation cover density. (2) initial conditions: the state variables at some initial time. (3) driving variables: the input variables that describe the processes that drive the evolution of the snowpack at each time step. Typically, at least precipitation and temperature are included. Radiative inputs and other weather conditions, such as relative humidity, cloudiness, etc., may also be included.

Modules

Figure 1 indicates the modules that comprise a generic snowmelt model. The following sections discuss the implementation of these modules, highlighting the differences between snowmelt models.

Partition of precipitation into rain and snow

The partition of precipitation into rain or snow is usually determined from the air temperature. The simplest approach, employed in the SHE model is separation based on a temperature threshold. If the air temperature T_a is less than a threshold T_0, usually taken as 0°C, the precipitation is snow. Otherwise, the precipitation is rain.

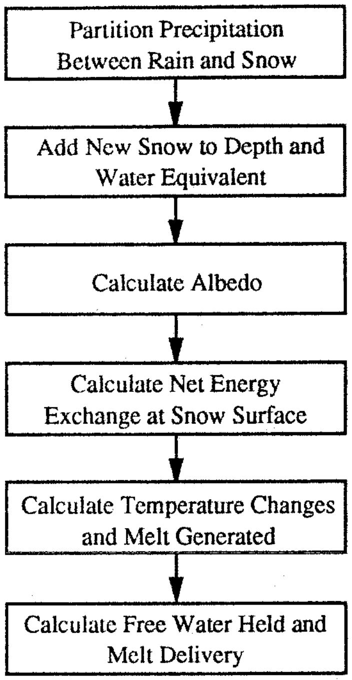

Figure 1. Structure of a modular snowmelt model.

To allow for a smoother transition from rain to snow, the USU model uses a proportional approach:

$$P_s = \begin{cases} P & T_a \leq T_s \\ \dfrac{T_r - T_a}{T_r - T_s} & T_s < T_a < T_r \\ 0 & T_a \geq T_r \end{cases} \tag{1}$$

$$P_r = P - P_s$$

where P is the water equivalent depth of new precipitation divided into rain P_r and snow P_s. T_a is air temperature, T_r a threshold temperature above which all precipitation is rain and T_s a threshold temperature below which all precipitation is snow. Between the threshold temperatures, typically -1.1 °C and 3.3 °C precipitation is assumed to be a mix of rain and snow, respectively. This is based on work by the U.S. Army Corps of Engineers (1956). Some researchers (Leu, 1988) interpret this probabilistically. When air temperature is between the thresholds, the probability of snow is given by an expression similar to (1).

The PRMS model also uses a proportional approach, but in terms of a single threshold, maximum and minimum daily temperatures and a monthly adjustment coefficient. We regard this as inappropriate with time steps shorter than a day, so our simulations use the proportional approach of the USU model.

The separation between rain and snow may be critical since rain on snow can result in high melt rates.

Albedo

Albedo is an important parameter in modeling of the surface energy fluxes. The USU and PRMS models assume an exponential decay with time of albedo, following a relationship given by the U.S. Army Corps of Engineers (1956). New snow has an albedo of 0.8 which decays to 0.4 after about 15 to 20 days. O'Neill and Gray (1973) have shown that, at least in the case of shallow snowpacks, there can be significant departures from this relationship. The SHE model has no representation of albedo, because in the temperature index approach, surface heat fluxes are a function only of the difference between air and snow temperatures. In the energy balance approach, net radiation is taken as an input with reflected radiation already subtracted from it. Vehvilainen (1991) discusses other possibilities including that albedo be a function of snow density or water equivalent.

Energy exchange

Exchanges of energy are the primary processes responsible for melting snow. When viewing the snowpack as a whole the energy exchanges at the surface and ground need to be considered. At the snow surface the important energy fluxes are net radiation, sensible heat, latent heat of evaporation (sublimation or condensation), and heat from rain. At the ground there is conductive heat transfer. Typical daily values of these fluxes (based on data from Male and Gray (1981) for Bad Lake Saskatchewan) are: net radiation, 1340 kJ/m^2; sensible heat, 725 kJ/m^2; latent heat of evaporation (condensation and sublimation), -262 kJ/m^2; and conduction to the ground, -100 kJ/m^2. Negative values indicate energy loss by the snow. They are indicative of the relative importance of the heat fluxes. Male and Gray (1981) describe in more detail the physics of these processes.

Many models ignore a lot of the physical complexity and calculate energy exchanges empirically based on air temperature. This has been found to work fairly well in practice. The approach employed by the SHE temperature index method (Danish Hydraulic Institute, 1981; Morris, 1982) is perhaps the simplest. Melt is given by

$$m = K\,(T_a - T_b)\,\rho \qquad (2)$$

where K is an index factor for depth of snow melted per unit time; T_a, air temperature; T_b a reference temperature (Usually 0°C) and ρ the snow specific gravity. This only applies when $T_a > T_b$ and implies the following addition of energy to the snow

$$Q_m = K\,\rho\,\rho_w\,L_f\,(T_a - T_b) \qquad (3)$$

where L_f is the latent heat of fusion of water and ρ_w the density of water. This is a parameterization of the net energy exchange at the snow surface, incorporating radiation, sensible and latent heat.

