A SIMPLE GIS-BASED SNOW ACCUMULATION AND MELT MODEL

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ABSTRACT

A simple distributed snow accumulation and melt (SAM) model was developed for use in GIS-based hydrologic models. Snow drifting is simulated using observed wind speed and distributed snow drift factors, which are generated as a pre-processing step using the SnowTran-3d model. Snowmelt is simulated through a mass and energy balance applied to a single layered snow pack. Snow surface temperatures are simulated without the requirement of an iterative solution using a simple damping depth approach. The SAM model was applied to a 2 ha watershed in Troy, ID having three years of detailed snow water equivalent (SWE) measurements. Snow surface temperatures predicted by the SAM model using a fixed snow damping depth of 0.05 m showed good agreement with SHAW model predictions. The root mean square error (E_{RMS}) between simulated and observed SWE across the site (10–46 mm) was consistent with and in some cases smaller than the E_{RMS} at points where the maximum predicted SWE was fit to field observations (21-26 mm). The SAM model is a relatively simple model that can be coupled to GIS, relies on readily available data, and requires limited parameter estimation.

INTRODUCTION

The transfer and release of water from a spatially distributed snow pack (snow accumulation and melt) is a key hydrologic process affecting the generation of surface runoff and pollutant transport. For practical watershed management purposes, the 'ideal' distributed hydrologic model strikes a balance between data availability and model complexity (Grayson et al., 1992), is coupled to geographic information systems (GIS), relies on readily available data, and requires little calibration so that transfer to watershed managers becomes feasible (Frankenberger et al., 1999). In this paper, we present a GIS-based snow accumulation and melt model (SAM) ideally suited for integration with distributed hydrologic models for watershed management applications.

Snow accumulation can be described well with complex blowing snow models (e.g. SnowTran-3D, Liston and Sturm, 1998), however the complexity of these models limit their direct application as practical management tools in simple distributed snowmelt models. For watershed management purposes a simple and more practical method for distributing snow over a landscape is by using static snow drift factors (the ratio between actual deposition of snowfall at a point to the measured snowfall in a local precipitation gage). Snow drift factors can either be estimated directly based on observed data, or generated through correlation between measured points and topographic indices, or generated directly using complex snow drift models (Prasad, et al., 2001).

Snow melt models can generally be lumped into four categories: 1. "Complex" mass and energy balance models (e.g., SHAW by Flerchinger and Saxton, 1989); 2. Temperature index models (see Maidment, 1993, page 7-24); 3. Hybrid temperature index models (Kustas, et al., 1994); and 4. "Simple" mass and energy balance models (Tarboton and Luce, 1996; Marks, et al., 1998; Wigmosta, et al., 1994). The "simple" mass and energy balance models fit the 'ideal' distributed hydrologic model as described above. The advantage of these models is that they physically represent the mass and energy transfer in a snow pack without requiring detailed, multi-layered, and in some cases, iterative numeric solutions. They provide a detailed representation of the spatial variability of the release water from a snow pack required in distributed hydrologic runoff and pollutant transport modeling. Typically, the level of complexity inherent in these models is determined by how they simulate the surface and snow pack temperatures.

The SAM model, presented in this paper is a "simple" model which is unique in that it does not require any iterative solutions, accounts for snow drifting using snow drift factors and predicts snow surface temperature using a simple damping depth approximation. The specific objectives of the paper are to describe the unique features of

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the SAM model, assess the accuracy of a simple snow surface temperature approximation using SHAW model simulations, and compare simulated snow water equivalent (SWE) to detailed point based SWE measurements and observed spatial SWE patterns made on a 10 x 15 m grid over a small catchment.

MODEL DESCRIPTION

The SAM model uses a mass and energy balance to predict distributed snow accumulation and melt. In this study, the SAM model operated in the Geographic Resources Analysis Support System (GRASS) (Neteler and Mitasova, 2002). Programming consists of batch scripts that use simple map algebra commands and functions available in GRASS 5.0. Conceptually the model maintains a continuous mass and energy balance of the single layered snow pack (plus a thin soil layer) similar to the UEB model (Tarboton and Luce, 1996). The energy content of the snow pack U (kJ/m^2) is defined relative to a reference state of water at 0 °C. The total mass of the snow pack W (expressed in water equivalent depth, m) includes both an ice phase and a liquid phase. Both the energy and mass balance equations are represented as:

