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MODELLING THE AREAL DEPLETION OF SNOWCOVER IN A FORESTED CATCHMENT

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ABSTRACT

Buttle, J.M. and McDonnell, J.J., 1987. Modelling the areal depletion of snowcover in a forested catchment. J. Hydrol., 90: 43–60.

Successful modelling of snowmelt runoff from drainage basins often requires information concerning changes in the snowpack area during the course of the melt. Such data can be provided through the use of feedback models which employ the snowpack's areal extent and observed or estimated melts to forecast the snow-covered area for the subsequent day. The structure of five of these models is examined along with the results of a field study examining snowmelt and snowpack depletion in a forested catchment in south-central Ontario. The predictions of snowcover depletion for each model are compared with the observed trends for three distinct melt environments. The results suggest that several of these models can be used successfully to simulate changes in snowcover extent during snowmelt in forested areas. Snowpack depletion in areas of discontinuous snowcover is best simulated by models that assume that melt occurs predominantly at the snowpack margins, while models that utilize observed spatial variations in peak snowpack water-equivalent and assume either uniform or spatially variable melt depths perform best in environments with continuous snowcover prior to melt.

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, retention and movement of water within the pack, distribution of the snow cover, and interactions between the snow-pack and the soil (Anderson, 1979). Of these processes, it is particularly important to determine the extent of snow-covered areas during the course of the melt, since these will be the zones where the largest energy exchange occurs and snowmelt is produced (Male and Gray, 1981). Several snowmelt hydrologic models, although not originally requiring areal snowmelt input, have been modified to accept satellite snow extent data for the generation of daily discharge volumes (Rango and Martinec, 1979). However, most small watershed snowmelt algorithms have neglected the importance and application of snow-pack delineation in improving melt estimates, although McDonnell (1985) demonstrated that the incorporation of observed snowpack depletion into

degree-day temperature index simulations resulted in a considerable improvement in model results.

While many studies have demonstrated the usefulness of remote sensing to monitor large-scale snowpack depletion (e.g., Rango et al., 1977), the modelling of snowmelt in smaller drainage basins may necessitate forecasting the percentage of the watershed covered by snow during the melt period. Anderson (1979) identified 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; 1985). A third approach to modelling snowcover depletion 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). This paper examines the effectiveness and applicability of some published simple numerical models of snowcover depletion.

MODEL STRUCTURE

Three such endogenous feedback models were presented by Ferguson (1984) (Fig. 1). The first assumes that the snowpack has a spatially uniform water-equivalent (W) and that it melts entirely at its margin (Fig. 1a). Thus the volume of meltwater (V) 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 non-uniform 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 (Fig. 1b). Equation (1) is also used to describe the snowcover depletion, but W is replaced by the constant mean value $\bar{W}$ (Ferguson, 1984). 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 areal extent (Fig. 1c). However, melt is assumed to be spatially uniform, and the depletion equation becomes:

$$A_{i+1} = (A_i^2 - V_i A_0/\bar{W}_0)^{0.5} \qquad (2)$$

where A_0 is the peak areal extent of snowcover and $\bar{W}_0$ is the initial mean water-equivalent depth. The proportion of the catchment area consisting of bare ground (%BG) at the start of day $i + 1$ can be expressed for all three models as:

$$\%BG_{i+1} = [(A_T - A_{i+1})/A_T] \times 100\% \qquad (3)$$

where A_T is the total catchment area.

All three of the models presented by Ferguson have little basis in reality. It is unlikely that the assumed simple relationships between water-equivalent
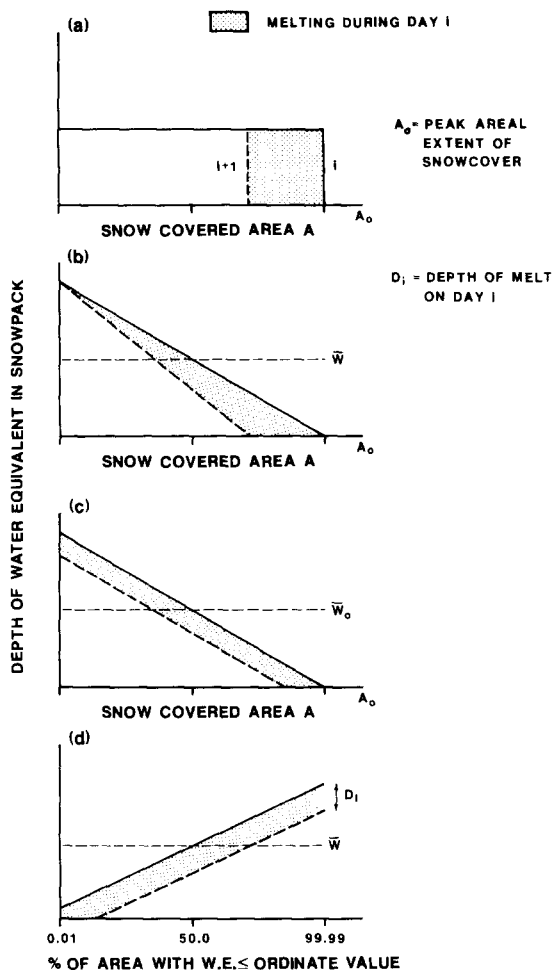
(a)

▦ MELTING DURING DAY I

A_o= PEAK AREAL
EXTENT OF
SNOWCOVER

I+1   I

SNOW COVERED AREA A A_o

(b)

D_i = DEPTH OF MELT
ON DAY I

$\bar{W}$

SNOW COVERED AREA A A_o

(c)

$\bar{W}_o$

SNOW COVERED AREA A A_o

(d)

D_i

$\bar{W}$

0.01   50.0   99.99

% OF AREA WITH W.E.≤ ORDINATE VALUE

DEPTH OF WATER EQUIVALENT IN SNOWPACK

Fig. 1. Schematic representation of four models of snowcover depletion: (a) spatially uniform water-equivalent, melt at snowpack margins (model 1); (b) spatially non-uniform water-equivalent, melt at snowpack margins (model 2); (c) spatially non-uniform water-equivalent, spatially uniform melt (model 3); (d) observed pattern of peak water-equivalent, spatially uniform melt (model 4). (a), (b) and (c) after Ferguson (1984); (d) after Dunne and Leopold (1978). See text for explanation.

and snow-covered area presented in Figs. 1a–c will be encountered in the field, considering the complexity of the snow accumulation process. In addition, these three models use an average depth of melt multiplied by the area of the snowpack to produce a melt volume that must be satisfied by the remaining water-equivalent of the snowpack. In reality, should the calculated depth of melt exceed the 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 (Fig. 1d).

