SNOWPACK DEPLETION IN A FORESTED CATCHMENT

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Introduction

The modelling of snowmelt runoff from drainage basins requires information pertaining to a number of processes, including snow accumulation, energy exchanges at the snowpack surface, the retention and movement of water within the pack, the distribution of the snow cover, and interactions between the snowpack and the soil (Anderson, 1979). Of these processes, it is particularly important to determine the location of snow covered areas during the course of the melt, since these will be the zones where energy exchange occurs and snowmelt is produced (Male and Gray, 1981). While many studies have demonstrated the usefulness of remote sensing to monitor large scale snowpack depletion (e.g. Hall, et al., 1985), the modelling of snowmelt in smaller drainage basins may necessitate the modelling of the percentage of the watershed covered by snow during the melt period. Anderson (1979) identifies two basic approaches to this problem - the zonal approach (e.g. U.S. Army Corps of Engineers, 1971) and the depletion curve approach (e.g. Martinec, 1980).

A third approach to modelling snowcover depletion that appears to be particularly suited to snowmelt runoff forecasts involves the use of endogenous feedback models. These use the areal extent of the snowpack and observed or calculated daily melt depths to determine the snow-covered area for the subsequent day, and require assumptions concerning the initial distribution of snowpack water-equivalent throughout the catchment and the spatial distribution of melt (Ferguson, 1984).

Ferguson (1984) presents three such models (see Figure 1). The first model assumes that the snowpack has a uniform water equivalent (W) and that it melts entirely at its margin (Figure 1a). Thus the volume of melt-water (V_i) produced on day i reduces the snow-covered area from A_i to

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

The second model assumes a nonuniform depth of initial water equivalent where the area covered by water-equivalent depth W decreases linearly with W, and where the melt rate also decreases to zero at the point of maximum water-equivalent (Figure 1b). Equation 1 is also used to describe the snowcover depletion, but W is replaced by the constant mean value $\bar{W}$. This model generates a curve of snowpack depletion over time that is identical to that produced by the first model. Ferguson's third model also assumes that water equivalent varies with extent (Figure 1c). However, melt is assumed to be spatially uniform, and the depletion equation becomes

$$A_{i+1} = (A_i^2 - V_i A_o/W_o)^{0.5} \qquad (2)$$

where A_o is the peak areal extent of snowcover and W_o is the initial mean water equivalent depth.

The three models use an average depth of melt multiplied by the area of snowpack to produce a volume of snowmelt that must be satisfied by the remaining water equivalent of the snowpack. In reality, should the calculated depth of melt exceed water-equivalent available to be melted at a point, as is often the case near the end of the melt season, then this difference is not satisfied by the removal of water-equivalent from those areas where the water-equivalent depth exceeds the depth of melt. This suggests that a fourth model, of the type presented by Dunne and Leopold (1978), may be more appropriate (Figure 1d). The detailed spatial pattern of peak water-equivalent within the catchment is required, and daily depths of melt are subtracted from the peak curve, resulting in a progressive depletion of the snow-covered area.

Study Area Description and Method

The study catchment used in this investigation is located near Dorset, Ontario and has been monitored intensively by the Ontario Ministry of the Environment as a part of its Acid Precipitation in Ontario Study (Figure 2). The Harp Lake (H4) watershed is largely forested with maple and birch, with some hemlock and balsam fir in poorly drained areas. Approximately 4 per cent of the watershed is in wetland and the relief is relatively severe with a 5 per cent grade.

Landscape units were subdivided into 3 basic classifications reflecting the relative coverage of the different vegetation - aspect types; open deciduous north-facing (ODNF), open deciduous south-facing (ODSF) and closed-conifer mixed (CCM) stands, representing 27.3%, 40.5% and 32.3% of the watershed area respectively (Figure 2).

