HYDROLOGICAL SCIENCE AND TECHNOLOGY
Volume 3, Number 1-2
American Institute of Hydrology
Pp. 53-59

On Improving Temperature-Index Snowmelt Simulations in Small Watersheds

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ABSTRACT

Degree-day temperature index models are used regularly at the small watershed scale, but rarely include indices of areal snowcover depletion. As a result, severe melt overestimates may occur, particularly toward the end of the melt period when the extent of snowcovered areas has declined. Results for the Harp Lake (H4) catchment show that simple numerical feedback models of snowcover depletion may be successfully incorporated into the degree-day approach, resulting in more realistic assumptions of temporal and spatial melt processes. Results for landscape unit subdivisions within the catchment showed statistically significant improvements in model performance; open deciduous south-facing zones (0.001 level), open deciduous north-facing zones (0.02 level) and closed conifer/mixed wooded areas (0.1 level).

KEY WORDS: Snowmelt, Temperature-Index Models, Snowcover Depletion.

INTRODUCTION

Studies of acidic deposition in the Harp Lake area of Central Ontario have been under way for more than a decade. Recent progress with dynamic and simple conceptual hydrogeochemical models (Christophersen et al., 1982) has been successfully extended (Seip et al., 1985) and applied descriptively (Rustad et al., 1986) to the Harp Lake (H4) catchment. While various studies have indicated possible improvements for the H4 model (Figure 1) through redefinement of water routing parameters in near-surface soils (A) and ground water (B) (e.g. Whitehead et al., 1986; Wheater et al., 1986), there has been little work related to improvements in the snowcover modelling compartment (S).

The H4 model utilizes a degree-day temperature-index (DDTI) submodel to compute daily snowmelt totals as an input volume to the catchment. This simplified approach is suited to areas with limited meteorological data and appears consistent with other more sophisticated energy balance computations for the area (Scheider et al. 1983). Some basic work on the application of DDTI simulations for the H4 catchment has been reported (e.g. Scheider et al., 1986); however, the general assumption of a constant snowcovered area has been adopted in this work. This standard

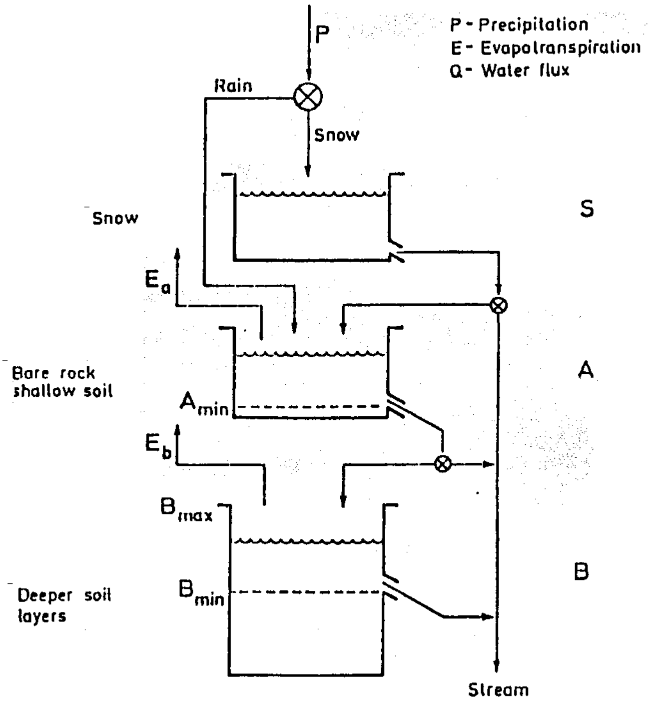

Figure 1. The H4 Hydrological reservoir model (after Christophersen et al., 1982).