$$\frac{dU}{dt} = Q_T + Q_r \tag{1}$$

$$\frac{dW}{dt} = P_r + P_s + E + M_r \tag{2}$$

where t is time, Q_T is the net incoming energy flux crossing the upper and lower boundaries of the snow pack, Q_r represents the rate of latent heat exchange in the snow pack due to refreezing or thawing, P_r is the rainfall rate, P_s is the snowfall rate, E is the sublimation from the snow pack, and M_r is the meltwater leaving the snow pack. Equations (1) and (2) are solved using a quasi-steady state assumption, where U and W for the current time can be determined directly from their quantities in the previous time step, $U^{t-\Delta t}$ and $W^{t-\Delta t}$, respectively.

Total incoming solar radiation at a point in the landscape is a summation of the direct, diffuse, and reflective components which was determined using the "r.sun" program available in GRASS 5.0. In addition to variability caused by slope and aspect, the r.sun program accounts for the shadowing effect for adjacent terrain and atmospheric scattering and attenuation by turbidity and cloud cover. The albedo of the snow surface is related to the age of the snow surface in days. The net longwave radiation is calculated as the difference between incoming atmospheric radiation and outgoing radiation emitted by the snow or soil surface. The emissivity of the atmosphere is calculated following the approach of Walter et al. (2005). The sensible and latent heat exchanges are driven by the near surface temperature and vapor density gradients and are limited by the resistance to heat transfer and vapor transfer by turbulent exchange mechanisms. The actual vapor density at the snow surface is calculated assuming the air is saturated at the temperature of the snow surface T_{ss}. Mass can be added and removed from the snow pack by condensation and evaporation. Any mass added to a snow pack will either add or remove heat from the snow pack depending on the temperature of the precipitation and the temperature of the snow. Heat conduction at the base of the active soil layer is assumed to be negligible over the winter season (Tarboton and Luce, 1996). The rate of latent heat exchange in the snow pack Q_r (kJ m^{-2} hr^{-1}) is determined by the net amount of water that freezes/thaws in the snow pack. The amount of liquid water held in the snow pack is limited by maximum water holding capacity of the snow pack.

The surface temperature T_{ss} (°C) is determined through an energy balance applied to a surface layer of thickness D_{ss} (m) as

$$T_{ss} = \frac{U_{ss}}{\rho_w c_p D_{ss}} \tag{3}$$

where c_p is the specific heat of the surface layer and ρ_w is the density of water. The energy content of the surface layer U_{ss} (kJ/m^2) is defined by

$$U_{ss} = U_{ss}^{t-\Delta t} + \left(Q_T + Q_r\right)\frac{D_{ss}}{D_{sd}}\Delta t \tag{4}$$

where D_{sd} (m) is the surface layer damping depth. The surface layer damping depth controls the fraction $\left(D_{ss}/D_{sd}\right)$ of the total energy exchange that is used to change the heat storage in the surface layer. This assumes the remaining fraction of the total energy exchange $\left(1-\left(D_{ss}/D_{sd}\right)\right)$ is conducted to the lower layer. If U for the entire snow pack is 0.0 kJ/m^2, meaning the energy fluxes for the current time step satisfy the cold content for the entire pack, then U_{ss} is also set equal to 0.0 kJ/m^2. This damping depth approach is similar to that used in the UEB model (Tarboton and Luce, 1996).

The proportion of rain and snow in the precipitation is determined using maximum and minimum air temperature thresholds. Snowfall at any point in the watershed is adjusted for snow drifting using a snow drift factor F (s/m) and measured wind speed u (m/s).

$$P_s = P\exp(Fu) \qquad \text{for} \qquad F \geq 0 \ \text{(Deposition)} \tag{5}$$

$$P_s = P[2 - \exp(-Fu)] \qquad \text{for} \qquad F < 0 \ \text{(Scour)} \tag{6}$$

A detailed description of each component in the SAM model is provided in Brooks (2003).

