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Development of improved methods for snowmelt forecasting

Annual Progress Report to The Scottish Office for the period November 1996 to October 1997

Institute of Hydrology
Crowmarsh Gifford
Wallingford
Oxfordshire
OX10 8BB
UK

Tel: 01491 838800
Fax: 01491 692424
Telex: 444293 ENVRE G

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CONTENTS

1. INTRODUCTION

This is the third progress report of The Scottish Office project "Development of improved methods for snowmelt forecasting" begun in March 1995 and employing data from IH's Monachyle Burn experimental catchment in Balquhidder, Scotland. Field monitoring activities and database management undertaken in the past year are first reviewed. The main part of the report details progress made within the year on snowmelt modelling. Results from new model formulations are obtained for the Monachyle Burn catchment. Due to the paucity of suitable data from Balquhidder, results have also been obtained for a second upland catchment: the Trout Beck in the Upper Tees, Northumbria. The report ends with a review of liaison activities related to the project.

2. FIELD MONITORING AND DATABASE MANAGEMENT

The 1996/97 snowmelt season was a disappointing one in terms of field monitoring in the Balquhidder catchment due to the lack of significant snowfalls. Snow occurred as early as November and the monitoring team were ill-prepared for such an early fall. Plans were put in place to monitor snow over the weekend of 23/24 November but difficulties of access allowed only one set of measurements to be made on 26 November. Depths of 65 and 68 mm water equivalent were recorded in the vicinity of the Lower and Upper Monachyle AWS sites respectively. No measurements of the subsequent thaw were made. Lack of snow later in the season resulted in a nil return in terms of useful snow monitoring in the Balquhidder catchment for the 1996/97 season.

The establishment of a model database for the Balquhidder catchment based on archived data had, in the previous report, identified January and February 1984 as a snow period suitable for model development and assessment. A further event has since been selected, covering the period 18 December 1995 to 28 February 1996. Model results obtained using both periods of data are reported in the next section.

To compensate for the lack of snow data from the Balquhidder catchment, the modelling work reported in the next section has also made use of data from Trout Beck in England. This catchment in the Upper Tees, 80 km from the Scottish border, will be indicative of conditions experienced in the Southern Uplands of Scotland, but not of the Scottish Highlands.

3. SNOWMELT MODELLING

3.1 Introduction

The second progress report presented preliminary model results for a snow event in Monachyle Burn in January and February 1984. The PDM (Probability Distributed Moisture) rainfall-runoff model was calibrated on a snow-free event to determine optimum parameter values. The full snowmelt model, comprising the PDM together with the PACK snowmelt module, was optimised on the snow event of 9 January to 28 February 1984. Initial results were very promising, yielding an increase in R^2 performance (the proportion of flow variability accounted for by the model) from 0.46 to 0.73 as a result of incorporating snowmelt into the model.

Further results on the use of both lumped and distributed snowmelt model formulations were presented at the Bridge of Allan seminar "The Snow Resources of Scotland" in March 1997. The results were summarised in a paper prepared for Scottish Natural Heritage and are presented in Section 3.2 below. The results indicate a very slight improvement in simulation performance using a distributed model formulation. Preliminary research into the use of multiple elevation zones, to represent temperature variation with height in a catchment and its effect on melt, suggested some advantage may exist for higher relief catchments.

Following these results, a new elevation-dependent snowmelt model formulation has been developed based on the PDM-PACK model. The model can be easily run using any number of elevation zones, and calculates changes with elevation of the depth and water equivalent of the snowpack over time. Observations of the position of the snowline in the catchment for two events have been used as an additional check on model performance. The new model formulation and simulation results are presented in Section 3.3.

3.2 Model assessment: lumped vs. distributed formulations

The model variants considered in the assessment comprise the PACK snowmelt module linked to one of two rainfall-runoff models which transform rainfall (and drainage melt from the snowpack) into catchment runoff. One of the models is a lumped conceptual model - the PDM (Probability Distributed Moisture) model - whilst the second is a more spatially distributed model, namely the SGM (Simple Grid Model). The PACK snowmelt module conceptualises the lying snow as being made up of dry snow that has yet to melt and wet snow which has melted but is still held in the snow pack. When the temperature is above the melt threshold (usually taken to be 1°C) the dry snow melts and contributes to the wet snow store. Water is released from the wet snow store at a rate dependent on the proportion of the pack that is melted snow, and is transformed into flow at the basin outlet by the rainfall-runoff model. Details of the snowmelt models used in this investigation are given in the NRA R&D Note 402 "Development of improved methods for snowmelt forecasting".

The above outline of coupling PACK and catchment models together assumes that a single PACK module functions as a lumped catchment-scale model of the snowmelt process. A simple distributed representation of the snowmelt process can be based on a partitioning of the catchment into elevation zones with a PACK module operating within each zone. Incorporating elevation zones provides a simple way of representing the change in temperature with elevation in a catchment, and its effect on melt, through the use of a temperature lapse rate.

The combined models were evaluated on the winter period 9 January to 28 February 1984 in the Monachyle Burn catchment in Balquhidder. Since only one snow period from this catchment is suitable for model assessment purposes, data from a second upland catchment was included in the assessment. This was the Trout Beck in the Upper Tees for which data from several snow events are available for modelling. The Trout Beck catchment drains a heather moorland area of 11.4 km^2 with an elevation range of 553 to 857 metres. The Monachyle drains an area of 7.7 km^2 with an elevation range from 302 to 892 metres with natural vegetation of heather, bracken and coarse grass. Snow core measurements in 1984 were made at Tulloch Farm, about 5 km away from the Monachyle catchment and at a lower elevation of 135 metres.

The performance of the model variants for the two catchments are summarised in Tables 1 and 2. Figure 1 presents a selection of results for Monachyle Burn, highlighting poor performance when snow is ignored (R^2=0.457), the improvement gained by incorporating a PACK snowmelt module with five elevation zones (R^2=0.873), and the use of a distributed rather than lumped (PDM) catchment runoff model (R^2=0.898).

Sample results for Trout Beck using the two catchment models are presented in Figure 2 for the snow period 4 to 30 December 1993. Ignoring the presence of snow produces a poor model simulation (R^2=0.484). Model calibration results were obtained using either daily snow core data or hourly snow pillow measurements. The snow pillow data in this case seem to offer no advantage over the daily snow core measurements when simulating river flow (R^2 of 0.839 compared to 0.854). A PDM snowmodel incorporating a full energy budget employing AWS data for Moor House was found to yield no improvement in model performance relative to the simple temperature index method. However, analysis of the AWS data within the framework of the energy budget melt formulation has proved useful in understanding the mechanism of melt during the main melt phase on 17 and 18 December 1993. The analysis reveals that melt can occur in almost equal measure by sensible heat exchange and by latent heat of condensation, as warm air near saturation in cloud condenses on the snowpack, with net radiation making little contribution. This provides an explanation for the success of the simple temperature index method for melt conditions experienced in upland Britain. Potential melt rates as high as 170 mm over two days are indicated by the particular event analysed.