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 that value is constructed using arithmetic probability paper. Thus the area covered by water-equivalent depth W changes non-linearly with W. The melt rate is assumed to be spatially uniform over the snowpack. Daily depths of melt are then subtracted from this peak curve, resulting in a progressive depletion of the snow-covered area, and the percentage of bare ground in the catchment is given by the intercept of the water-equivalent curve with the abscissa.

Although Ferguson (1984) stated that model 3 performed better than either model 1 or 2 during his work on snowmelt runoff modelling in Scotland, he did not present any results to support this conclusion. Indeed, we are unaware of any detailed examination of the relative merits of the various numerical snow-pack depletion models available for use in snowmelt runoff forecasting. This is despite the fact that many mathematical models used to forecast daily runoff require a continuous evaluation of snow cover extent during the melt (Leaf, 1969). Therefore, the aim of the present study is to test the ability of each of the models described above to simulate observed snowpack depletion in a drainage basin, using measured values of water-equivalent and short-term melt depths as inputs.

STUDY AREA DESCRIPTION AND METHOD

The watershed used in this investigation (Harp Lake Four) is located near Huntsville, Ontario (45°20′N, 79°10′W) and has been gauged both chemically and physically since 1976 by the Ontario Ministry of the Environment as part of its Lakeshore Capacity and Acid Precipitation in Ontario studies (Fig 2). Approximately 25–30% of the annual precipitation in this region occurs as snow. It melts from mid-March to late April and generates an average of 49–77% of the annual runoff within a six-week period (Scheider et al., 1983). This represents the most important event of the hydrologic year, and at this time the lakes, wetlands and limited groundwater bodies of the region are recharged with meltwater. In addition, intensive studies have identified the potential for significant biotic effects during spring melt, when the pulse of waters of low pH and elevated aluminum is introduced into the aquatic system.

The Harp Lake Four watershed is 119.8 ha in area and largely forested with sugar maple (*Acer saccharum*), yellow birch (*Betula alleghaniensis*) and beech (*Fagus grandifolia*), including some hemlock (*Tsuga canadensis*) and balsam fir (*Abis balsanea*) in poorly drained areas. Approximately 4% of the watershed is wetlands and the general relief of the basin is relatively severe with a 5% grade. The northeast arm of the catchment is characterized by prominent scarps and ridges, as is the southeast corner of the watershed. In the western sections of the basin, the relief is subdued, and large areas of swamp, muskeg and standing water have developed on an essentially flat bedrock surface

A 32-point snow course was established within the catchment to assess
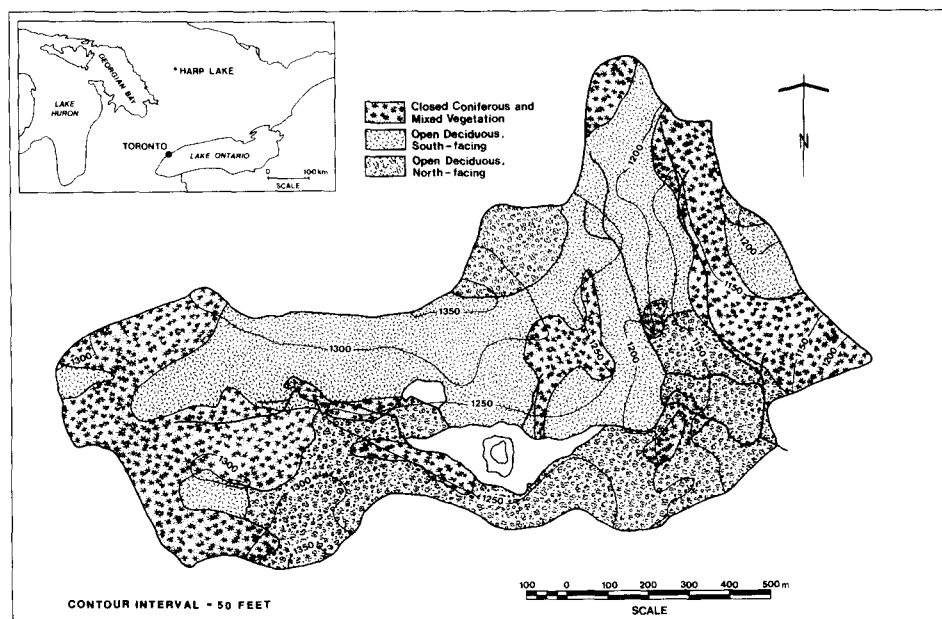
Fig. 2. Harp Lake Four study catchment, showing the three vegetation-aspect landscape units.

temporal trends in basin snowpack water-equivalent during the 1984 spring melt. Landscape units were subdivided into three basic areas reflecting the relative coverage of the different vegetation-aspect types: open deciduous north-facing (ODNF), open deciduous south-facing (ODSF) and closed coniferous/mixed (CCM) stands, representing 27.3, 40.5 and 32.2% of the watershed area respectively (Fig. 2). Daily surveys of snowpack water-equivalent were made using a Meteorological Service of Canada (MSC) snow tube during periods of active melt. Air temperatures and precipitation were continuously recorded at an Ontario M.O.E. meteorological station located on the basin divide. Hourly streamflow was recorded at a flume and stilling well assembly located at the basin outflow. The flume pool was heated to prevent freezing under sub-zero conditions. Differences between the daily point water-equivalent values were adjusted to give daily point melt depths based on the continuous streamflow and air temperature records, as described in McDonnell (1985). The amount of bare ground within each landscape unit was determined by a visual ground survey concurrent with the daily snow survey.