The USU model (Riley et al., 1966) also employs a temperature index approach, but incorporates the effect of slope, aspect, vegetation and albedo. The surface melt is given by

$$m = K\,K_t\,I_s/I_h\,(T_a - T_b)(1-A) \qquad (4)$$

I_s is a radiation index, calculated from solar angle, latitude, slope and aspect. Incident radiation is I_s times the solar constant. I_h is the radiation index for a horizontal site at the same location. K_t is a vegetation transmission coefficient and A is albedo. Atmospheric absorption and scattering is neglected in this parameterization of radiation effects. This approach does have a conceptual problem in that it is incorrect to adjust the sensible and latent heat components by a radiation index ratio or albedo. This may be a problem on steep shaded north facing slopes where the radiation index is zero, but the snow still melts due to warm temperatures and sensible heat transfers. Also, radiative melt may occur on south facing slopes when $T_a < T_b$. The USU model also includes some sensible heat transfer at the surface when there is a temperature gradient in the snow. The snow surface is assumed to follow the air temperature, except when this is greater than freezing, and the changes in temperature within the snowpack are modeled by a finite difference approximation to the heat flow equations. However, when the snow is isothermal in the melt phase, there is no temperature gradient so sensible heat transfer is only modeled through the temperature index expression. Some of these problems with modeling radiation with a temperature index may be overcome by an additive, rather than multiplicative term for radiation. Bengtsson (1986) suggests the following expression for modeling melt.

$$m = K\,(T_a - T_b) + (1-A)S_w/L_f \qquad (5)$$

where S_w is incoming solar or shortwave radiation.

The snow component of the PRMS model (Leavesley, 1973; Leavesley et al., 1983) actually incorporates these ideas by modeling each flux separately then adding the results. Incoming shortwave radiation is given by:

$$S_w = F(T_{max})\,I_o\,I_s \qquad (6)$$

where I_0 is the solar constant and the function $F(T_{max})$ attempts to parameterize atmospheric absorption and cloudiness effects in terms of the daily maximum temperature T_{max} and is different for each month. Then net shortwave radiation is given by

$$Q_{sw} = S_w (1-A) K_t \tag{7}$$

Longwave radiation is modeled by the Stefan-Boltzman black body radiation law with factors to account for transmission and absorption by vegetation. Sensible and latent heat fluxes are modeled by a temperature index approach, with transfer coefficient or melt factor K_{eh} a parameter dependent on thermal conduction properties of the snow and vegetation.

The SHE model also has an energy budget option which can be used if detailed meteorological information is available (Danish Hydraulic Institute, 1981; Morris, 1982). Net radiation is taken as an input assumed to be measured, and sensible and latent heat transfers are modeled using turbulent boundary layer theory, as a function of the difference in temperature between the air and snow, as well as wind and moisture in the atmosphere. The expressions are very similar to temperature index methods, i.e. linearly related to the temperature difference, with the proportionality constant a function of wind speed. Sufficient data to drive the SHE energy balance model, in particular net radiation data is rare, and the only data we have that is appropriate is that collected at the CSSL. However it may be possible to model radiation, as in the PRMS model, and incorporate this with the more physically based models of sensible and latent heat to obtain a better energy balance model. Many researchers appear to be taking this approach (Dozier, 1979; Male and Granger, 1981; Marks, 1978; Vehvilainen, 1991).

All the models considered (SHE, USU and PRMS) include the heat carried by rain, assumed to be at the air temperature. The energy added is then determined from the heat capacity of water and latent heat of fusion in the case of rain falling on a nonmelting snowpack. The latent heat of fusion is large and can rapidly bring the snowpack to isothermal conditions at 0°C resulting in the initiation of melt and runoff. Ground heat fluxes do not play a large role in the models considered. The USU model assumes a constant ground temperature of 0°C. The SHE energy balance model assumes a constant ground flux and the PRMS model neglects ground heat fluxes.

Melt and temperature changes

Energy transferred to the snowpack through the fluxes discussed above results in temperature increases and melting. The PRMS and SHE models simulate the entire pack with one average temperature. The PRMS model treats the snow surface as a separate layer with negligible heat content, for the purposes of energy exchanges. Changes in temperature are controlled by the latent heat of ice and water equivalent of frozen snow. When the snow is isothermal, the latent heat of fusion gives the quantity of meltwater generated. In contrast, the USU model considers temperatures at the snow surface, 1/3 depth, 2/3 depth and ground level. Since the surface (air temperature) and ground temperatures (0°C) are fixed, the two internal temperatures describe the temperature condition of the snow. These change with time due to the diffusion of heat approximated using finite difference equations and the infiltration and refreeze of meltwater assumed to be generated at the surface.

Free water holding and delivery of melt

Meltwater generated due to energy fluxes, usually at the snow surface, does not runoff immediately but trickles down through pores in the snow and may be held by capillary forces in the snow. Each model had a different approach to representing this. The SHE model has a lag time for the release of melt runoff, based on the thickness of the snowpack, ranging from 2 hours for a 1 m snowpack to 11 hours for a 3 m snowpack. Since snowpack depths only change significantly on time scales of weeks to months, this lag will not affect the intensity of delivery of melt and was not implemented. The PRMS and USU models both regard the snowpack as having a finite liquid-holding capacity, which is filled before any runoff is released. In the USU model, this liquid-holding capacity is a function of the snow water equivalent and density, whereas in the PRMS model it is a fixed proportion of the snow water equivalent. Other approaches, such as a release of runoff proportional to the free water content, up to the liquid holding capacity, are also possible.