MODEL APPLICATION

The SAM model was tested using a three year data set (2000-2002) from a 2 ha watershed located near Troy, ID (latitude 46.75 °N; longitude 116.75 °W). The bowl shaped catchment shown in Figure 1 drains primarily to the north and was maintained in a continuous perennial grass cover under the Conservation Reserve Program. Meteorologic measurements available on site included hourly shortwave radiation, relative humidity, air temperature, wind speed, and precipitation. Precipitation measurements were made using an unshielded tipping bucket rain gage with a CS705 (Campbell Scientific Inc.) antifreeze siphoning snow adapter during 2001 and 2002. Precipitation data during sub-freezing weather for the 2000 winter season were taken from Moscow ID cooperative weather station located roughly 20 km to the west. A 5 m DEM was developed for the site using a detailed site survey. Snow water equivalent (SWE) measurements were made at three locations throughout the site on a weekly to bi-monthly basis depending on snow accumulation and melting conditions. Three locations, P1 – P3 (Figure 1), were chosen to represent the range of spatial variability across the site: P1 represents a snow scour location, P2 represents a snow deposition location, and P3 represents a location where the snow melting rate corresponds roughly to the catchment average snow melting rate. Detailed snow surveys including snow depth measurements made on a 10 x 15 m grid throughout the site were conducted twice in 2000, twice in 2001, and four times in 2002.

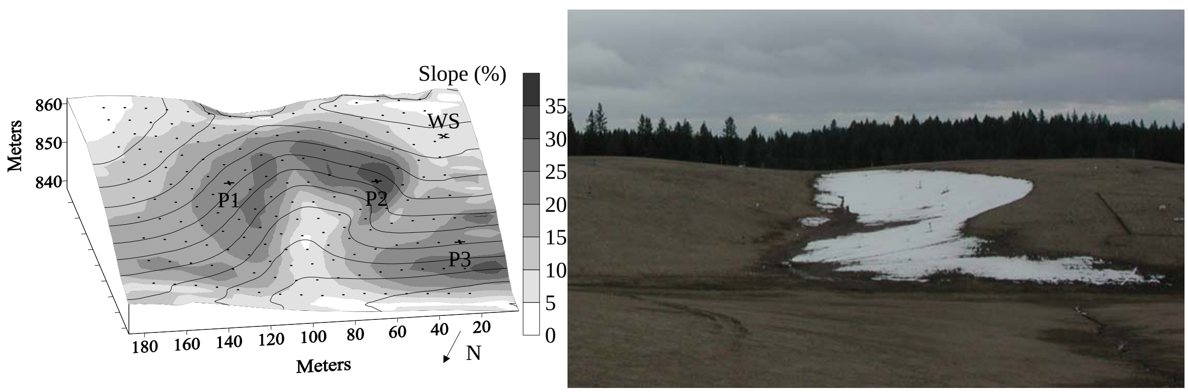

Figure 1. Land slope (%) of the study site draped over the DEM (left). Filled points identify the 10 x 15 m snow survey grid. WS identifies the weather station. Picture on right taken April 1, 2002 looking south.

Table 1. Statistical assessment of snow surface damping depth approach.

Parameter	**2000**	**2001**	**2002**	**All Years**
Snow damping depth, D_{sd} (m)	0.065 (0.05)	0.030 (0.05)	0.045 (0.05)	0.047 (0.05)
E_{RMS} (°C)	2.8 (2.8)	3.4 (3.5)	3.1 (3.1)	3.1 (3.1)
M_D (°C)	-0.8 (-0.9)	-0.6 (-0.2)	-0.4 (-0.3)	-0.6 (-0.5)
R^2	0.63 (0.66)	0.65 (0.57)	0.75 (0.74)	0.68 (0.66)

RESULTS AND DISCUSSION

The SAM model was applied to the Troy, ID catchment using an hourly time step. Input to the model included hourly solar radiation, relative humidity, windspeed, air temperature, and precipitation. The effective or active soil layer depth D_e was taken to be 0.4 m (Tarboton and Luce, 1996). Snow drift factor maps were fixed by scaling drift factor maps generated by the SnowTran-3D blowing snow model (Liston and Sturm, 1998) to known snow drift factors at points P1-P2. Starting with a uniform 0.5 m snow layer spread evenly across the entire watershed, the SnowTran-3D model redistributed the snow pack using an 8 m/s wind from a fixed direction for 2 days. The drift factors were determined by dividing the final snow depth by 0.5 m. These snow drift factors were then scaled to match the relative amount of snow drifting that occurred each year using the maximum observed snow depth at points P1 and P2.