Early investigations into the use of multiple elevation zones suggested that model performance may be improved through the use of more rather than fewer zones. Tables 1 and 2 both indicate an increase in flow simulation accuracy with number of elevation zones. Prompted by these initial findings a new model has been developed, based on the PDM snowmodel, that can divide the catchment into any number of zones using DTM-derived elevation data to determine a (near-continuous) distribution of elevations in a catchment. This new model is described and assessed in the following sections.

3.3 Elevation-dependent model

Partitioning a catchment into a finite number of elevation zones can be used to take into account the variation in temperature, and its impact on snowmelt, for the purposes of snowmelt forecasting at the catchment scale. The results shown in Tables 1 and 2 suggest that best model performance is often achieved with the largest possible number of elevation zones. The improved model simulations gained through the use of more zones has prompted the development of a snowmelt model that uses a near-continuous distribution of elevations in the catchment. This distribution of elevations takes the form of the well-known hypsometric curve (Bras, 1990))

The hypsometric curve, $F(z)$, is a distribution function which defines the proportion of a catchment that lies below a given elevation, z. It can be computed easily from a digital terrain model (DTM) and can also be expressed as a frequency function of catchment elevation, $f(z)$. The Institute of Hydrology's DTM is configured on a 50 m resolution grid with elevation held to a precision of 0.1 m. For modelling purposes it has been used to derive a hypsometric curve to a precision of 1 m. Figure 4 shows the hypsometric curve for

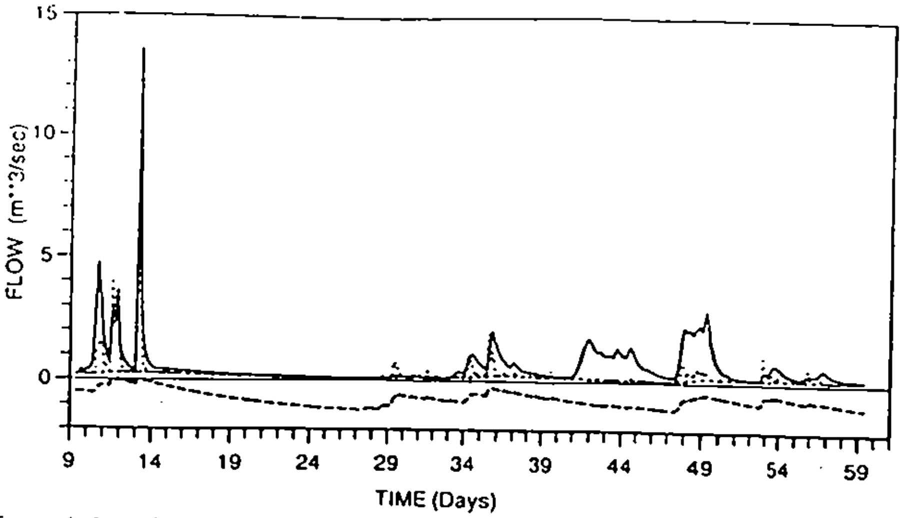
Table 1 Assessment of model performance for Monachyle Burn, Balquhidder, 9 January to 28 February 1984

Model features	Objective function	R^2: PDM model	R^2: SGM model
Ignores snow	Flow	0.457	0.519
(a) Updated using snow we and depth			
	Snow WE	0.998	0.999
Single elevation zone	Flow	0.799	
Five elevation zones	Flow	0.811	0.843
(b) Updated using snow we and depth			
	Snow WE	0.904	0.909
Single elevation zone	Flow	0.816	
Five elevation zones	Flow	0.873	0.898

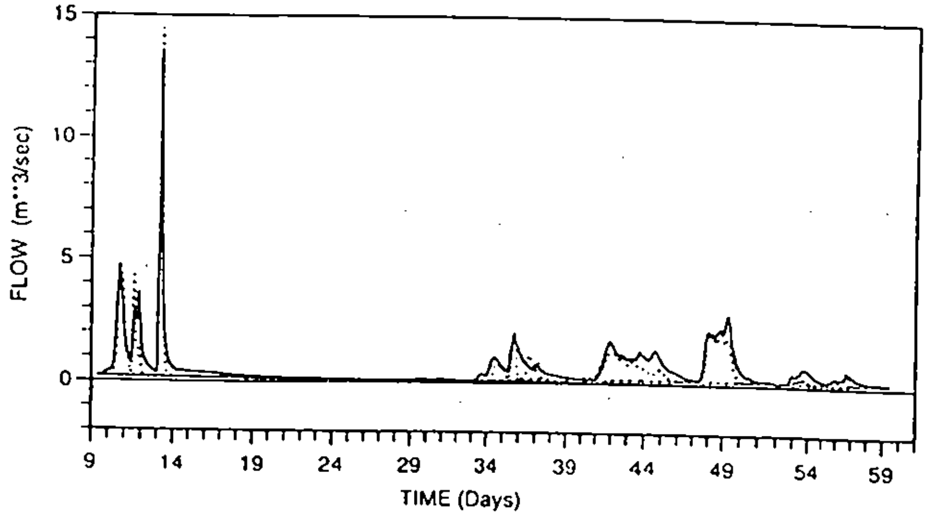
Table 2 Assessment of model performance for Trout Beck at Moorhouse, 4 to 30 December 1993

Model features	Objective function	R^2: PDM model	R^2: SGM model
Ignores snow	Flow	0.484	--
(a) Updated using snow we and depth			
	Snow WE	0.999	0.999
Single elevation zone	Flow	0.727	0.840
Five elevation zones	Flow	0.753	0.841
Ten elevation zones	Flow	0.787	--
Single elevation zone, energy budget	Snow WE	0.999	--
"	Flow	0.639	--
(b) Updating using Snow WE only			
Single elevation zone	Snow WE	0.944	0.944
(c) Snow pillow data			
	Snow WE	0.924	0.940
Five elevation zones	Flow	0.747	0.476