RESULTS AND DISCUSSION

Characteristics of the 1984 melt

Figure 3 shows the spatial variation in peak water-equivalents for the three landscape units prior to the onset of melt. It highlights the large spatial

TABLE 1

Summary of peak water-equivalent, melt rates and melt durations, Harp Lake Four basin, Spring 1984

Landscape unit	Mean peak W–E* (mm)	Standard deviation of peak W–E* values (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

*Water-equivalent.

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. These peak water-equivalent patterns are summarized in Table 1, along with the daily melts measured for each of the landscape units and the length of the melt period for each unit. There was considerable temporal variability around these mean
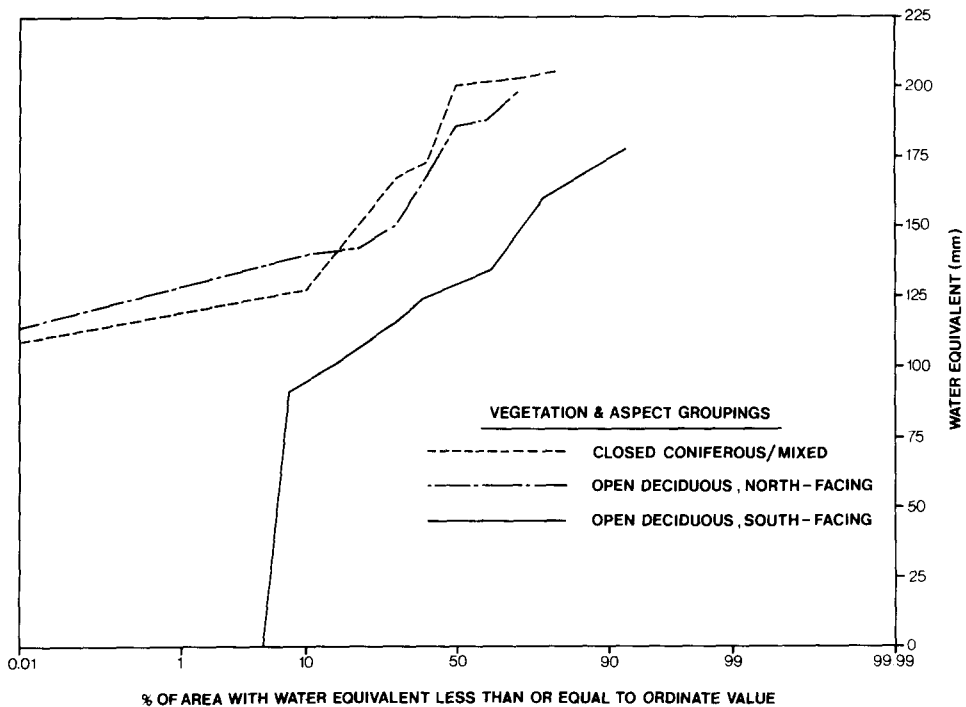

Fig. 3. Spatial distribution of peak water-equivalent, spring 1984 melt period.
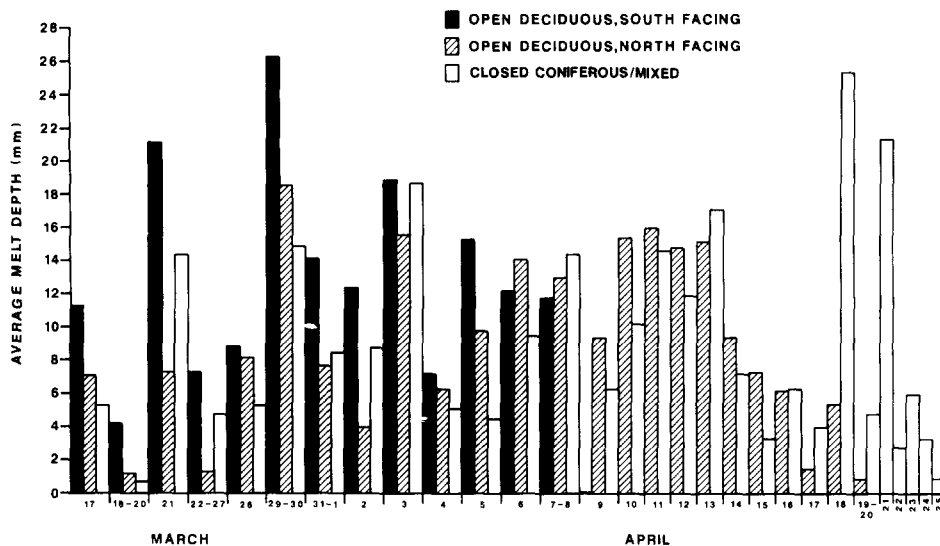
Fig. 4. Average melt depths for the three landscape units, based on the snow tube survey results.

melt rates as indicated by Fig. 4, which presents the short-term average melt depths for each area.

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. The influence of the conifers in shielding the snowpack from direct-beam solar radiation also appears to explain the protracted melt period in the CCM area when compared to the melt duration for the ODNF unit (Table 1). These variations in melt response between the three landscape units produced distinctly different snowpack area depletion curves during the 1984 melt (Fig. 5).