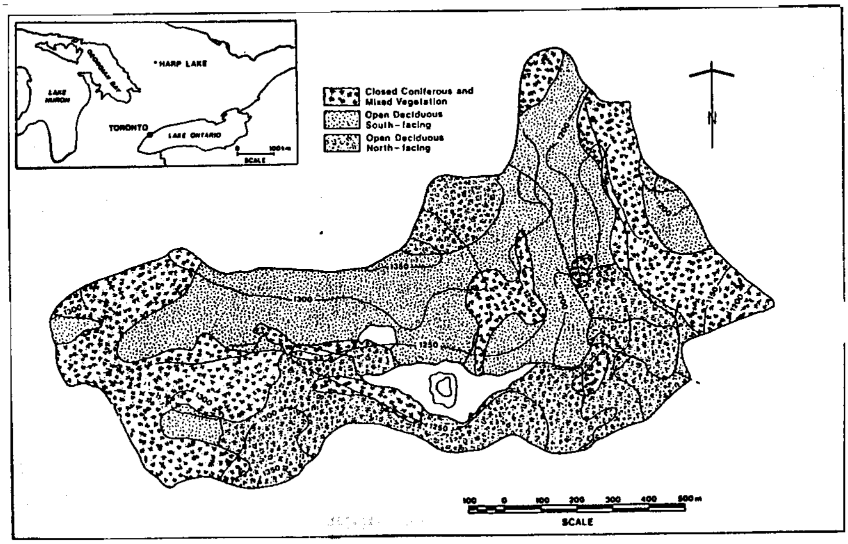

Figure 2. The H4 catchment showing the three vegetation-aspect landscape units.

approach often results in severe melt overestimates particularly toward the end of the melt period, when many zones are snow-free.

Buttle and McDonnell (1987) examined the effectiveness and applicability of five simple numerical feedback models of snowcover depletion. This paper presents a brief case study of how DDTI simulations may be improved by incorporation of modelled values of the spatial extent of bare ground throughout the snowmelt.

STUDY CATCHMENT AND METHODS

The H4 catchment (Figure 2) is largely forested with sugar maple (*Acer saccharum*), yellow birch (*Betula alleghaniensis*), and beech (*Fagus grandifolia*), while some hemlock (*Tsuga canadensis*) and balsam fir (*Abies balsamea*) are present in poorly drained areas. Landscape units within the catchment were subdivided into three broad classifications reflecting the relative coverage of the different vegetation-aspect types: open deciduous south-facing zones (ODSF), open deciduous north-facing zones (ODNF) and closed coniferous mixed wooded areas (CCM), representing 27.3%, 40.5% and 32.3% of the catchment area respectively (Figure 2). The CCM zone occupied flat low-lying areas of the catchment and was not assigned an aspect type.

A 32 point snow course was established within the catchment and snowpack water equivalent, depth and density within each of the vegetation-aspect groups were determined daily during the 1984 spring melt (Julian Day 75-110) using a Meteorological Service of Canada (MSC) snow tube. Bare ground development was determined by ground survey concurrent with the daily snow course survey.

DDTI Model

The mean daily air temperatures along with daily precipitation totals for the melt period were incorporated into a DDTI model (Scheider et al., 1983) comparable to that used in compartment (S) of the H4 model (Figure 1). The method used air temperature and precipitation as indices of heat exchange between the snowpack and the environment. A 1.5°C threshold mean daily temperature (below which all precipitation was considered to be snow) was selected based on data provided by Scheider et al. (1983). The model indicated that if mean daily air temperature remained below 1.5°C, all precipitation was accumulated in the snowpack. Otherwise, the melting of the pack was simulated using the following:

$$M = 1.3T \qquad (1)$$

$$M = (3.5 + 0.012P)T + 1.2 \qquad (2)$$

where M is the daily amount of snowmelt (mm/day), T is the mean daily air temperature (°C) and P is the total daily precipitation. Equation 1 was used during dry weather conditions, while equation 2 was applied to days experiencing rainfall. The model also incorporated a 3% liquid water snowpack retention to account for pack ripening.

Snowcover Depletion Models

Buttle and McDonnell (1987) showed that the optimum model for bare ground computation depended on the nature of the melt environment that it was being applied to. Thus, well-exposed areas possessing a discontinuous, shallow snowpack (e.g. ODSF) were handled by a model which assumed that melt takes place at the snowpack margins, while the assumption of uniform melt appeared more effective in regions of deep, continuous snowcover (e.g. ODNF and CCM zones).