(a) No snowmelt component, PDM catchment runoff model



(b) PACK module with PDM catchment runoff model



(c) PACK module with Simple Distributed Model

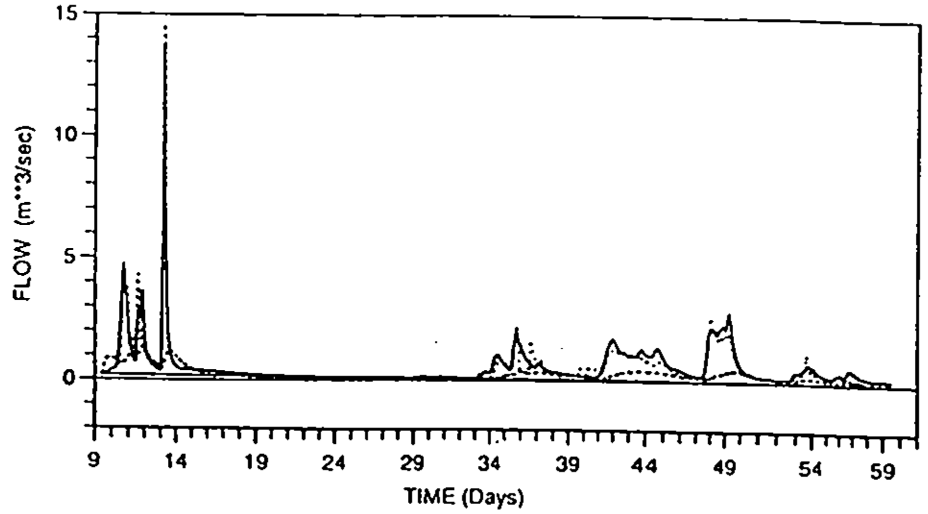
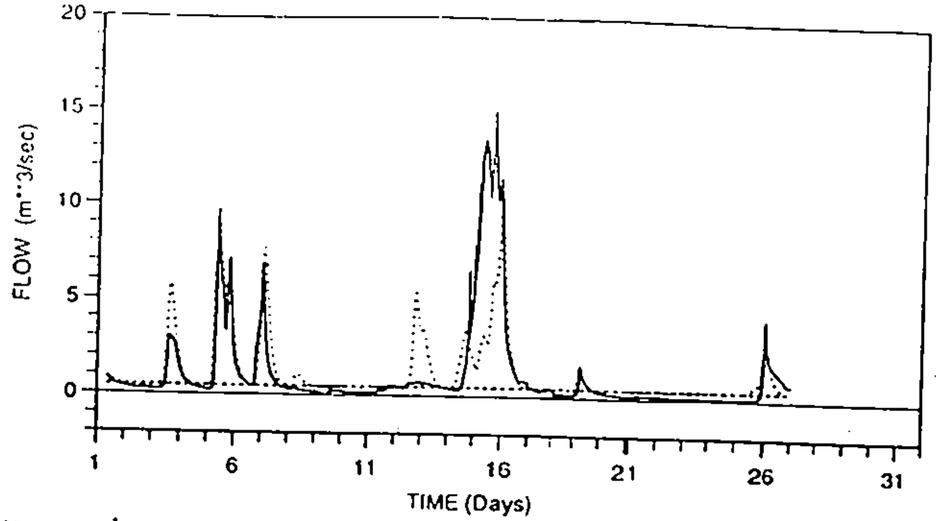
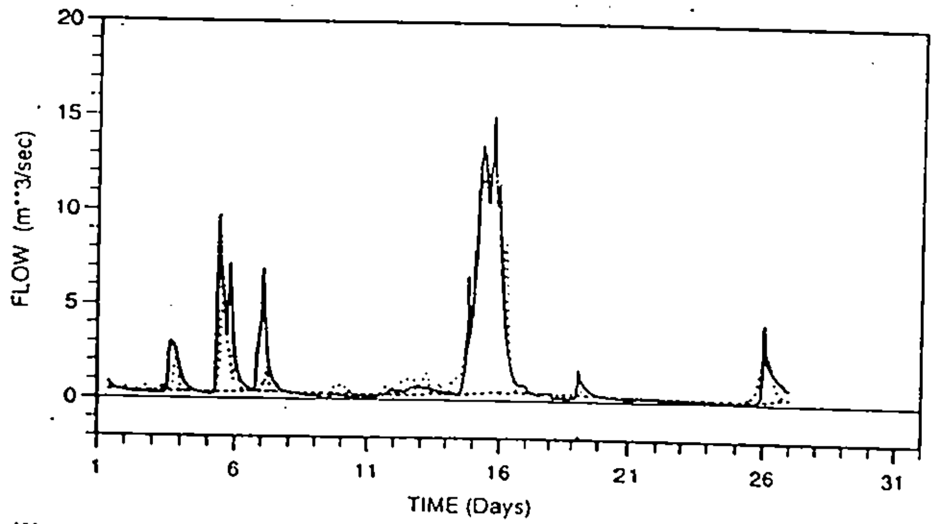


Figure 1 Effect of no snowmelt component and lumped (PDM) and distributed catchment runoff models; Lower Monachyle Burn near Balquhidder, 9 January to 28 February 1984