Sensitivity analysis

The field results indicated substantial variability about the average melt-depth values and the peak snowpack water-equivalents within each vegetation/aspect group, and therefore a sensitivity analysis was conducted in order to evaluate the influence of these two variables upon the modelled output. Models 1, 2 and 3 were run using the mean peak water-equivalent $\pm$ one standard error. Secondly, the average daily melt depths for each area (Fig. 4) were adjusted using their respective standard errors, and these adjusted values were input to each of the four models.
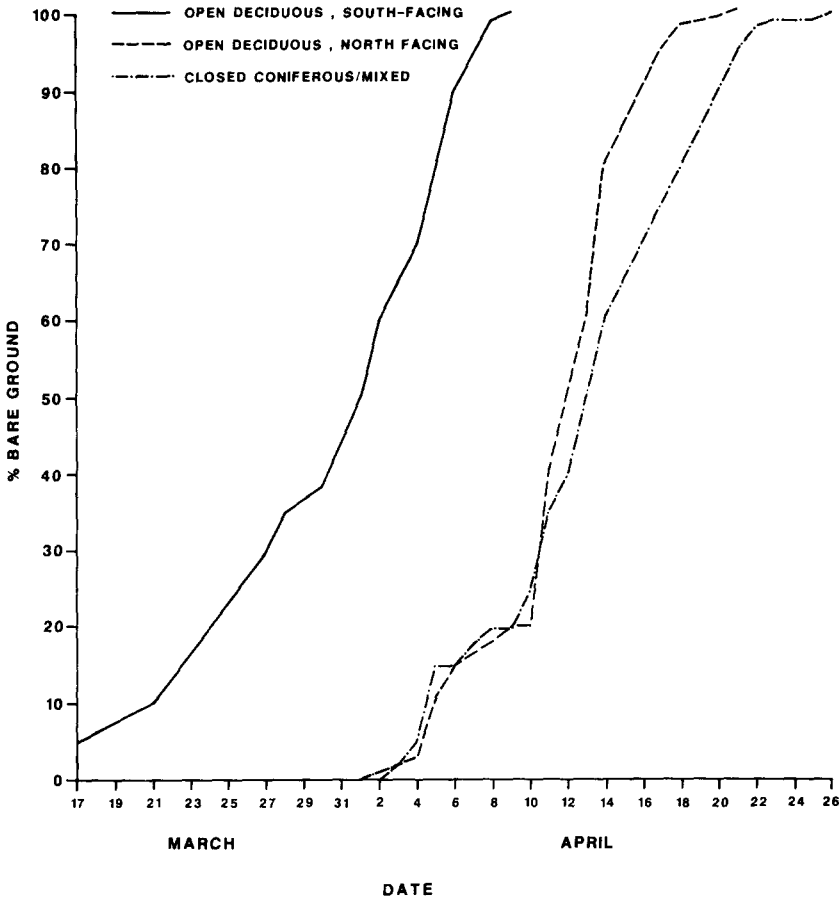
Fig. 5. Observed trends in % bare ground development, spring 1984.

Peak water-equivalent

Figure 6 shows the influence of variations in peak water-equivalent upon the % bare ground forecasts for the ODSF unit. Model 4 was not included in this analysis as the spatial variability in peak water-equivalent is directly incorporated into its structure. As Fig. 6 reveals, the other three models are relatively insensitive to variations in peak water-equivalent, although their influence upon the output of model 3 is slightly more pronounced than for models 1 and 2 at the end of the melt period. In addition, a mis-specification of peak water-equivalent does not result in any change in the forecast start of bare ground development.

Melt depths

The sensitivity of the models to errors in the input melt depths is demonstrated in Fig. 7 for the CCM landscape unit. All four models are greatly

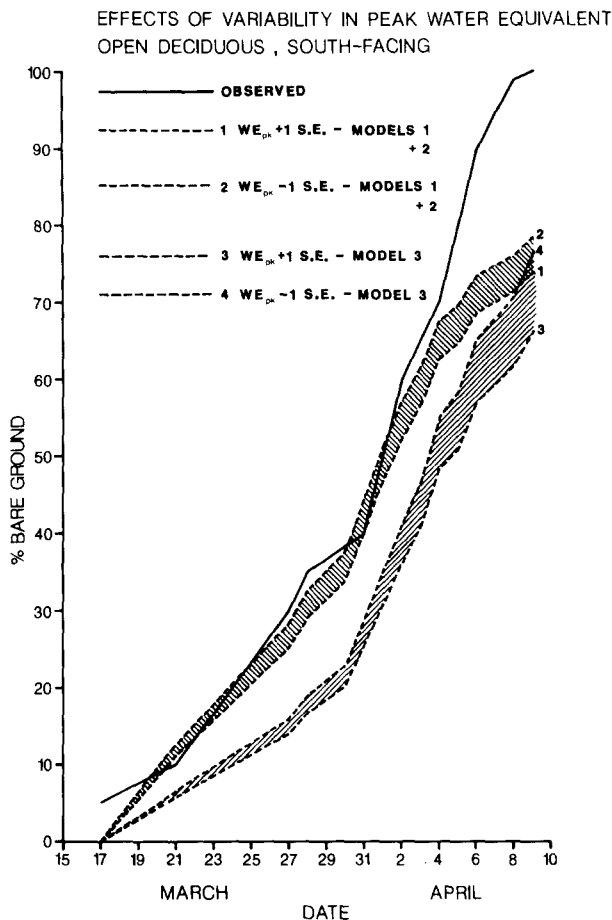EFFECTS OF VARIABILITY IN PEAK WATER EQUIVALENT
OPEN DECIDUOUS , SOUTH-FACING

Fig. 6. Model sensitivity to variations in peak water-equivalent, ODSF landscape unit.