Snowpack water equivalents within each of these groups were sampled daily using an MSC snow tube. Precipitation during the melt season was measured at an Ontario Ministry of the Environment met. station, located on the catchment boundary. Differences between the daily point water-equivalent values were adjusted to give daily point melt depths based on continuous streamflow and air temperature records. The amount of bare ground within each landscape unit was also determined concurrent with the daily snow survey.

Results and Discussion

Table 1 presents summaries of the peak water-equivalents and daily melts measured for each of the landscape units, along with the length of the melt period for each unit. Figure 3 shows the spatial variation in peak water equivalents for the three landscape units, while the observed increases in percent bare ground over the melt period are displayed in Figure 4a.

Table 1. Peak water-equivalent, melt rates and melt durations, Harp Lake, Spring 1984

Landscape Unit	Mean Peak Water-Equivalent (mm)	Standard Deviation of Peak W-E (mm)	CV (%)	Mean Daily Melt Rate (mm d^{-1})	Standard Deviation of Mean Daily Melt Rates (mm d^{-1})	CV (%)	Melt Duration (d)
ODSF	127	29	22.8	12	7	58.3	23
ODNF	168	30	17.9	9	5	55.6	33
CCM	168	38	22.6	9	6	66.7	37

The results indicate that the ODSF areas possessed lower peak water-equivalent values, higher daily melt rates and shorter melt durations than the ODNF and CCM landscape units. The ODSF slopes receive more direct beam solar radiation than ODNF areas as a result of their aspect, while the dense conifer stands in the CCM landscape unit intercept more incoming solar radiation than the leafless deciduous trees in the ODSF unit. In addition, Figure 3 highlights the large spatial variability in peak water-equivalent values within each of the landscape units, with the greatest range being present in the ODSF areas, where there was roughly 5% bare ground at the beginning of the main melt period.

Mean daily melt rates for each landscape unit for the 1984 melt were input to each of the four models, and Figures 4b to 4d show the predicted snowpack depletion curves as well as the observed trend. Table 2 presents some measures of goodness-of-fit of each of the four models - the sum of the absolute deviations between observed and predicted values, the mean difference between observed and predicted, and the standard deviation of the differences between observed and predicted. It is apparent that none of the models is a perfect simulator of observed trends in % bare ground. It should be noted that there is considerable variability in the daily point melt depths around the mean daily melts that were input to the models, and that the observed % bare ground values may be in error. Nevertheless, some general comments may be made.

Table 2. Goodness-of-Fit measures for the Four Snowpack Depletion Models

Landscape Unit	Model	Sum of the Absolute differences between observed and predicted values (%)	Mean Difference between observed and predicted values (%)	Standard deviation of the differences between observed & predicted values (%)
ODSF	1, 2	117.5	8.1	8.7
	3	260.7	18.6	9.1
	4	306.9	21.9	16.2
ODNF	1, 2	438.1	-5.4	20.4
	3	378.6	4.7	19.3
	4	216.0	10.6	13.3
CCM	1, 2	499.0	-8.0	18.4
	3	361.0	1.2	14.5
	4	190.5	5.4	10.3

Models 1 and 2 were the worst simulators of % bare ground for ODNF and CCM areas, where they overpredicted % bare ground on average. They gave the best simulation of % bare ground for ODSF areas, which implies that the assumptions of marginal melt, or higher melt at the snowpack edges, are most applicable to areas possessing discontinuous snowcover, as was the case for the ODSF unit. The main reasons for increased melt at snowpack margins are that a thinner pack transmits more light, resulting in heating of the ground and increased heat flux to the pack, and the reduction in albedo that occurs as vegetation begins to protrude above the snow surface.

In all three cases model 4 underpredicted % bare ground until late in the melt season or, as in the case of the ODSF areas, on the final day of melt. However, in terms of the sum of the absolute deviations between observed and predicted values, this model performed better than the others for the ODNF and CCM landscape units, while in terms of mean deviation, model 3 was superior for these areas. This suggests that the assumption of a spatially uniform melt depth may be more applicable to areas of more uniform snowcover at the start of melt and higher peak water-equivalents. Finally, only model 4 generated 100% bare ground in all three cases on or before the observed end of melt, with the other models leaving snow covering significant proportions of the landscape units. This, combined with its superior performance in those zones with continuous snowcover, suggests that model 4 would be the best model of snowpack depletion for use in conjunction with snowmelt runoff forecasts for the Harp Lake basin.