(a) No snowmelt component



(b) Snow survey data



(c) Snow pillow data

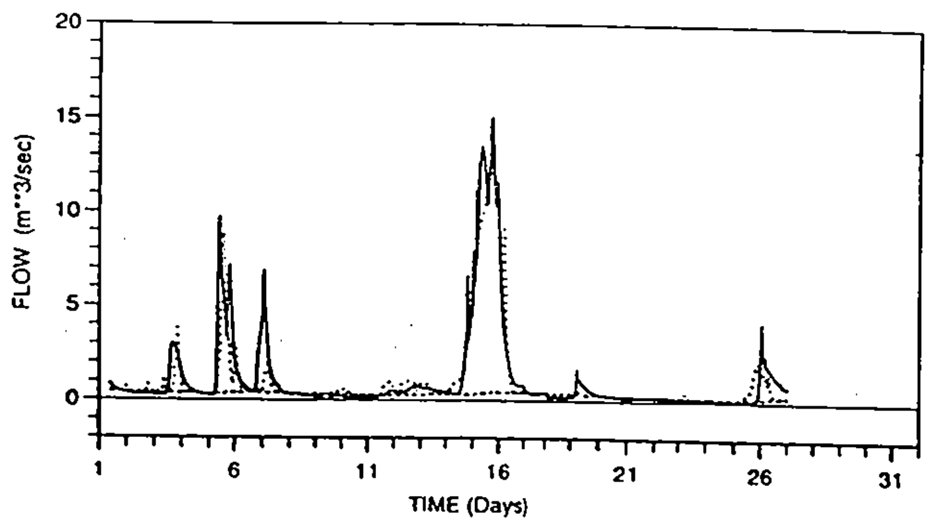
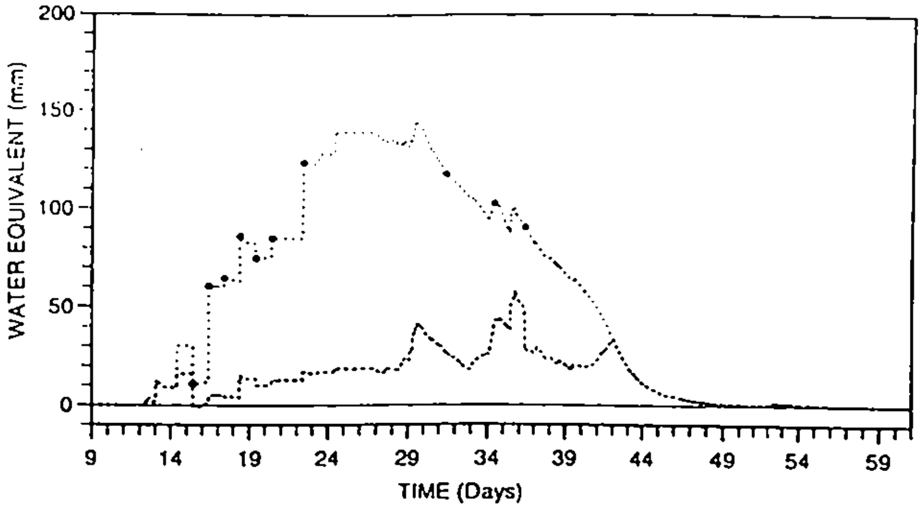
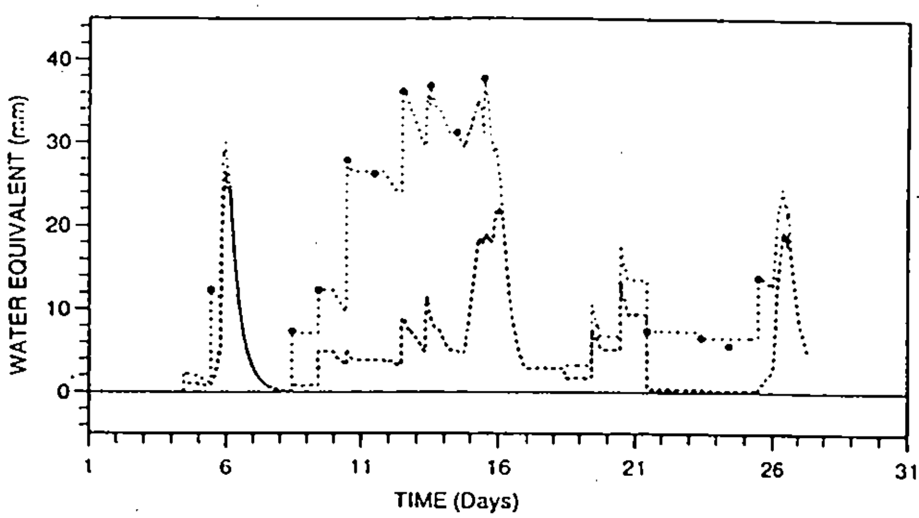


Figure 2 Effect of no snowmelt component and snowmelt models calibrated using snow survey or snow pillow data; Trout Beck, 4 to 30 December 1993, PDM catchment model

(a) Snow survey measurements: Monachyle Burn, 9 January to 28 February 1984



(b) Snow survey measurements: Trout Beck, 4 to 30 December 1993



(c) Snow pillow measurements: Trout Beck, 4 to 30 December 1993

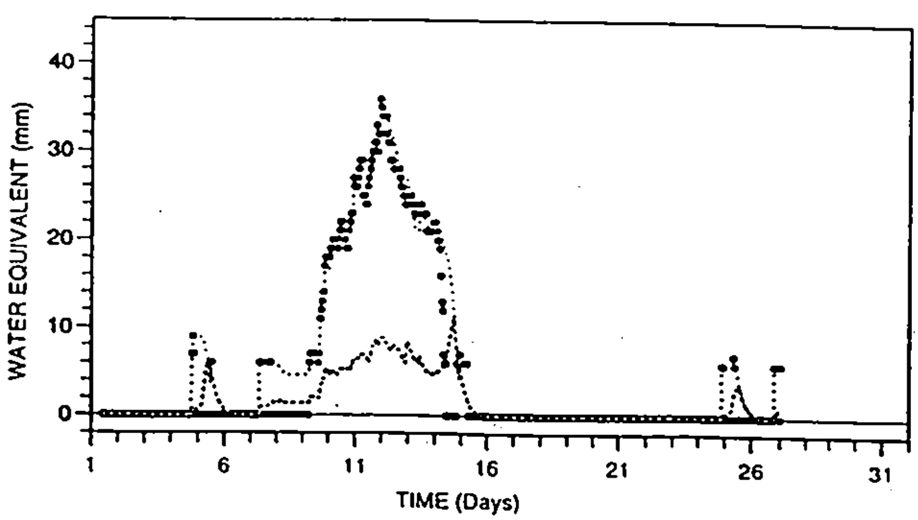


Figure 3 Measured (large dots) and predicted (dotted line) snow water equivalent, and wet snow component (dashed line) using snow survey and snow pillow observations elevation, f(z)