influenced by changes in their melt input, this sensitivity being most pronounced in the case of model 4 and least evident for models 1 and 2. This range in sensitivity appears to be due to differences in model structure. In the case of models 1, 2 and 3, any non-zero melt depth must result in the production of bare ground at the start of the melt period. This accounts for their overprediction of the date of the appearance of bare ground. The assumptions of uniform melt and a linear decrease in peak water-equivalent with area make model 3 more responsive to changes in the size of melt input than models 1 and 2. As for model 4, the predicted trend in % bare ground is a function not only of the short-term melt depths employed but also the spatial distribution of the peak water-equivalents (Fig. 3). As a result of the flattening of the tails of the peak water-equivalent distribution when plotted on arithmetic probability paper, minor changes in the daily melt input can produce disproportionately large variations in % bare ground. This is particularly evident at the start of the melt period, where an increase in the daily melts by one standard error above the mean causes the
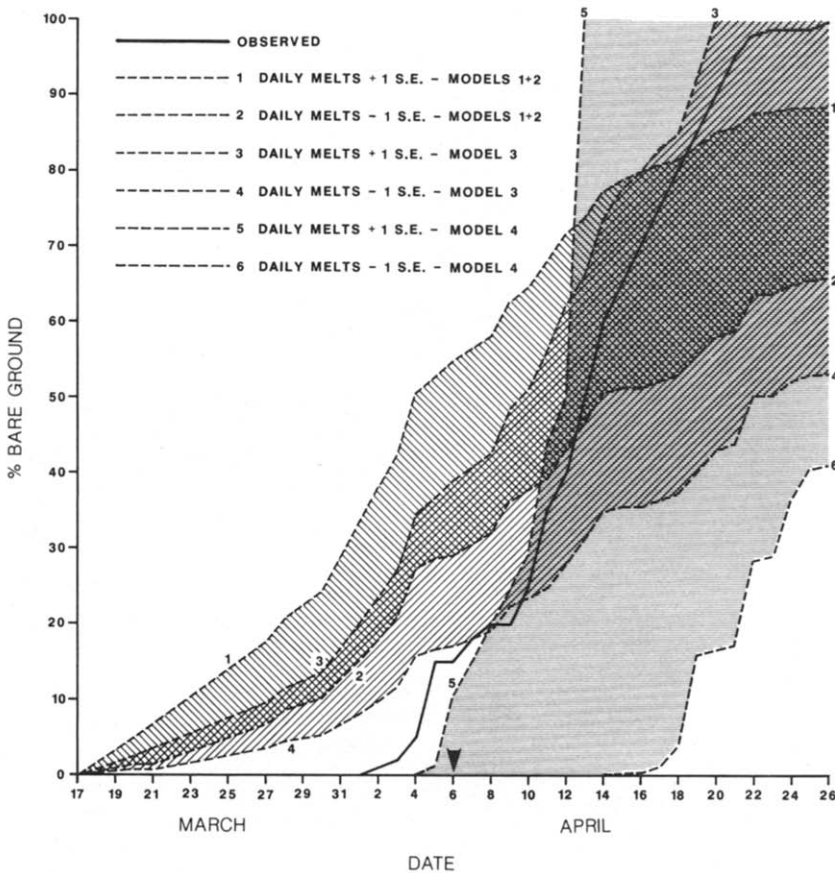
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Fig. 7. Model sensitivity to variations in daily melt rates, CCM landscape unit. Arrow indicates the start of bare ground development forecast by model 4 using daily average melt values.

spatial extent of the snowpack to begin to decrease two days before that forecast using the average daily melt values, and ten days before that forecast using the melt depths one standard error below the mean (Fig. 7).

Model 5 — Non-uniform melt inputs

The sensitivity of model 4 to variations in the input melt depths suggested that the model results would be improved if some measure of the spatial variability in the short-term melt depths could be incorporated into the model structure. The result was the development of model 5 (Fig. 8), which uses the same procedure as model 4 for predicting % bare ground, but which assumes that the daily melt varies inversely with the depth of water-equivalent over the area of interest. Consideration of the physical controls on snowmelt suggests

(a)

% OF AREA WITH W.E. ≤ ORDINATE VALUE

X̄+2S.E. MELT DEPTH   WATER-EQUIVALENT
                              DEPTH

MELT
DEPTH   X̄

X̄-2S.E.

0.0   50.0   100.0

% OF AREA WITH MELT DEPTH ≥
ORDINATE VALUE

(b)

%BG ₍ᵢ₋₁₎

DEPTH OF
WATER
EQUIVALENT
IN SNOWPACK

M.D.ᵢ =
X̄-2S.E.

M.D.ᵢ = X̄

M.D.ᵢ =
X̄+2S.E.   0.01   50.0   99.99

% OF AREA WITH WATER EQUIVALENT ≤
ORDINATE VALUE

M.D.ᵢ = MELT DEPTH ON DAY I
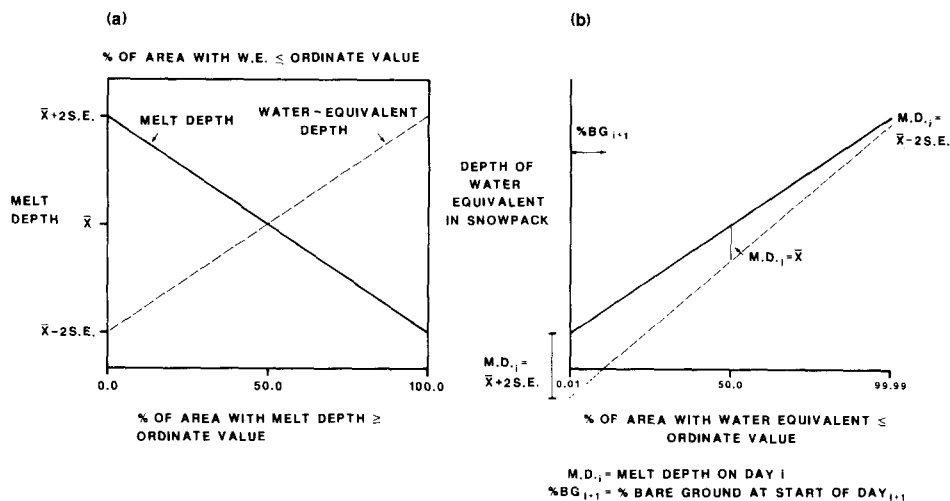%BG₍ᵢ₋₁₎ = % BARE GROUND AT START OF DAY₍ᵢ₋₁₎

Fig. 8. Schematic representation of a model of snowcover depletion incorporating spatially variable melt inputs: (a) assumed relationship between daily melt depth and water-equivalent depth over the snow-covered area; (b) application of the melt depth distribution to the water-equivalent vs basin area curve, resulting in % bare ground forecast. See text for explanation.

a number of reasons for higher melt over shallower snowpacks. These include: (1) the ability of a thinner snowpack to transmit more light, resulting in heating of the ground and increased heat flux to the pack; (2) the increased roughness length (and therefore accelerated turbulent exchanges) that results as vegetation begins to protrude above the snow surface; (3) the influence of this protruding vegetation and accompanying litter fall upon the radiative exchanges at the snowpack surface; and (4) potential advection of heat from surrounding bare surfaces to the snowpack.