References

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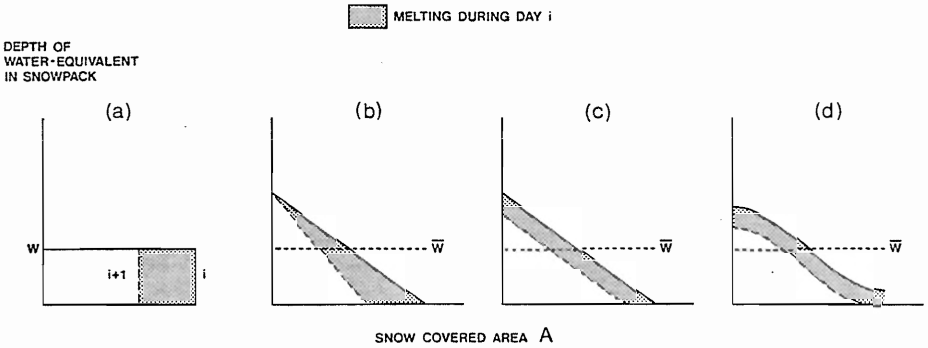

Figure 1. Graphical representation of four models of snowcover depletion.

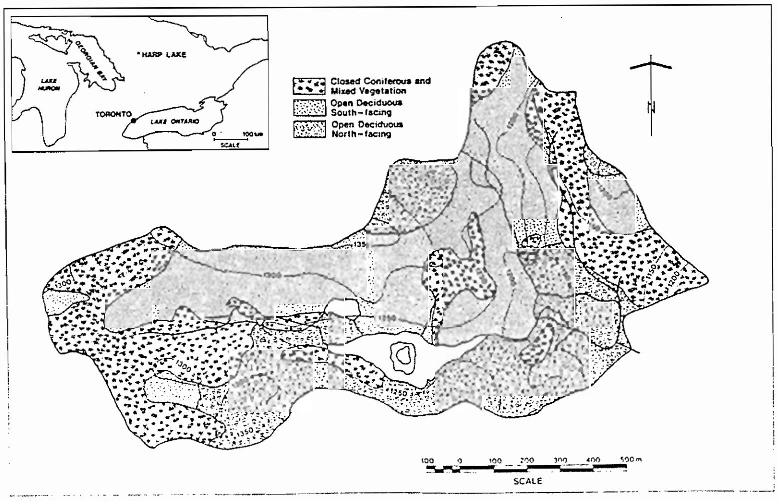

Figure 2. Harp 4 study catchment, showing the three vegetation-aspect landscape units.

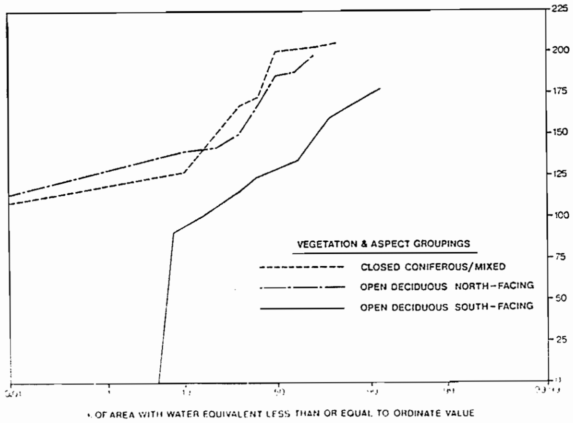

Figure 3. Spatial distribution of peak water-equivalents, Spring 1984 melt period.