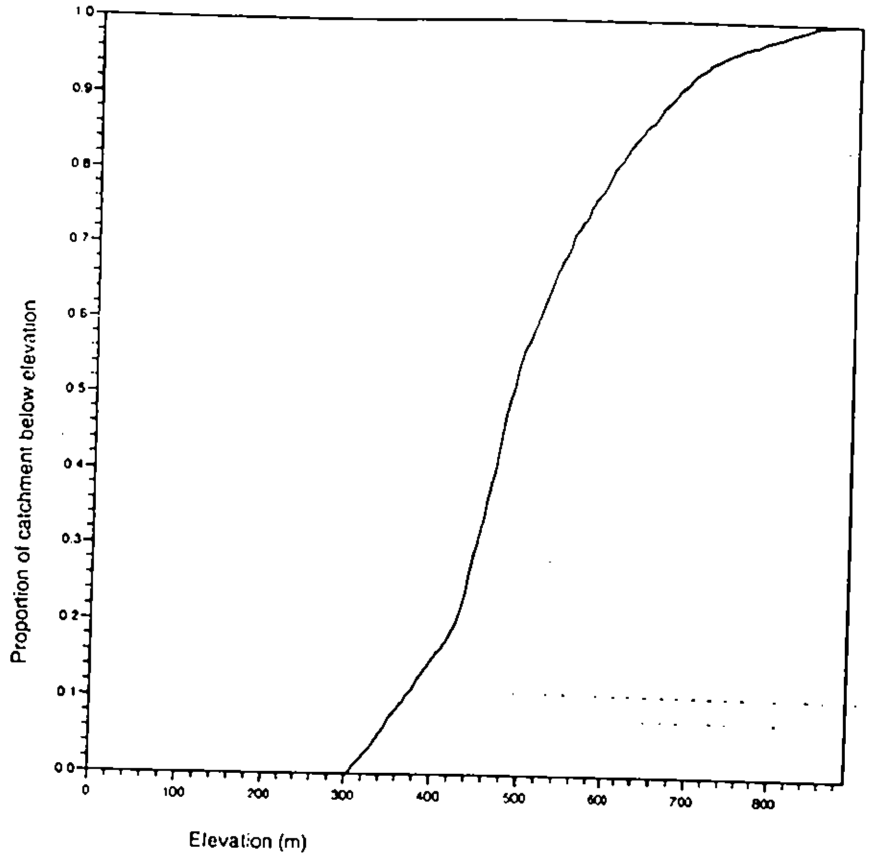


Figure 4 Hypsometric curve for the Monachyle Burn, Balquhidder

the Monachyle Burn catchment. The importance of the distribution function, F(z), is that it can be coupled with a temperature-elevation model to define the proportion of the catchment over which snow melts, or the proportion that receives its precipitation in the form of rain rather than snow (if a simple temperature threshold is used to discriminate between rain and snow).

For example, consider the lapse rate model of temperature

$$T_i = T_j + \alpha(z_i - z_j) \tag{1}$$

where temperature T_i at location i is given in terms of the temperature at another location j, T_j, and the difference in elevation between locations i and j, with α the temperature lapse rate. If T_m is the temperature above which melt occurs (usually taken to be at or above the zero degree isotherm), and T_{aws} and z_{aws} are the temperature and elevation of the automatic weather station (AWS), then the critical elevation below which melt occurs is given by

$$z_m = z_{aws} + \frac{T_{aws} - T_m}{\alpha} \; . \tag{2}$$

Similarly, the threshold temperature that determines whether a region experiences rain or snow, T_s, coupled with the lapse rate temperature model, can give a value for the elevation, z_s, above which snowfall occurs during precipitation over the catchment. Then $F(z_s)$ will give the proportion of the catchment which receives precipitation in the form of rain. Figure 5 shows a cross-section through a catchment illustrating this delineation of areas of snowfall and melt according to altitude.

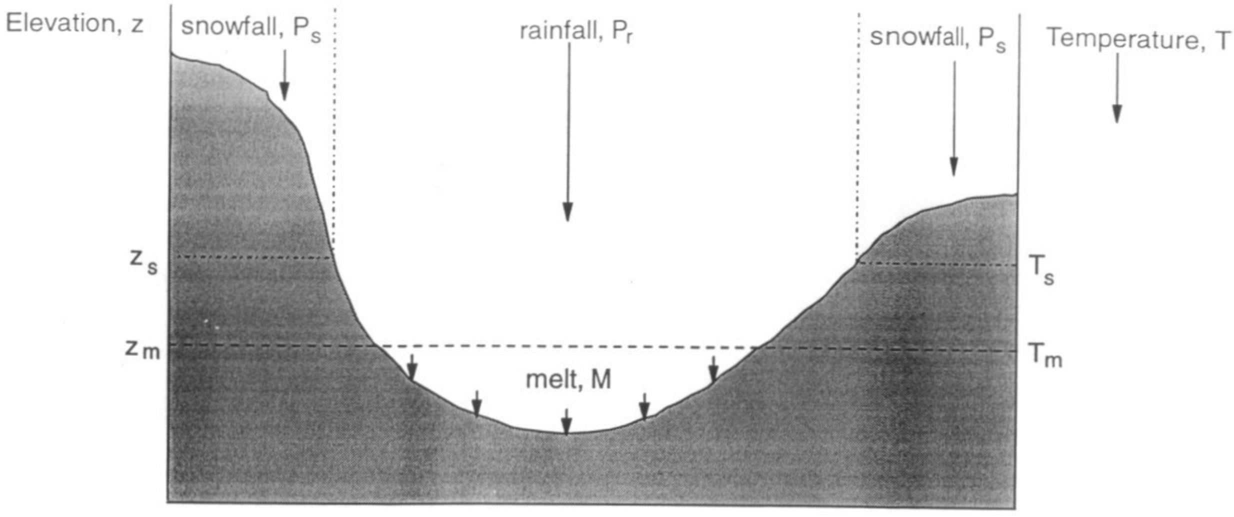


Figure 5 Cross-section through a typical catchment showing zones of snowfall and melting

3.3.1 Model Formulation

At each point in the catchment, a simple two-store snow pack is assumed containing dry (not melted) and wet (melted) snow, with water equivalents W and S respectively. The pack receives precipitation in the form of rain or snow, melts according to the temperature at that point (which in turn is dependent on its elevation), and the melted water drains from the pack into the rainfall-runoff model, in this case the PDM.

Making the assumption that snow/rain occurrence and melting are dependent only on the temperature at a point, and therefore dependent only on elevation, then W and S are also only dependent on z, that is $W=W(z)$ and $S=S(z)$. This also assumes uniform precipitation over the catchment (or precipitation which varies under the control of a precipitation lapse rate which is solely elevation dependent). Hence each contour in the catchment is assumed to have the same snowpack.

Dry snow

Adopting the model formulation of the PACK module (Moore *et al.*, 1995), which partitions the snow pack into dry and wet (melted) snow, the following elevation-dependent model can be constructed.

During the n'th time interval of duration Δt after some initial time t_o, the potential melt at contour z, $M^n(z)$, is

$$M^n(z) = \max\{\beta(T^n(z) - T_m), 0\} = \max\{\alpha\beta(z_m^n - z), 0\} \tag{3}$$

where β is the melt factor, α is the temperature lapse rate (~0.0059°C/m), and z_m^n is the critical elevation below which melt occurs at that time.

The water equivalent of the dry snow component of the pack, W(z), is updated via

$$W^{n+1}(z) = \begin{cases} \max\{0, W^n(z) - M^n(z) + P_s\}, & z \le z_c^n \\ W^n(z) + P_s, & z > z_c^n \end{cases} \tag{4}$$

where P_s represents the water equivalent of the fresh snow that has fallen in the time interval.