Unfortunately, the relatively small number of points in the daily snow course (32 points covering the entire catchment) did not enable the detailed spatial pattern of melt within each landscape unit to be determined. Instead the spatial variations in melt were approximated using the daily point melt depth data and the aforementioned assumption of an inverse relationship between melt depth and snowpack water-equivalent. By assuming: (1) that 50% of the snow-covered area has a daily melt depth greater than or equal to the mean melt depth ($\bar{X}$) for that day; (2) that the area with the lowest water-equivalent has a melt depth equal to the mean plus two standard errors ($\bar{X} + 2SE$); and (3) that the portion of the snowpack with the highest water-equivalent experiences a melt depth equal to the mean minus two standard errors ($\bar{X} - 2SE$), it becomes possible to construct a hypothetical distribution of melt depths over the snow-covered area (Fig. 8a). It is important to note that there is no theoretical justification for assuming such a distribution. Analysis of the frequency distributions of the daily melt depths for each landscape unit revealed that they did not possess any consistent form. Therefore the distribution in Fig. 8a was adopted solely for the sake of computational convenience. This
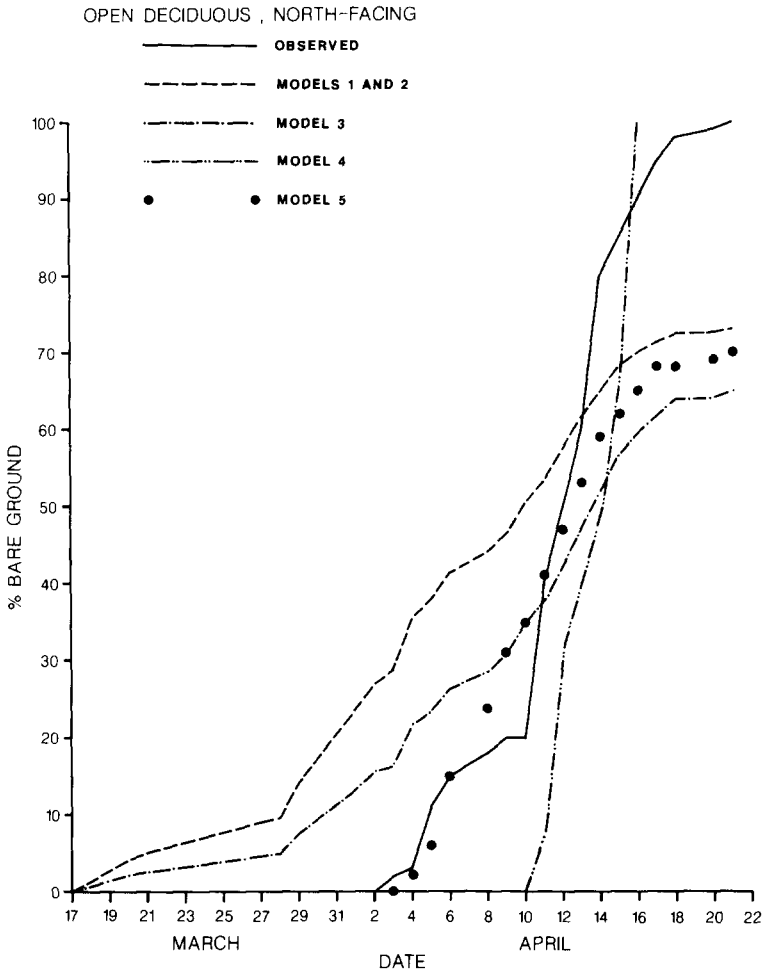
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Fig. 9. Observed and predicted trends in % bare gound development, ODNF landscape unit.

relationship between melt depth and snow-covered area is adjusted using the observed mean melt depth and standard error about that mean for a given day. The resultant distribution of melt depths is then applied to the curve relating water-equivalent to the percentage of the basin area with a snowpack water-equivalent less than or equal to that value (Fig. 8b). As with model 4, the % bare ground in the basin at the start of the next day is given by the intercept of the water-equivalent curve with the abscissa.

Model performance tests

The mean peak water-equivalent depths (Table 1) and the short-term average melt depths (Fig. 4) for each landscape unit were input to the five models described above, and the results are presented in Figs. 9–11.
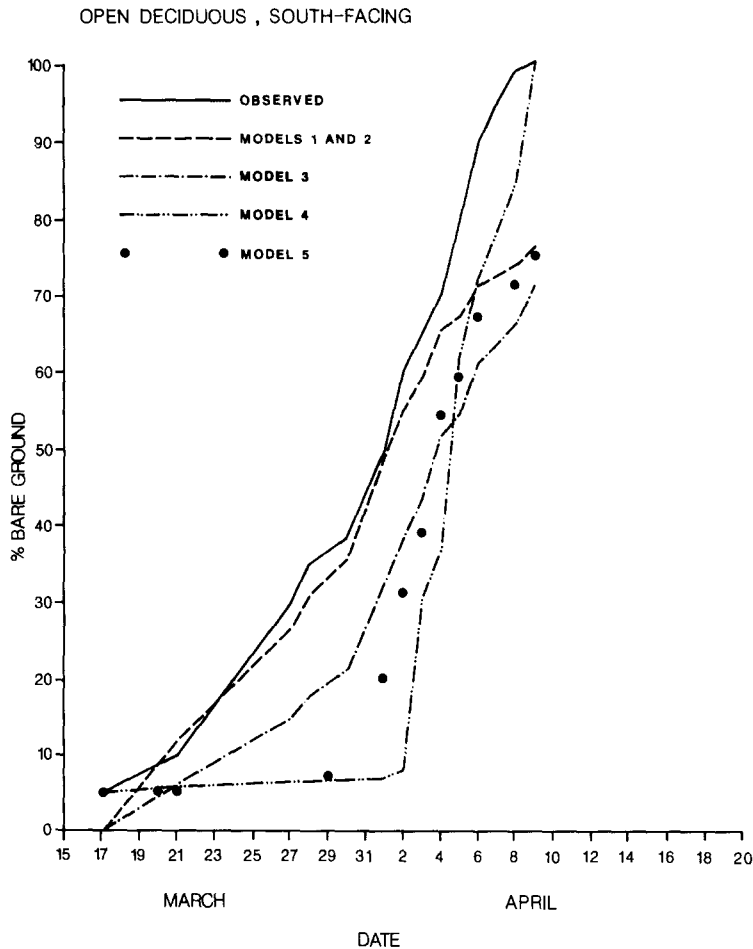
OPEN DECIDUOUS , SOUTH-FACING

Fig. 10. Observed and predicted trends in % bare ground development, ODSF landscape unit.