In the models considered, snow depth does not play a direct role in the modeling of melt. The most fundamental variable is water equivalent. However, depth is a fundamental state variable describing the snowpack, and may be one of the few measurements available to verify model performance. In the USU model, depth is determined from the density of new snow, a function of air temperature during deposition. There is a settling or compaction of the snow, modeled as an exponential decrease with time to a maximum density of 0.6.

Liquid-holding capacity, as well as movement of heat within the snowpack, are functions of the total depth. In the PRMS model depth is calculated in a similar way, but plays a lesser role since it is only used in determining the diffusion of heat into the snow. In the SHE model, the snowpack is simply assumed to have a constant density, and depth is a function of water equivalent.

DATA

We used data from the Central Sierra Snow Laboratory (CSSL) and the Atwood Lake SNOTEL station. The CSSL located 1 km east of Soda Springs, CA, maintains comprehensive data relevant to snow. It is at latitude 39°19'N and an elevation of 1100 m. We obtained their meteorological data and snow observation data for the winter of 1985-1986. The meteorological data is reported each hour and consists of temperature, radiation, humidity, precipitation, and wind measurements at two levels in a 40 x 50 m clearing and in a mixed conifer fur forest with 95% forest cover. Snow depths and water equivalent are measured daily (except on weekends) and 10 lysimeters in the clearing and two lysimeters in the forest record the melt runoff each hour. We used the temperature and precipitation, and in the case of the SHE model, net radiation, relative humidity and wind speed measurements to drive our snowmelt models using one hour time steps. The remaining data (snow water equivalent, depth, melt runoff) were compared to model output.

The SNOTEL system operated by the Soil Conservation Service (SCS) reports daily maximum, minimum and average temperature, precipitation, and snow water equivalent as measured by snow pillows from a well-distributed network of stations in the western U.S. We used data from the Atwood Lake SNOTEL station in the Uinta Range, Utah, at an elevation of 3304 m, and latitude 40°44'N for the melt season of 1986. To run our models, we used 6-hour time steps with temperatures as follows:

midnight	-	6 am	daily minimum
6 am	-	noon	daily average
noon	-	6 pm	daily maximum
6 pm	-	midnight	daily average

MODEL PARAMETERS

Table 1 lists the parameters used. Our aim is to have a portable snowmelt model that can be implemented without calibration at any site and used to predict erosion. Therefore, whenever possible we used published parameter values, or made reasonable a priori estimates and kept these fixed. A single parameter was used to calibrate each model. This parameter was the melt factor K for the USU and SHE temperature index models, the sensible heat transfer coefficient K_{eh} for the PRMS model, and the ground heat flux G for the SHE energy balance model. Calibration was done visually to obtain a good fit to observed snow depth and water equivalent at the CSSL open site for the melt period (3/3/86 to 5/26/86).

RESULTS

Figure 2 shows the performance of various models at predicting depth and water equivalent for the melt period. Figure 3 shows temperature, precipitation, and modeled and observed melt runoff for the same melt period. The observed runoff is an average from 9 melt lysimeters. There was considerable variation between the lysimeters with total season melt recorded ranging from 1.1 to 4 m, but the average 2.37 m is fairly close to the recorded total season precipitation of 2.24 m. Figure 4 shows the results when the whole season at the CSSL open site is simulated. Note that the performance is, in general, poor. The models predict melt early in the season that is not observed. The SHE energy balance model based on measured net radiation performs best. Figure 5 compares the measured radiation to radiation estimated by the PRMS model.

Since water equivalent was not recorded at the CSSL forest site, Figure 6 shows the simulated and observed snow depths for the melt period (3/3/86 to 6/6/86). The parameters used were the same as for the open site, with an additional site variable, cover density of 95%. The PRMS and USU models have functions which relate cover density to a vegetation transmission coefficient. Modeled melt runoff is compared to the observations in Figure 7. The observed runoff is an average of two lysimeters at the forested site.

Figure 8 shows the observed and modeled water equivalent for the melt period at the Atwood Lake SNOTEL station.