Wet snow

Wet snow water equivalent, S, is updated via

$$S^{n+1}(z) = \begin{cases} S^n(z) + W^n(z) + P_s, & W^{n+1}(z) = 0, \\ S^n(z) + M^n(z) + P_r(z), & W^{n+1}(z) > 0. \end{cases} \tag{5}$$

$P_r^n(z)$ is the precipitation, P, falling in the form of rain at z, and is given by

$$P_r^n(z) = \begin{cases} P, & z < z_s, \\ 0, & z \ge z_s, \end{cases} \tag{6}$$

where z_s is the critical elevation below which precipitation falls as rain rather than snow.

If the dry snow component is fully depleted, the rainfall bypasses the wet store and contributes directly to $I^{n+1}(z)$, the drainage input to the rainfall-runoff model; that is

$$I^{n+1}(z) = \begin{cases} P_r^{n+1}(z), & W^{n+1}(z) = 0, \\ 0, & W^{n+1}(z) > 0. \end{cases} \tag{7}$$

Finally, the drainage from the wet pack is calculated via

$$\begin{aligned} S^*(z) &= \max\{0, S^{n+1}(z) - S_c^*(S^{n+1}(z) + W^{n+1}(z))\}, \\ I^{n+1}(z) &= I^{n+1}(z) + k_2 S^*(z)(1-k_1) + k_1 S^{n+1}(z), \\ S^{n+1}(z) &= S^{n+1}(z) - I^{n+1}(z). \end{aligned} \quad (8)$$

Here, k_1 and k_2 are storage time constants (with units of inverse time) controlling drainage from the wet pack store. The quantity S_c^* is the critical water capacity above which water in store drains at a high rate, governed by k_2. Water in store below S_c^* drains at a slower rate, governed by k_1. Below a threshold temperature, T_c, no drainage is allowed to occur.

Total drainage to the catchment

The average depth of meltwater draining over the catchment is given by

$$I = \int_{z_1}^{z_2} I^{n+1}(z) f(z) dz \quad (9)$$

and the total volume of meltwater produced is AI, where A is the total area of the catchment. The integral limits z_1 and z_2 are usually taken to be z_{min} and z_{max}, the lower and upper elevation limits of the catchment; however,,calculation of the integral can be accelerated by concentrating only on that portion of the catchment where melt occurs. In this case, z_1 and z_2 are calculated as follows:

$$\begin{aligned} z_1 &= \max[z_0, z_{min}], \\ z_2 &= \min[z_{max}, \max[z_m, z_c, z_s]], \end{aligned} \quad (10)$$

where z_0 is the position of the edge of the snowpack (the "snowline"), z_m, z_c and z_s are the elevations corresponding to temperatures T_m, T_c and T_s, and $z_2 > z_1$.

For computational purposes an estimate of the average drainage depth across the catchment, I, can be calculated by replacing the integral in (9) with a summation involving discretised values for f(z). The frequency function of catchment elevation, f(z), is computed to a precision of 1 m using the DTM elevation data. Since the DTM derives from Ordnance Survey contour data, with elevation held to 0.1 m, a finer precision function could be calculated if required. If the DTM is unavailable for a particular catchment, f(z) could be "approximated" by a continuous function such as the truncated beta distribution, with z_{min} and z_{max} obtained manually from maps and the slope parameter inferred by optimisation. A standard beta distribution could be used after standardisation.

3.3.2 Model evaluation

The new snowmelt model has been tested on the two study catchments, Monachyle Burn and Trout Beck. A second, more recent snow event has been identified for the Monachyle Burn covering the period 18 December 1995 to 28 February 1996; this event has now been included in the model evaluation. The model has been assessed in two ways. Firstly, snowline observations available for the two snow events in the Monachyle Burn have been used to test whether the model is able to identify the snowline position correctly. Secondly, the accuracy of the model to simulate flow is assessed for different numbers of elevation zones, in order to determine the optimum number of zones to use for each catchment. Results are presented below for each assessment.

Snowline position evaluation

Two periods of lying snow in the Monachyle Burn, 12 years apart, have been used for evaluating the model's ability to predict snowline elevation: 14 January to 30 May 1984 and 22 December 1995 to 28 February 1996. For each period, daily snowcore measurements of depth, density and water equivalent, together with snowline observations are available, as well as hourly AWS temperature and humidity data and 15 minute raingauge data.

The main difference in the datasets for the two periods is the location of the snow survey site. In 1984 daily snow cores were made at Tulloch Farm situated about 5 km south-east of the gauging station at an elevation of 135 metres. The snow cores for the 1995/96 period were taken at the site of the AWS in the Lower Monachyle at an elevation of about 470 metres.

For each period, hourly temperature together with daily snowline data and snow survey measurements were used for model input together with DTM-derived measurements of the upper and lower range of elevation and the height of the AWS. Daily snow survey measurements were used to estimate the water equivalent of fresh snowfall in the following manner. If measurements of snow water equivalent were available then an increase in the daily observations was taken as an indication of fresh snow. If missing, but snow depth data were available and showed an increase, then the water equivalent of fresh snowfall was calculated indirectly using

$$\Delta W = \rho \Delta D, \qquad (11)$$

where ρ is the most recently available measurement of snow density and ΔW and ΔD are the increases in dry snow water equivalent and depth respectively.

The model for dry snow outlined in Section 3.3.1 is used to determine the variation with elevation of W with temporal changes in temperature and fresh snowfalls. At each time-step, the elevation, z_0, at which $W(z_0)=0$, and $W(z)>0$, for $z>z_0$ is identified.

The minimum elevation above which lying snow is present is called the "snowline". It is interpreted here as the elevation above which dry snow (visible white snow) is present; wet (melted) snow is considered to be held in the form of water in the snow matrix. Although in reality there would be a certain amount of spatial variability in the location of the edge of the snowpack, it is assumed that an approximate snowline elevation can be determined by eye.

Evaluation results: 14 January 1984 to 30 May 1984

Snow was present in the Monachyle catchment for most of this four and a half month period.

The observer recorded the position of the snowline to the nearest 100 m. The minimum and maximum elevations recorded were 200 and 1000 m, the latter corresponding to a catchment free from lying snow. Eleven snowfalls were identified between 14 January and 29 February, with snow depths ranging from 2 to 50 mm of water equivalent. Snow survey measurements are not available after the end of February; however, the snowline records show only one fresh snow event after this time on 23 March so it would appear that the absence of these data is not likely to significantly affect the analysis.

The snowmelt-elevation model was applied to the 1984 snow and temperature data and initialised on the fresh fall of snow on 14 January. An hourly time-step was used by the model and at each step a profile of the dry snow water equivalent with elevation was calculated. The position of the snowline, z_0, was identified as being the elevation above which snow was present; these calculated snowline values were compared with the daily catchment observations. Only one model parameter affects the modelled snowline, the melt factor in equation (3), β, which determines the amount of melt associated with each temperature increase. This parameter was adjusted to achieve the best model fit, using the R^2 goodness-of-fit criterion and visual judgement as guides. The final model gave an R^2 of 0.74 using a melt factor $\beta = 2.6$ mm/day/°C. A lower value for β yielded an even higher R^2, but was not considered to give as good an overall representation of the snowline movement.