When evaluating the ability of a model to simulate observed response, it is not sufficient to simply perform a visual comparison of graphical output. Instead the hydrologist requires an objective function to provide a quantitative measure of the goodness-of-fit between measured and modelled results. As Fleming (1975) notes, there is presently no assessment available to define the best objective function for use in hydrological modelling. It was decided, therefore, to employ a number of objective functions, because different statistics deal with different properties of the data and, as Aitken (1973) points out, some objective functions distinguish between random and systematic model errors while others do not.

Table 2 presents goodness-of-fit results for the models for the three melt environments. Columns (1)–(4) contain the values of a number of simple objective functions that were presented by Ward (1984):
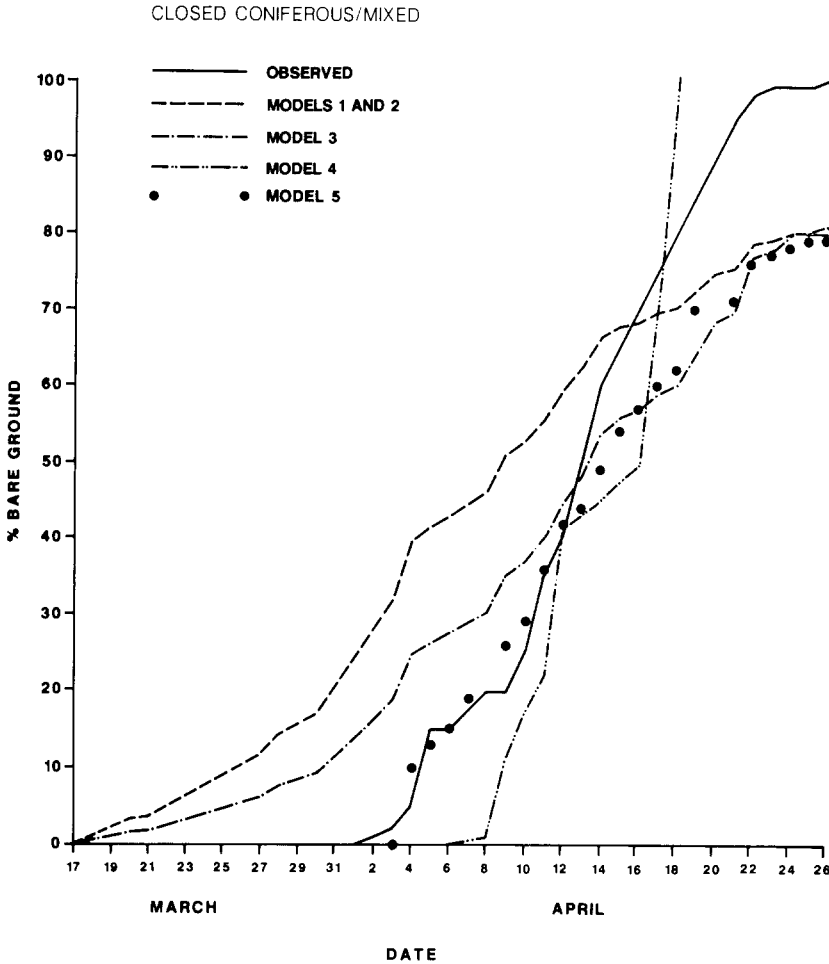
CLOSED CONIFEROUS/MIXED

Fig. 11. Observed and predicted trends in % bare ground development, CCM landscape unit.

$$\text{ERR (Total error)} \; = \; \sum_{i=1}^{n} (\text{Obs}_i - \text{Pred}_i)^2$$

$$\text{PAE (Percentage average error)} \; = \; \frac{[(\text{ERR}^{1/2}/n] \times 100}{\sum_{i=1}^{n} \text{Obs}_i}$$

$$\text{APE (Average percentage error)} \; = \; \left\{ \sum_{i=1}^{n} [(\text{Obs}_i - \text{Pred}_i)/\text{Obs}_i \times 100]^2 \right\}^{1/2} \Big/ n$$

$$\text{EFF (Model efficiency)} \; =$$
$$\left\{ \left[\sum_{i=1}^{n} (\text{Obs}_i - \overline{\text{Obs}})^2 - \text{ERR} \right] \Big/ \sum_{i=1}^{n} (\text{Obs}_i - \overline{\text{Obs}})^2 \right\} \times 100$$

where:

Obs_i = observed value for time period i

$Pred_i$ = predicted value for time period i

$\overline{Obs}$ = mean of the observed values

n = number of time periods

The characteristics of each of these functions are described in detail by Ward (1984). Clearly the model which provides the best fit to the observed data is one which minimizes ERR, PAE, and APE, while at the same time maximizing its efficiency, EFF.

It is apparent from Figs. 9, 10 and 11 and Table 2 that none of the models is a perfect simulator of observed trends in % bare ground. It should be noted that the surveyed % bare-ground values may be in error, and that substantial errors may arise from the use of daily snow-tube surveys to estimate daily melt values. Nevertheless, some general comments may be made.

Examination of Table 2 indicates that models 1 and 2 gave the best simulation of % bare ground for ODSF areas, despite their unrealistic structure. This implies that the assumption of marginal melt, or higher melt at the snowpack edges, is most applicable to areas possessing discontinuous snowcover, as was the case for the ODSF unit prior to melt. For both the ODNF and CCM areas, those models incorporating the observed spatial variations in peak snowpack water-equivalent (models 4 and 5) performed best. This is highlighted by a comparison of models 3 and 4. Both assume a spatially variable peak water-equivalent and a spatially uniform melt. However, the superior performance of the latter model demonstrates that the use of the observed spatial pattern of

TABLE 2

Goodness-of-fit measures for the five snowpack depletion models

Landscape unit	Model	ERR (1)	PAE (2)	APE (3)	EFF (4)	Sign (5)
ODSF	1, 2	2447.2	0.4	0.77×10^1	84.6	0.01
	3	6756.4	0.7	0.12×10^2	57.6	0.001
	4	10,159.8	0.8	0.14×10^2	36.2	0.01
	5	8055.8	0.7	0.13×10^2	49.5	0.001
ODNF	1, 2	10,956.4	0.5	0.16×10^{10}	77.5	0.001
	3	9265.9	0.4	0.92×10^9	80.9	0.001
	4	4706.0	0.3	0.11×10^2	90.3	0.001
	5	5506.0	0.3	0.68×10^1	88.7	0.001
CCM	1, 2	11,614.2	0.3	0.12×10^{10}	77.4	0.001
	3	6192.3	0.2	0.64×10^9	88.0	0.001
	4	2724.5	0.1	0.86×10^1	94.7	0.001
	5	4314.0	0.2	0.64×10^1	91.6	0.01

peak water-equivalent produces a better fit of the observed trend of % bare ground development than the assumption of an inverse linear relationship between peak water-equivalent and areal extent of the snowpack.