Assessment of snow surface temperature simulation

In the absence of observed snow surface temperature data, the snow surface layer damping depth D_{sd} was determined by calibration to hourly snow surface temperatures predicted by the SHAW model (Flerchinger and Saxton, 1989), a complex, multi-layered, coupled mass and energy balance model. The snow surface layer thickness D_{ss} was fixed at 3 mm, representing the average thickness of the snow surface layer used in the SHAW model in water equivalent depth. Table 1 lists the root mean square error (E_{RMS}), the mean difference between simulations and observations (M_D), and the coefficient of determination (R^2) for the calibrated D_{sd} parameter for each year versus using a constant D_{sd} of 0.05 m for all the years. Although the calibrated D_{sd} for each year differed, in only one of the three winters, 2001, did the E_{RMS} increase when using a fixed D_{sd} of 0.05 m. The average E_{RMS} for all the years was 3.1° C. Considering that the average diurnal fluctuation in T_{ss} simulated by the SHAW model was 9.1° C this is equivalent to a 34% error in predicted T_{ss}. The simulated snow surface temperature using the SAM model matched well with the extreme temperature fluctuations induced primarily by long wave radiative cooling. For example, the minimum recorded air temperature during the 2001 winter season was –15° C however, according to the SHAW and SAM models, the snow surface temperature dropped to -28° C and -27° C, respectively. The spatial variability of snow surface temperatures was also well represented by the SAM model

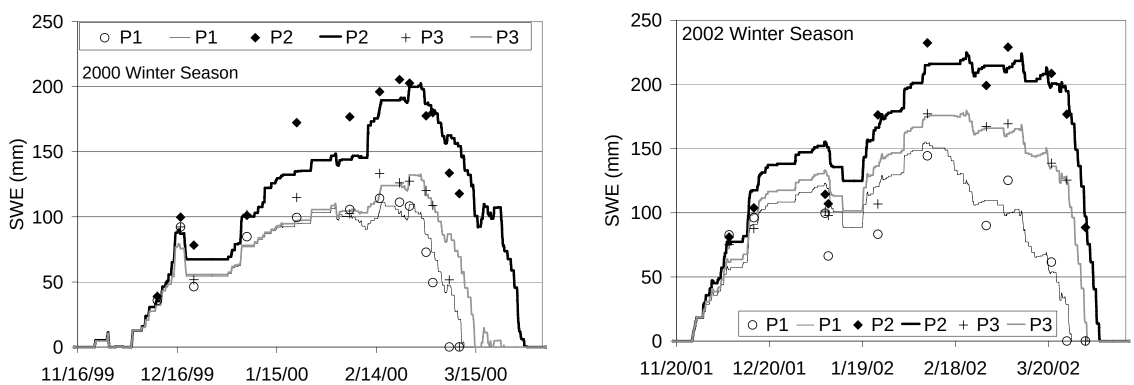

Figure 2. Predicted and observed SWE over the 2000 (left) and 2001 (right) winter seasons for locations P1-P3. Observed data are shown as points; predicted data are shown as lines.

Table 2. Statistical assessment of predicted and observed SWE at points P1-P3.

Year	Location	E_{RMS} (mm)	M_D (mm)	R^2	Net Snowfall (mm)
2000	**P1**	17	5	0.87	196
2000	**P2**	20	4	0.86	258
2000	**P3**	23	3	0.66	196
2001	**P1**	33	-17	0.68	121
2001	**P2**	26	-13	0.84	124
2001	**P3**	22	-9	0.86	119
2002	**P1**	25	9	0.73	150
2002	**P2**	20	6	0.88	210
2002	**P3**	17	7	0.90	167
All Years	**P1**	26	-2	0.67	
All Years	**P2**	23	-4	0.86	
All Years	**P3**	21	-1	0.81	

over a wide range of environmental conditions. During clear days the spatial variability in snow surface temperature was greatest due to variability in shortwave solar radiation, whereas both models show little to no variability in snow surface temperature across the site during the warm overcast days.

Assessment of SWE Simulation

Although the maximum predicted SWE was calibrated to match the predicted SWE at points P1-P2 using the scaled drift factor, the temporal accumulation of snow throughout the year was simulated reasonably well at locations P1-P3. Figure 2 shows predicted and observed SWE at points P1-P3 for the 2000 and 2002 winters. Table 2 describes statistically the agreement between observations and predictions. The E_{RMS} between predicted and observed SWE during the 2002 winter season, which showed the greatest spatial variability in snow accumulation, was actually less than the E_{RMS} during the 2001 season, which had minimal snow drifting. The model did indicate a discrepancy between the observed and predicted snow accumulation at P2 during the 2000 season (Figure 2). The observed SWE increased by 71 mm between 1/6/2000 and 1/21/2000, whereas only a 35 mm increase in SWE was predicted for this period. The early season error in predicted snow accumulation possibly indicates that snow drifting did not occur during a precipitation event but rather between storms when high wind speeds coincided with dry surface snow conditions which were susceptible to detachment and transport.