Table 1

MODEL PARAMETERS

Notation	Value	[1]Model	Description
K	0.0004 m/°C/hr	U	Melt factor (calibrated from CSSL data)
K_{eh}	0.8 cal m^{-2} hr^{-1} $°C^{-1}$	P	Sensible heat transfer coefficient (calibrated from CSSL data)
K	0.00054 m/°C/hr	S_t	Temperature index melt factor (calibrated from CSSL data)
T_r	3.33°C	U, P	Temperature above which precipitation is rain (Bowles et al., 1975)
T_s	-1.11°C	U, P	Temperature below which precipitation is snow (Bowles et al., 1975)
C_{eff}	28 cal m^{-1} hr^{-1} $°C^{-1}$	P	Parameter in effective thermal conductivity (Anderson, 1968) $K_{eff} = C_{eff}\,\rho^2$
C_v	0.0063 m^2/hr	U	Thermal diffusivity coefficient (Leu, 1988)
K_a	0.00833 hr^{-1}	U, P	Albedo decay coefficient (U.S. Army Corps of Engineers, 1956)
A_{new}	0.8	U, P	Albedo of new snow (U.S. Army Corps of Engineers, 1956)
A_{min}	0.4	U, P	Minimum albedo (U.S. Army Corps of Engineers, 1956)
A_{t_1} A_{t_2}	0.002 m 0.5	P	Albedo is reinitialized to A_{new} when A_{t_1} m of snow with less than A_{t_2} fraction of rain has fallen (Leavesley et al., 1983)
K_s	0.00417 hr^{-1}	U, P	Snow settling and compaction coefficient (Leu, 1988)
ρ_{max}	0.6	U, P	Maximum snow relative density
ρ_{min} $C_{\rho i}$ $T_{\rho i}$	0.05 3.24 x 10^{-4} $°C^{-2}$ -17.8°C	U, P	Parameters in function for determination of new snow density (Leu, 1988) $\rho_{new} = \rho_{min} + C_{\rho i}\,(T_a - T_{\rho i})^2$ when $T_a > T_{\rho i}$ and ρ_{min} when $T_a < T_{\rho i}$
L_{cf}	0.05	P	Liquid holding capacity factor $L_c = L_{cf}\,W$
L_{cf} L_{cg}	0.05 0.125	U	Parameters in liquid holding capacity function (Eggleston et al., 1971) $L_c = \{L_{cf} + L_{cg}\,\mathrm{Max}\,(0, \rho - 0.4)\}\,W$
ρ_s	0.44	S_t, S_e	Snow relative density
G	2.9 cal/m^2/hr	S_e	Ground heat flux (calibrated from CSSL data)
Z_o	2 x 10^{-5} m	S_e	Snow aerodynamic roughness height
ε_a	[2]0.9	P	Emissivity of air

Notes:

[1] The model each parameter applies to is indicated as follows: U = USU model, P = PRMS model, S_t = SHE temperature index model, and S_e = SHE energy balance model.

[2] Leavesley et al. include procedures for adjusting this when storms are predominantly convective, and between rainy and non-rainy days. This was not done. U.S. Corps of Engineers (1956) report ε_a between 0.76 and 1 depending on atmospheric moisture.

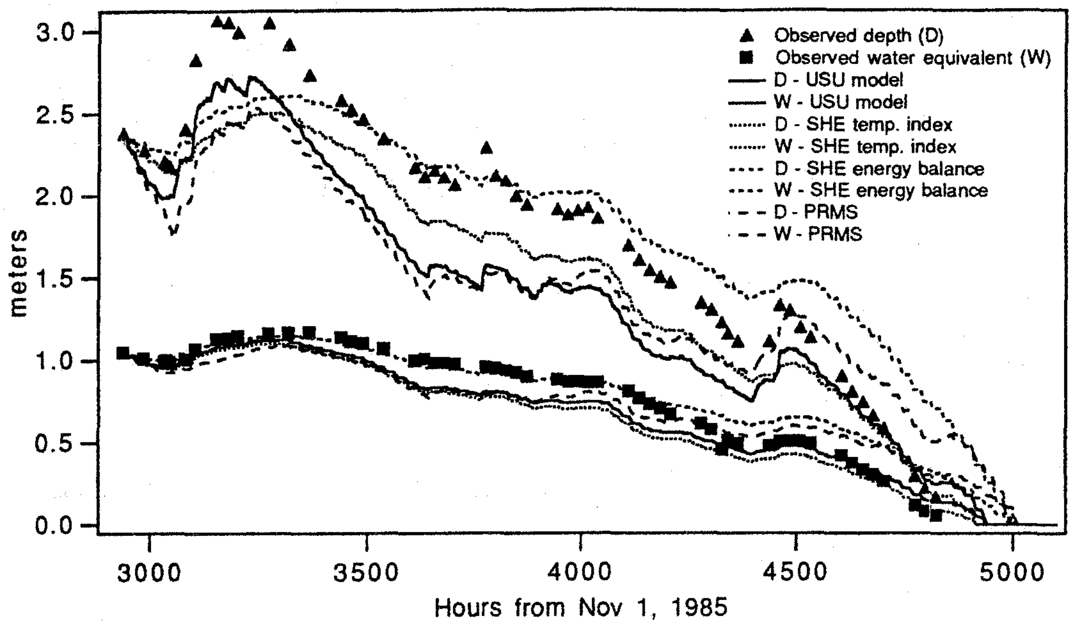

Figure 2. Depth and water equivalent comparisons during the melt period at the CSSL open site (3/3/86 - 5/26/86).

DISCUSSION

Figure 2 indicates that all of the models successfully model the seasonal depletion of the snowpack water equivalent. If this is the only variable of interest complex models are therefore not necessary, and a simple temperature index will suffice. Snowpack depth is not as well represented, indicating difficulty with the parameterization of density. Based on the runoff, temperature and precipitation data presented in Figure 3, we see that there is a rain on snow event resulting in a high runoff peak around hour 3050 (3/8/86). In Figure 3(d) we compare the observed to modeled runoff for this event and see that all the models represent the peak runoff fairly well. Some smoothing due to flow through the 2 m deep snowpack is not represented, resulting in a dip in modeled melt runoff during a break in rainfall not present in measured melt runoff. In Figure 3(e) the modeled and observed runoff is compared during the spring melt. We see that all models represent the diurnal cycle well, however the temperature index models (USU and SHE temperature index) underestimate the daily peak flows. The PRMS and SHE energy balance models, which are radiation driven, model the peak flow well.