An endogenous feedback model (Ferguson, 1984) was used for the ODSF zone, which maintained bare ground areas prior to the start of melt. The model (referred to here as model A) assumed that the snowpack had a spatially uniform water equivalent (W) and that it melted entirely at its margin (Figure 3a). The volume of meltwater (V) produced on day i reduced the snowcovered areas from Ai to:

$$A_{i+1} = A_i - V_i / W \qquad (3)$$

The second model (model B; after Dunne and Leopold, 1978) was used for the ODNF and CCM zones which maintained continuous snowcover prior to melt. Based on a detailed survey of peak water equivalent within the catchment, a curve relating water equivalent to the percentage of the basin area with a snowpack water equivalent less than or equal to a given value was constructed using arithmetic probability paper (Figure 3b). Thus the area covered by water equivalent depth W changed non-linearly with W, and the melt rate was assumed to be spatially uniform over the snowpack. Daily depths of melt were then subtracted from this peak curve resulting in a progressive depletion of snowcovered area, and the percentage of bare ground in the catchment was given by the intercept of the water equivalent curve with the abscissa.

RESULTS

DDTI simulations were reasonable for the CCM and ODNF zones, largely because of the dense overstorey and reduced exposure to shortwave radiation (Figure 4). However model performance for the ODSF zones was poorer, and field results indicated that the ODSF areas possessed lower peak water equivalent depths, higher daily melt rates and shorter melt durations than the ODNF and CCM landscape units (Buttle and McDonnell, 1987). Melt in the ODSF areas was dominated by shortwave radiative inputs as well as by sensible and latent heat fluxes, none of which are directly related to air temperature (Male and Gray, 1981). This accounts for the poor prediction of snowmelt in such well-exposed areas using a temperature-index model, and this result has also been obtained in other snowmelt modelling studies (e.g. Fitzgibbon and Dunne, 1980).

Bare ground computations (employing models A and B) were used to compute the catchment area effectively producing melt at the rate specified by the temperature-index simulation, and the computed trends in snowpack water equivalent are shown in figure 4. In each landscape unit, the incorporation of bare ground computations decreased mean differences and the sum of the absolute differences between observed and predicted water equivalent values (Table 1). To test the significance of these improvements, a simple t-test for paired data (Chase, 1967) was employed:

$$t = \bar{D}/(SD/\sqrt{N}) \qquad (4)$$

where $\bar{D}$ is the mean difference between modified (i.e. incorporating bare ground computations) and unmodified (standard DDTI) model outputs, SD is the standard deviation of the differences in model outputs, and N is the number of observations.

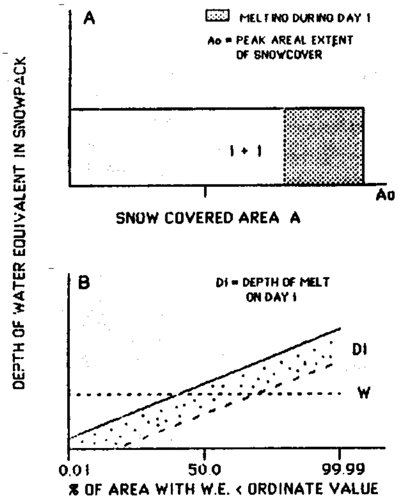

Figure 3. Schematic representation of snowcover depletion models A and B. See text for explanation.