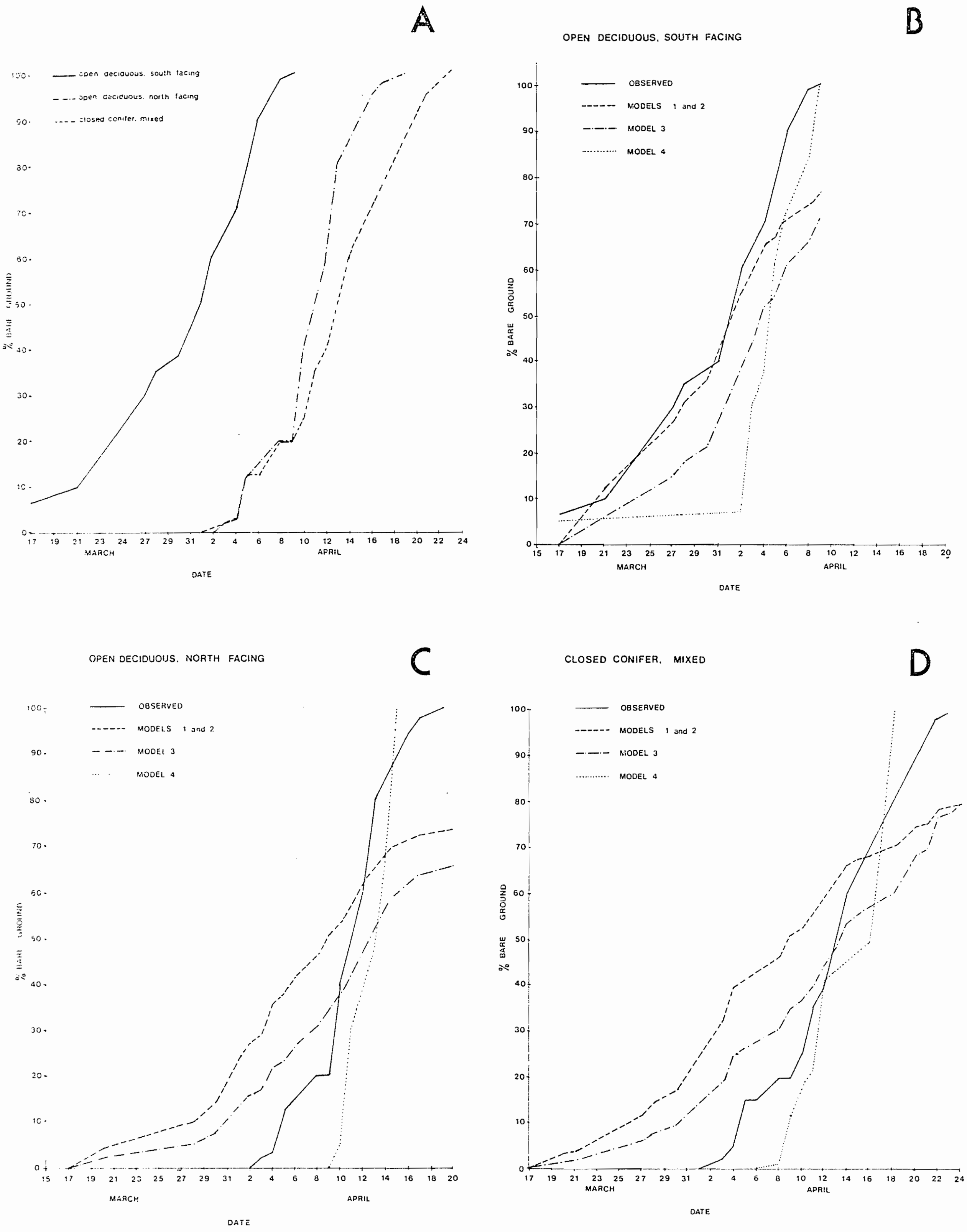

Figure 4. Observed and predicted trends in % bare ground development, Harp 4 catchment, Spring 1984 melt period.