Figures 2 and 3 showed that the models performed well for the melt period (which they were calibrated to). On modeling the whole season accumulation and melt as shown in Figure 4, all models severely underestimate accumulation. This is because the temperature index components simulate melt whenever temperature is above 0°C during the day, but the transfer of cold to the snowpack and refreeze at night is probably underestimated. The SHE energy balance model, based on measured radiation, performed best. However, the PRMS model which simulates radiation performed poorly, possibly due to a poor representation of the longwave radiation loss at night, which is sensitive to air emissivity, a variable we had little information on. In Figure 5, the PRMS modeled radiation compares fairly well to observations in the melt period. In Figure 6, only the PRMS model successfully models the decrease in snow depth in the forest. The failure of the SHE temperature index model is expected, because the melt factor was not adjusted. The failure of the USU model is probably due to the vegetation transmission factor parameterization (Eggleston et al., 1971):

$$K_t = e^{-4\,C_d} = e^{-4 \times 0.95} = 0.022$$

where Cd is cover density, resulting in an unreasonably small K_t. The PRMS vegetation transmission factor for this cover density, based on Figure 10 in Leavesley et al.(1983), is 0.1. The failure of the SHE energy balance model suggests that net radiation is not a large factor in melt in the forest, and parameterizations of sensible and latent heat transfers using turbulent boundary layer theory are probably incorrect in the forest.

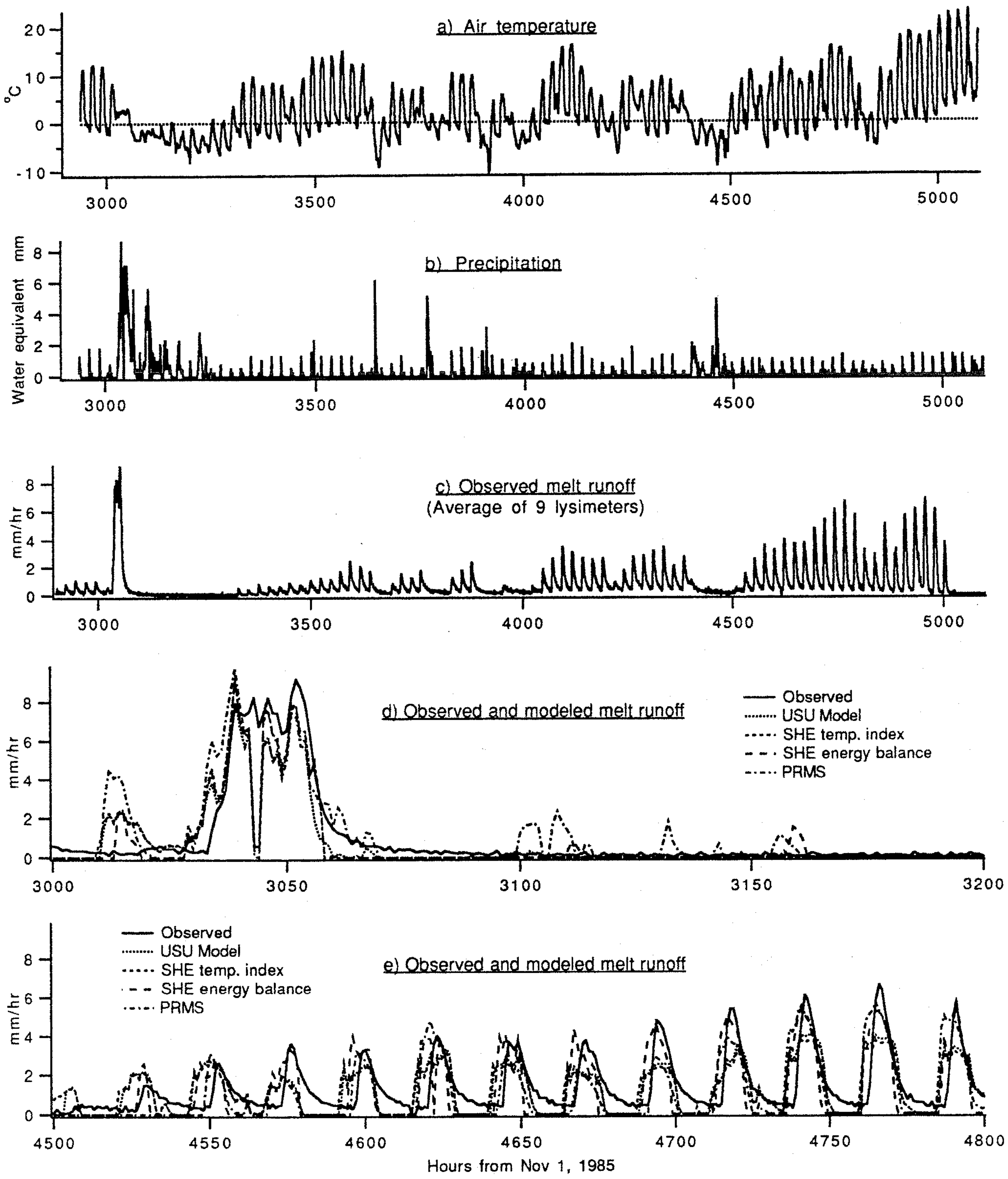

Figure 3. CSSL open site data from 3/3/86. a) Air temperature, b) precipitation, c) observed runoff, d) observed and modeled runoff from 3/6 to 3/14, e) observed and modeled runoff from 5/7 to 5/20.