Figure 6 shows a time series of observed (bold line) and calculated (dotted line) snowline positions from 14 January onwards. The period 14 January to 29 February for which snow survey data are available resulted in very little snowmelt and the catchment remained completely covered in snow (with the snowline recorded as lying below the catchment, at 200 m). This behaviour was reproduced well by the snowline model. After the 29 February

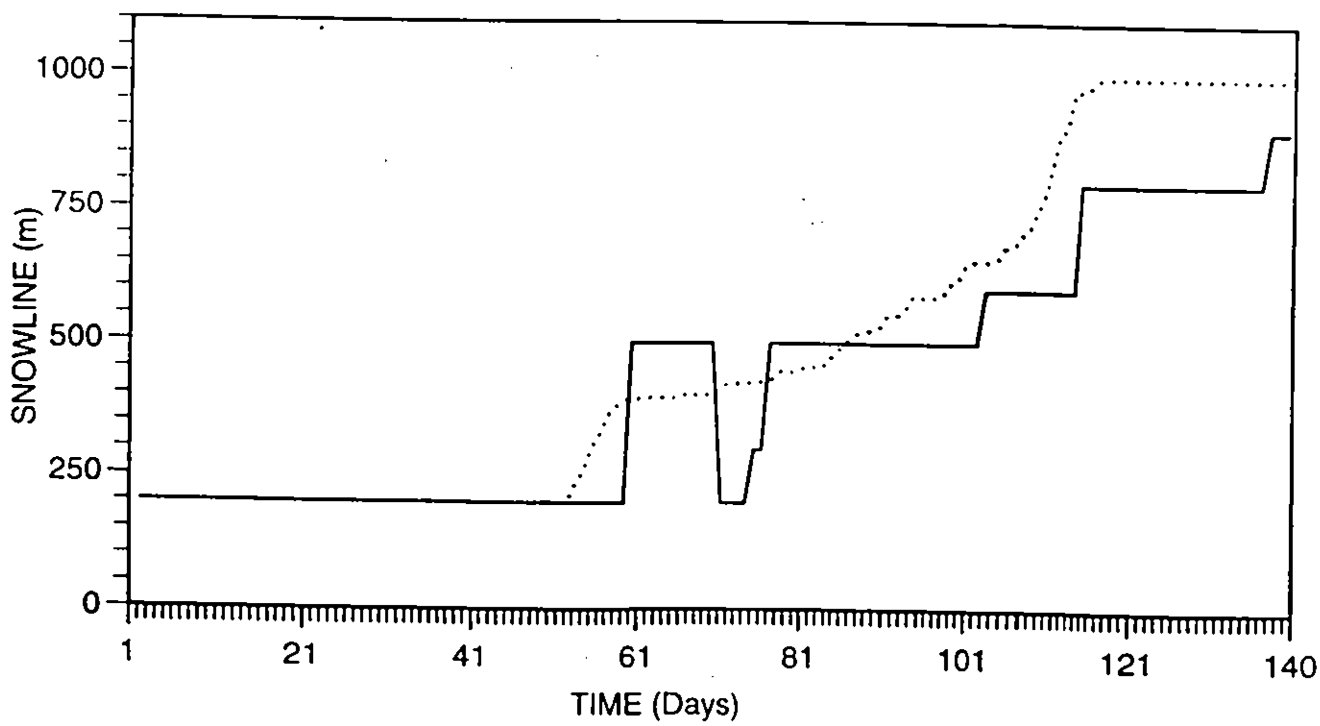


Figure 6 Observed (continuous line) and model simulated (dotted line) snowline elevations, Monachyle Burn, 14 January to 30 May 1984

the pack melted gradually over a period of three months until the end of May. The model gives a reasonable fit for these months, although the downward movement of the snowline on the 70th day (23 March) which corresponded to a small snowfall in the catchment was not reproduced at all because of the lack of snow survey data after the end of February.

Evaluation results: 22 December 1995 to 28 February 1996

Snow survey measurements made in the vicinity of the Lower Monachyle AWS at an elevation of 470 m are available for the period of lying snow from 22 December 1995 to 15 February 1996. These measurements would be expected to provide a better representation of snow conditions in the catchment than the 1984 measurements, made 5 km away at Tulloch Farm. The observer for this period recorded the elevation of the snowline to the nearest 100 m, and the range of recorded values was 0 to 1000 m, the latter corresponding to a catchment free from lying snow.

Eight snowfalls were detected ranging from 1.8 to 30.6 mm of water equivalent. The model was initialised on a fresh fall of snow on 22 December. A time series of the position of the snowline is shown in Figure 7 which reveals a fairly good model simulation of the snowline position. Figure 8 shows the time-lapse graphs of W(z) against elevation for the first 30 days at a daily interval. It shows the pack melting in the lower elevation areas first and then receding to the higher elevations after 30 days. The R^2 statistic for this simulation, obtained after manually adjusting the melt factor, was 0.655. The optimum value for the melt factor, β, was 4.4 mm/day/°C. The snowfall on the 30th day of the model run (21 January) which