The inclusion of spatially varying melt depths into model 4 (model 5) does not appear to have increased its performance substantially. While there has been a minor improvement in the fit of the observed % bare-ground data in areas of discontinuous snowpack (ODSF unit), the goodness-of-fit measures in Table 2 suggest that model 5 may be slightly less effective than model 4 in simulating snowpack depletion. This may be the result of the assumed spatial distribution of daily melt depths incorporated in model 5 (Fig. 8). The use of a different distribution of melt depth vs. snow-covered area may lead to significant increases in model performance.

Where model 5 *is* an improvement over model 4 is in its ability to simulate accurately % bare ground in the early stages of development for the ODNF and CCM landscape units. This phase of the snowmelt period is of great hydrological importance since the water-equivalent depths stored in snowpacks at such times are larger than near the end of the melt. Thus errors in % bare ground estimates at the start of bare ground development are of greater significance to forecasts of water volume remaining in storage in the snowpack than are errors of the same magnitude occurring when the water-equivalent of the remaining snowpack is quite low.

A drawback to the use of these statistical measures is that they fail to distinguish between random and systematic model errors. Therefore a simple sign test (Aitken, 1973) was employed as a fifth criterion of fit. This required the determination of over- or underprediction of daily % bare ground for each model. The number of runs of successive daily over- or underpredictions was then compared with the expected number assuming random variations around the observed % bare ground line. According to Aitken (1973) a model introduces a systematic error to its predictions when a Chi-square test indicates that the number of runs is significantly less than the expected number. Column (5) in Table 2 presents the level of significance at which the observed number of runs was found to differ from the expected value. From these results, it appears that all five models generate systematic errors for each of the three landscape units. This is confirmed by an examination of Figs. 9, 10 and 11.

These systematic errors are particularly pronounced for models 1, 2 and 3 for the ODNF and CCM areas. The models consistently overpredict the onset and development of bare ground at the start of the melt, while underpredicting % bare ground at the end of the melt period. Overprediction arises from the model structure and the assumption that the calculated meltwater volume (melt depth × snowpack extent) must be satisfied by the remaining water-equivalent of the snowpack. The rapid initial shrinkage of the snow-covered area leads to a dramatic reduction in calculated melt volumes which must be supplied by the remaining snowpack at roughly the mid-point of the melt period. This negative feedback results in the models leaving snow on the ground when none should exist.

The systematic underprediction of % bare ground for ODSF areas by models 3 and 4 may be due to the application of a spatially uniform melt to a discontinuous snowpack. In the case of model 5, actual melt rates in areas of thin snowcover may have been greatly in excess of the assumed rates ($\bar{X} + 2\,\mathrm{SE}$). This underprediction is less severe for models 1 and 2 due to their assumption of marginal melt, as mentioned above.

The source of the systematic errors in models 4 and 5 when applied to the ODNF and CCM units is less obvious. One possibility for model 4 may be errors in the average melt-depth values used as input. These melt depths may be too low at the beginning of the melt period, as suggested by the results of model 5, where the assumption of higher melt rates over thinner snowpacks generates a much better fit of observed snowpack depletion. Another source of error in model 4 may be an insufficiently detailed specification of the distribution of peak water-equivalents in the landscape units, particularly in the tails of the distributions (Fig. 3). Overestimation of the lowest peak water-equivalent in the basin combined with underestimation of the maximum water-equivalent depth could produce the systematic errors observed. Model 5's estimates of % bare ground begin to deviate systematically from the observed values during the final stages of melt, and this is likely due to the assumed relationship between melt depth and the depth of snowpack water-equivalent. While this relationship appears to function satisfactorily at the start of snowcover depletion, near the end of the melt period the standard error of the daily mean melt depths could become a large proportion of the mean melts. This meant that the daily melts applied to those areas with deep snowcover were often very low or zero, resulting in substantial portions of these landscape units (20–30%) remaining snowcovered at a time when the actual snowpack had vanished.

CONCLUSIONS

Information on changes of the snow-covered area within a drainage basin is important for the modelling of its short-term snowmelt runoff output. This study has shown that simple numerical models can be successfully used to simulate snowpack depletion. However, the optimum model to be used for such forecasts appears to depend on the nature of the melt environment that it is to be applied to. Thus well-exposed areas possessing a discontinuous, shallow snowpack may be handled using a model which assumes that melt takes place at the snowpack margins, while the assumption of uniform melt appears more warranted in regions of deep, continuous snowcover. Results indicate that a model of the type described by Dunne and Leopold (1978) (models 4 and 5) generates simulations of snowcover depletion in such areas that are superior to those obtained using the endogenous feedback models described by Ferguson (1984). The inclusion of some measure of spatial variations in daily melt depths to the Dunne and Leopold model (model 5) led to very accurate estimates of % bare ground during the initial two-thirds of the melt period for the CCM and ODNF landscape units. However, a drawback to the use of models 4 and

5 is the requirement of the detailed spatial pattern of water-equivalent in the basin prior to melt, which necessitates a field sampling program or some method of remote sensing of snowpack water-equivalent (e.g., aerial surveys of natural gamma radiation as described by Goodison et al., 1981). A final observation that applies to all of the models tested is their sensitivity to errors and/or variations in the daily melt-depth inputs. This reinforces the need for the accurate measurement or estimation of melt prior to utilizing such data in snowmelt runoff models.

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