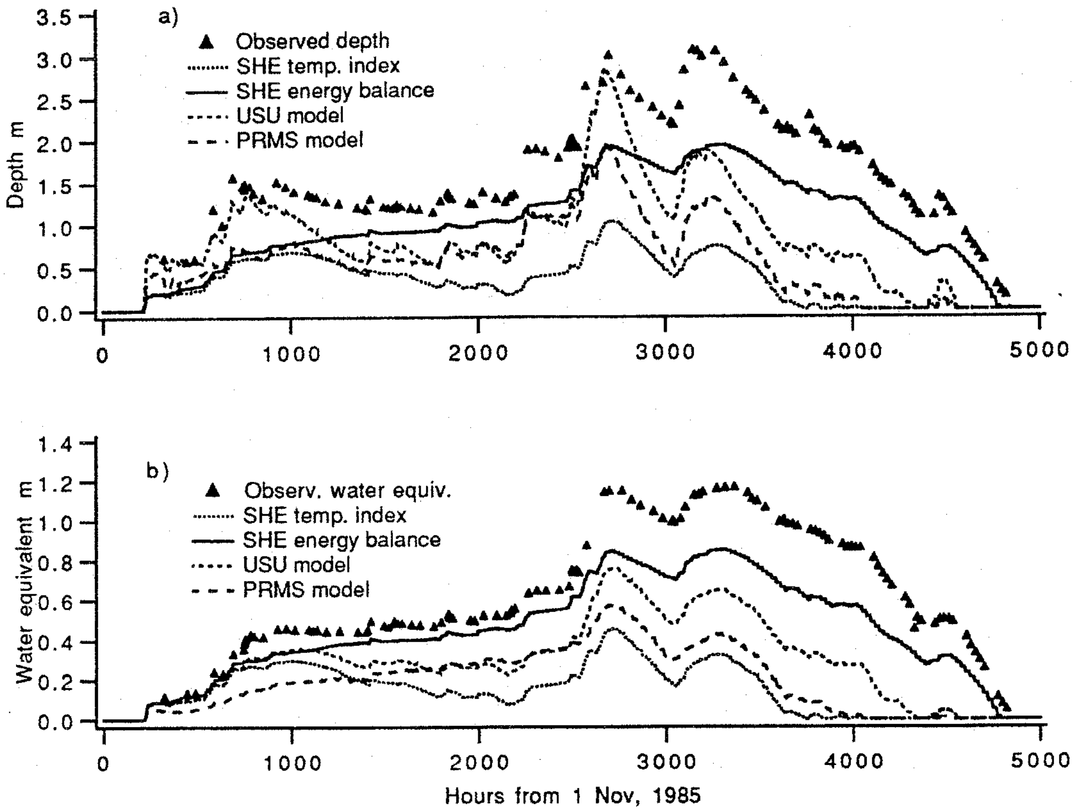

Figure 4. Comparison of modeled and observed snow depth (a) and water equivalent (b), for the winter of 1985/86, CSSL open site.

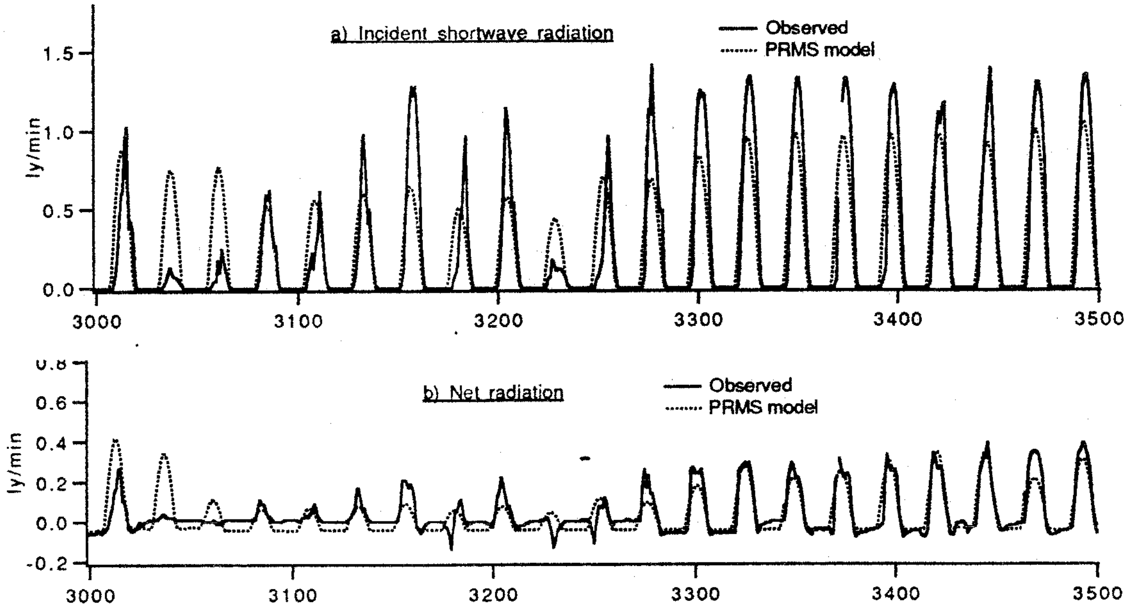

Figure 5. CSSL open site data from 3/6/86 to 3/26/86. a) Observed and modeled incoming shortwave radiation, b) observed and modeled net radiation.