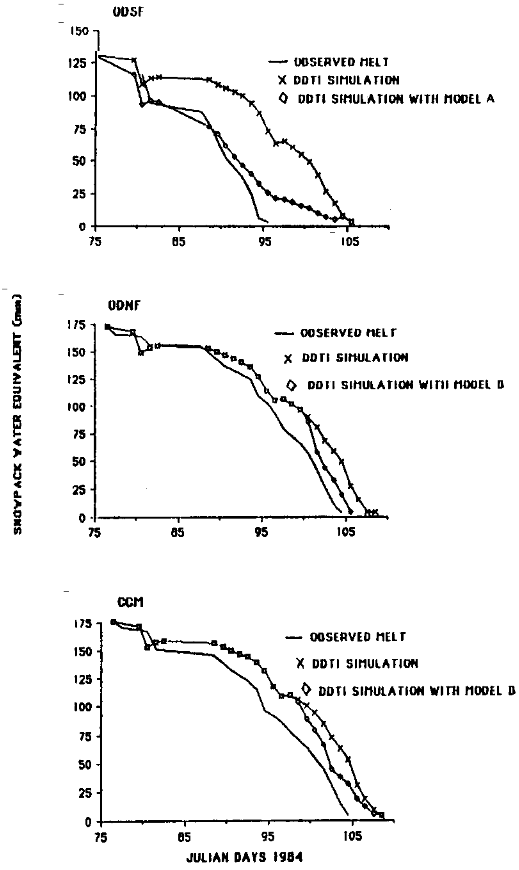

Figure 4. Observed versus modelled change in snowpack water equivalent for the 1984 melt period incorporating models A and B.

Table 1. Goodness-of-fit measures for the DDTI simulation and DDTI simulation incorporating snowcover depletion models A (ODSF zone) and B (ODNF and CCM zones).

Landscape Unit	Model	Sum of the Absolute Differences Between Observed and Simulated Values (mm)	Mean Difference Between Observed and Simulated Values (mm)	Standard Deviation of the Difference Between Observed and Simulated Values (mm)
ODSF	DDTI	999.7	29.8	24.1
(n=17)	DDTI+ModelA	190.9	10.6	8.3
ODNF	DDTI	452.4	13.7	14.6
(n=23)	DDTI+ModelB	309.8	10.3	9.2
CCM	DDTI	627.2	19.0	14.6
(n=26)	DDTI+ModelB	482.2	14.6	9.7

Each landscape unit experienced a better fit between observed and predicted values as a result of the incorporation of bare ground computations. Predictions of snowpack water equivalent for the CCM and ODNF zones showed improvements over values obtained assuming a temporally-constant snowcovered area, and were significant at the 0.1 and 0.02 significance levels respectively. Consideration of areal depletion of snowcover in the ODSF zone resulted in an improved model performance that was significant at the 0.001 level. This marked improvement in the ODSF zone is largely due to the fact that this zone maintained bare ground areas prior to melt and therefore experienced considerable overestimates early in the DDTI simulations. This once again underscores the importance of bare ground considerations in making the degree-day approach more realistic in terms of where melt occurs and over what area within a catchment.

DISCUSSION

Bare ground development through a melt period is an important consideration for snowmelt modelling, but rarely considered at the small watershed scale. Results from this investigation and others (e.g. Ferguson, 1984) show that snowcover depletion can be successfully built into a simple small watershed DDTI snowmelt simulation, rather than being ignored or imposed exogenously. Furthermore, the optimum model for bare ground computation depends on the melt environment (i.e. vegetation, slope, and aspect characteristics) that it is being applied to.

In the case of hydrogeochemical modelling, it is even more essential to determine the zones producing melt, not only for improved volumetric melt estimates, but also for better meltwater chemistry simulations. For example, if certain landscape vegetation-aspect groups within a catchment melt at varying rates, then the chemical flushing within these groups may be staggered, producing a more protracted acidic pulse.

Johannessen and Henriksen (1978) reported that 50-80% of the pollutant load in the snowpack was lost within the first 30% of the meltwater. Similar studies in the Harp Lake area have supported these results (Jeffries and Snyder, 1981). If, however, the first 30% of meltwater is dominated by a single landscape unit (e.g. open exposure, steep south-facing), then modelling of these spatial and temporal components becomes more complex, requiring detailed information on the extent of snowcovered area. Even though the DDTI approach does not distinguish melt rate computations on the basis of slope, vegetation or aspect, modelled bare ground values provide a reasonable approximation of the varying melt/depletion components occurring on a spatial scale, leading to improved melt and chemical flux estimates.

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