The predicted melt of the snow pack agrees well with measurements made at each of the three locations. The appreciable differences in the melting of the snow pack observed at P1-P3 during the 2002 season are replicated well by the SAM model (Figure 2). The 2001 winter showed an over-prediction of the melting of the snow pack which was caused by a snowfall event which was incorrectly described as a rain event. The snow surface albedo therefore remained low and caused accelerated melt. Overall, the comparison between SWE measurements and predictions does not identify any consistent error caused by the approximations incorporated into the snowmelt components of the model.

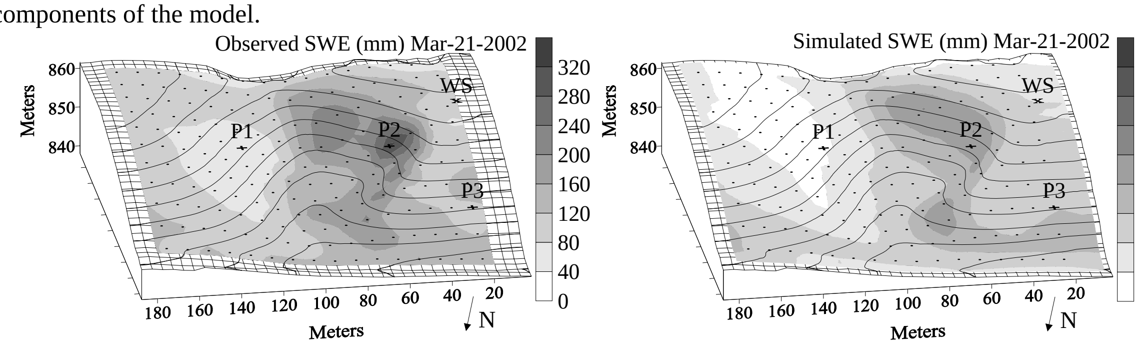

Figure 3. Observed (left) and simulated (right) SWE for Mar-21-2002.

The SAM model shows good agreement between simulated SWE and the 10 x 15 m detailed snow surveys conducted each winter. Figure 3 shows maps comparing the observed and simulated spatial distribution in SWE for the 2002 season which had noticeable snow drifting. Despite the slight over-prediction of the SWE, the relative distribution of snow cover seems to be replicated well by the model. Although the observed map indicates a high point near P2 the drift had roughly the same shape as indicated by the simulated map (see Figure 1). A more precise representation of this drift in the map would require measurements at a finer resolution than available here. Despite a high point at the center of the snow drift, the close match between observed and predicted SWE shows that the snow drifting algorithm was performing well. The E_{RMS} for 9 dates having detailed snow surveys ranged from 10 mm to 47 mm with an average E_{RMS} of 28 mm.

SUMMARY AND CONCLUSIONS

As process-based hydrologic models become more widely used in watershed management and restoration there arises a need for simple algorithms that can be used in simulate the accumulation and release of water from a snow pack. A simple GIS-based snow accumulation and melt (SAM) model is presented, which simulates the mass and energy balance of a single layered snow pack. The close agreement between spatially detailed SWE measurements over a three year period throughout a small non-forested catchment indicates that the model is able to simulate the accumulation and melt of a snow pack.

The SAM model was developed without the need for complex iterative solutions that slow run times and limit the flexibility of the model. The model also was developed such that it could be incorporated into existing GIS software programs simple map algebra commands and functions. A simple damping depth approximation was developed to predict hourly snow surface temperature. Simulated snow surface temperatures agreed well with SHAW model predictions over a range of temperatures and environmental conditions. A constant damping depth was used for all years. Further research is needed to determine how sensitive this damping depth is to the thermal conductivity of the snow surface layer. Snow drifting was simulated in the model using snow drift factors which were adjusted based on measured wind speed. In this study, snow drift factor maps were created by linearly scaling snow drift factor maps generated by the SnowTran-3D model using point-based SWE measurements at a depositional and scouring site. Although in one year there was an indication of incorrect timing of snow drifting, there was generally good agreement between measured and predicted snow accumulation patterns. Without general access to the SnowTran-3D, future applications of this approach may have to rely on other approaches to develop snow drift factors.

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