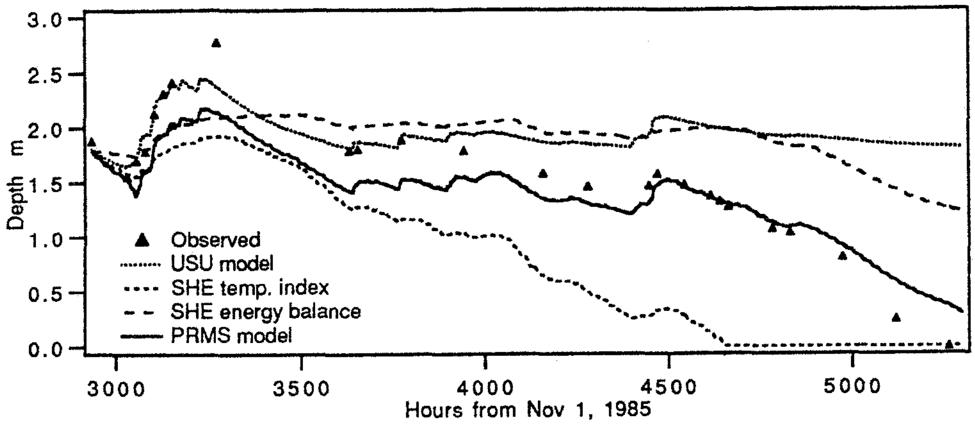

Figure 6. Depth comparisons during the melt period at the CSSL forested site (3/3/86 - 6/6/86).

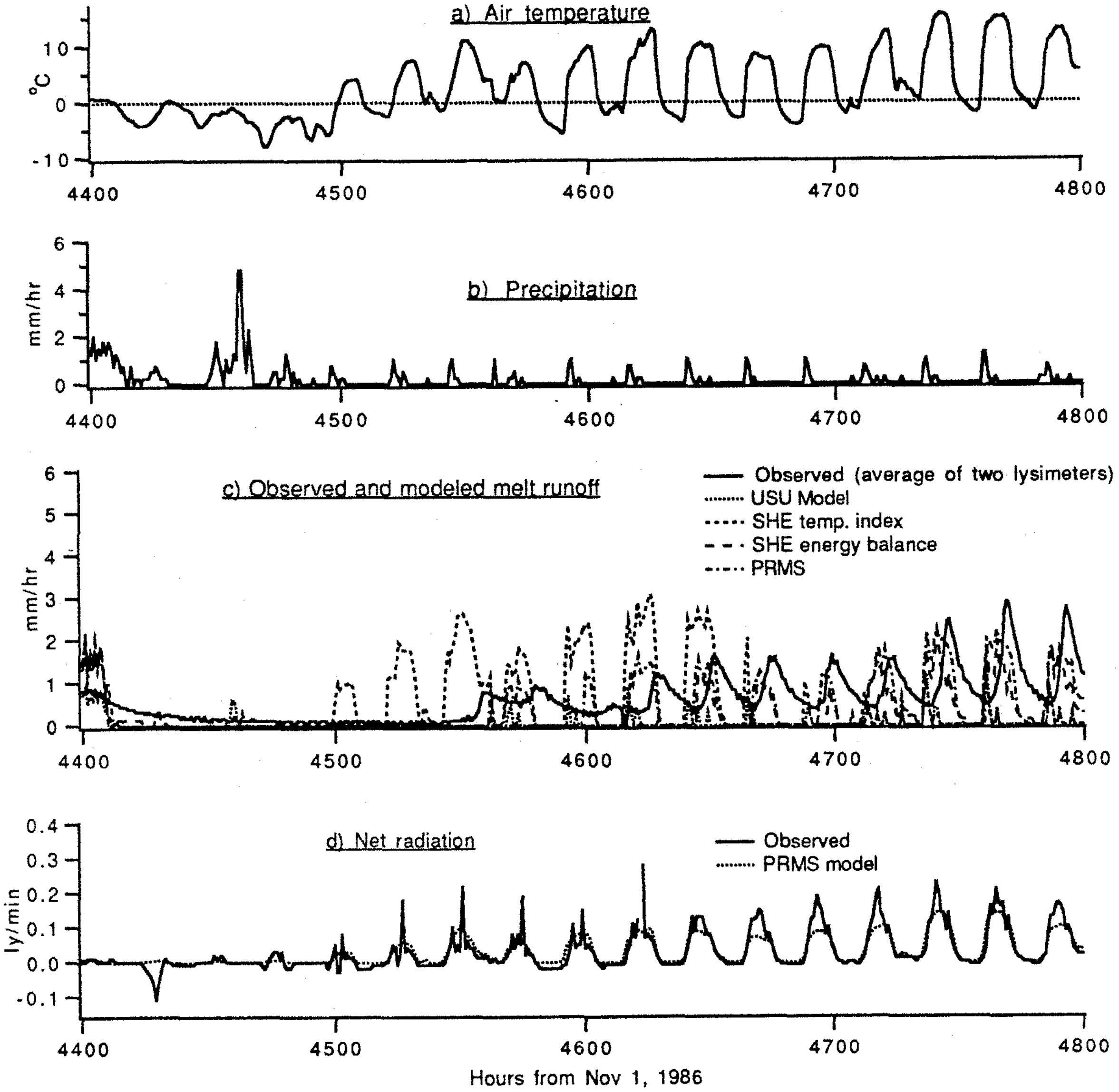

Figure 7. CSSL forest site data from 5/3/86 to 5/19/86. a) Air temperature, b) precipitation, c) observed and modeled melt runoff, d) observed and modeled net radiation.

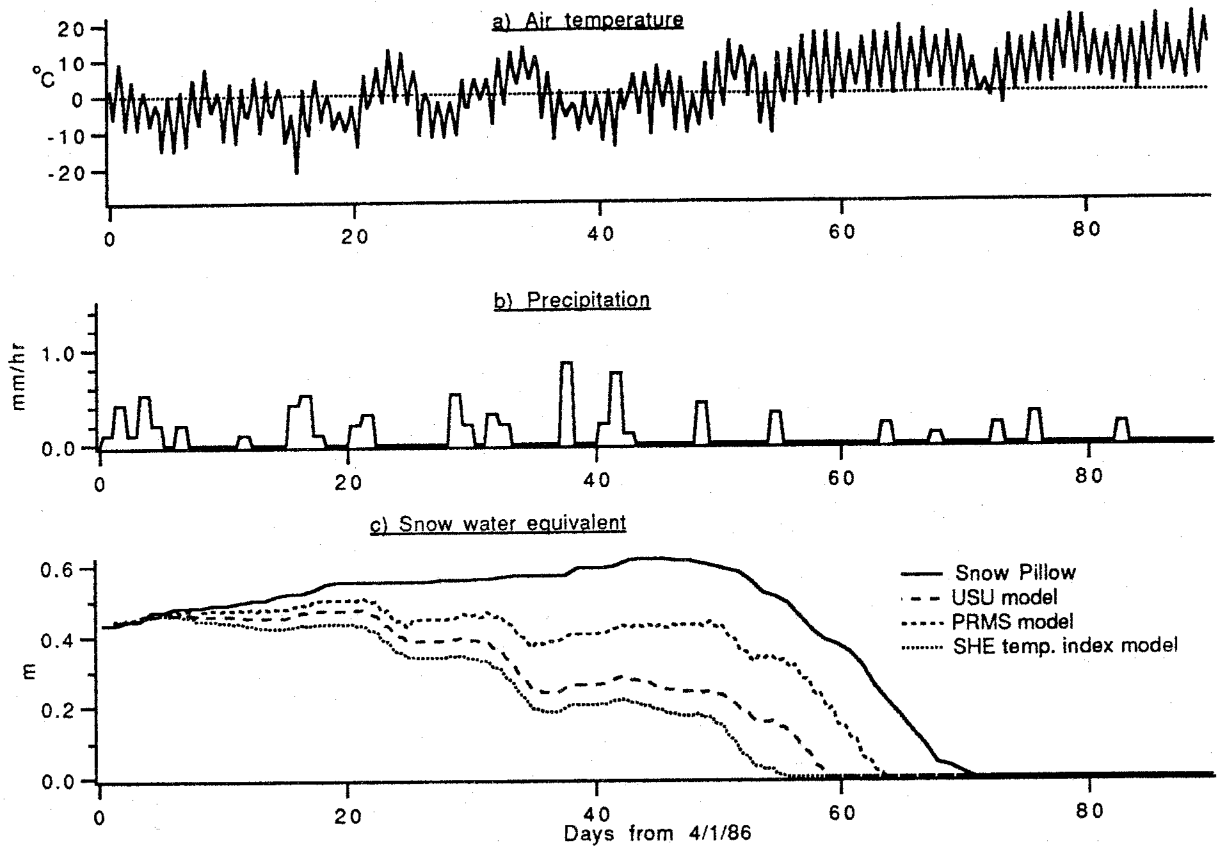

Figure 8. Atwood Lake SNOTEL data. a) Air temperature, b) precipitation, c) modeled and observed snow water equivalent.

The comparisons of observed and modeled runoff at the forest site shown in Figure 7 reflect poor performance of some models in this situation. The radiation-based models (PRMS and SHE energy balance) perform best, while the SHE temperature index model severely overestimates melt runoff until the pack is depleted at about hour 4670. The USU model also severely underestimates melt runoff.

In Figure 8 the models were driven by temperature and precipitation data recorded at a SNOTEL site. The parameters used were those calibrated for the CSSL open site, and in the case of the SHE temperature index and USU models, depletion is too fast. The PRMS model appears most promising for being transportable to other sites.

CONCLUSIONS

The simple energy balance models considered have the potential to model rapid melt runoff that can cause erosion. A model based on radiation components added to temperature index parameterizations of sensible and latent heat fluxes, such as the PRMS model, appears most promising. Additional research is necessary to identify the best method of modeling radiation, especially longwave heat loss at night, and modeling the loss of sensible and latent heat during the accumulation phase, at times when air temperatures are less than 0°C at night. One possibility is to allow negative heat fluxes when $T_a < T_b$. It may also be more reasonable to replace the reference temperature T_b by the average snow temperature, or snow surface temperature.

The occurrence of rain or snow can result in high runoff rates. The models reproduce this effectively when the temperature and precipitation conditions are known, as in this study. A few degrees error in temperature could indicate snow rather than rain, and the modeled melt runoff would be incorrect. More work, incorporating data from different locations with varied site properties (slope, aspect, albedo and vegetation), is required to develop a truly portable snowmelt model for the prediction of erosion.

Modeling the rate of delivery of melt runoff, at short time scales, for prediction of erosion is a new challenge which provides a harsh test of snowmelt model performance.

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