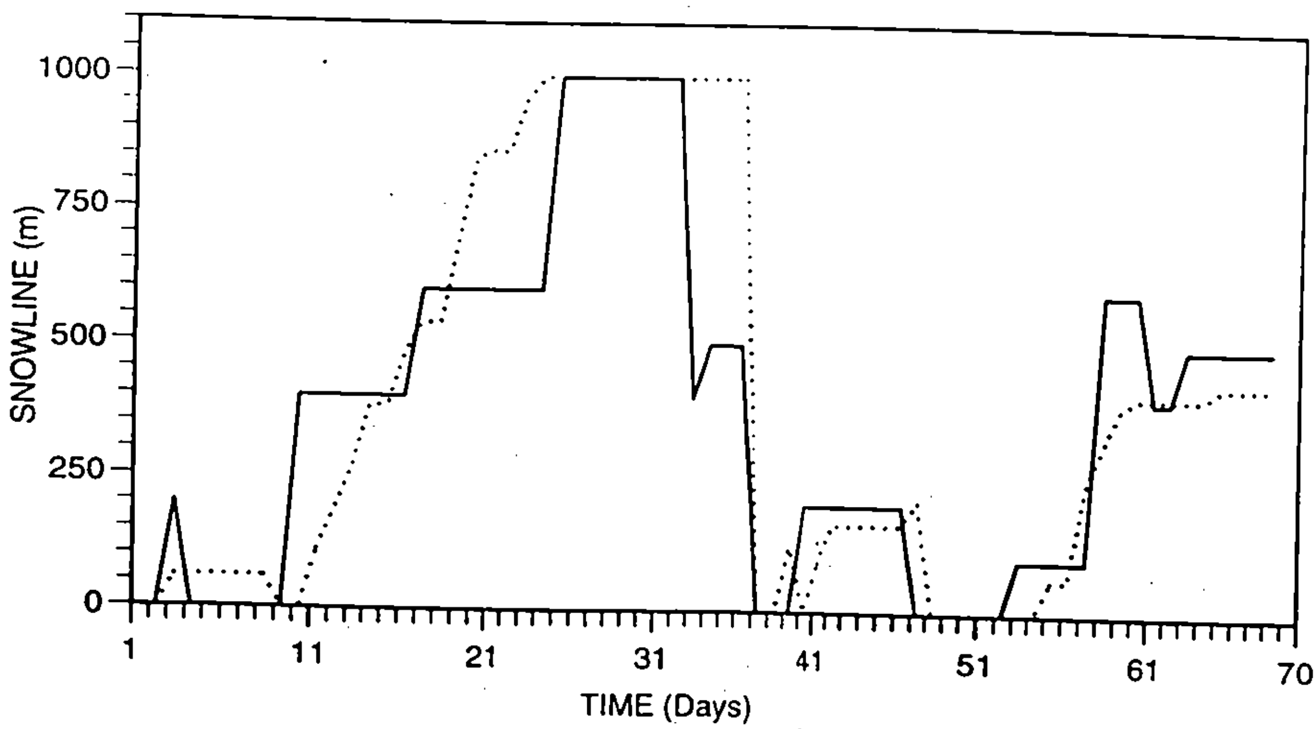


Figure 7 Observed (continuous line) and model simulated (dotted line) snowline elevations, Monachyle Burn, 2 December 1995 - 28 February 1996

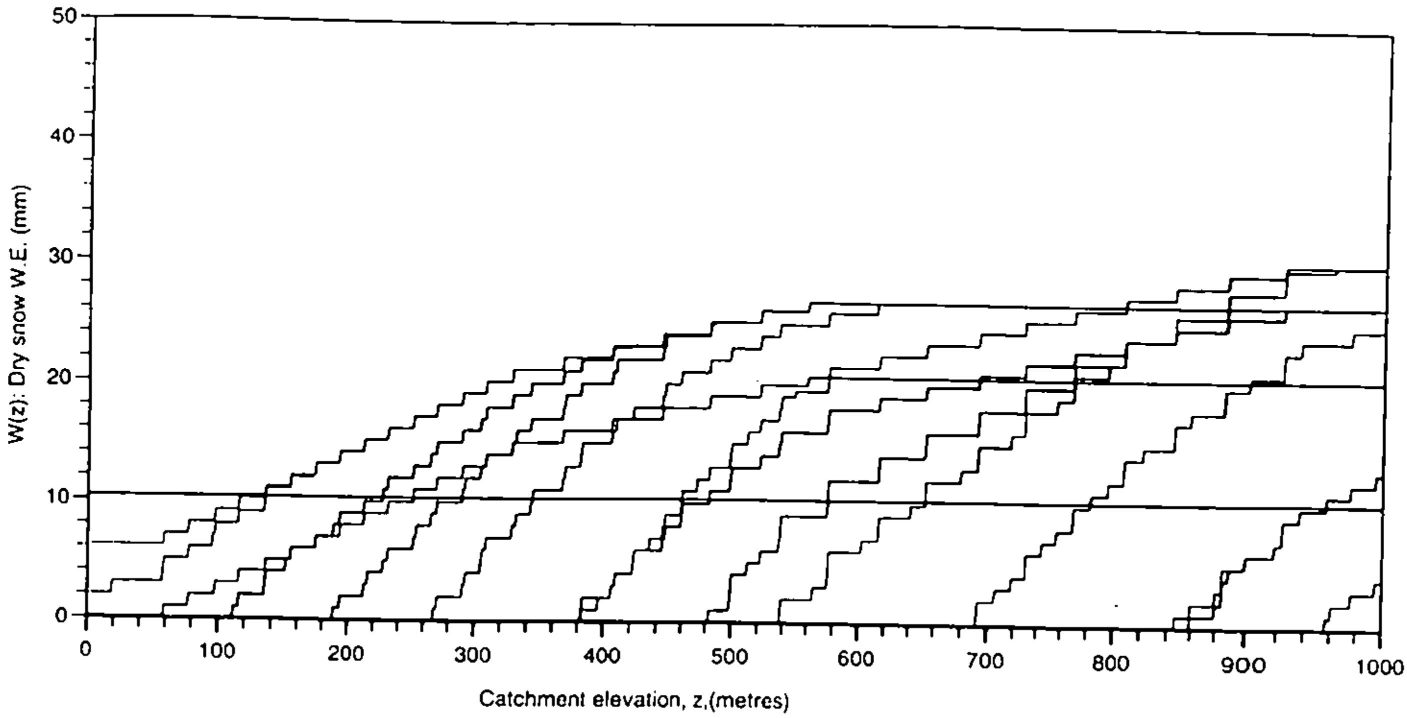


Figure 8 Time lapse profiles of dry snow water equivalent with changing elevation

resulted in the snowline falling from 1000 m to 400 m was not reproduced by the model because the snow survey recorded no snow at the site (at 470 m) on that date. It is likely that any fresh snow falling over the previous 24 hour period had melted at the snow survey site and was therefore not detected.

Discussion

The snowline simulation model has been tested on two periods of lying snow, winter 1984 and 1995/96, and has been shown to perform reasonably successfully within the limitations of the available data. For each period the melt factor parameter, β, was adjusted to achieve the best model fit obtaining significantly different values for the two periods: 2.6 and 4.4 mm/day/°C respectively. This difference is thought to be due to the different locations of the snow survey sites used for the two periods. The 1984 survey was carried out at an elevation of 135 m, which is below the lowest point in the Monachyle catchment, and where the snow is more likely to have melted over the 24 hour period between observations than in the catchment. Hence, it is likely that the snow survey measurements will be an underestimate of the amount of snow in the catchment, and therefore a lower melt factor is necessary to stop the modelled snowline progressing up the catchment faster than it should: a shallower snow pack will melt away faster than a deeper one resulting in a faster moving snowline. The 1995/96 melt factor of 4.4 mm/day/°C is more consistent with literature values of around 4 mm/day/°C (Moore *et al.*, 1996).

Whilst the availability of data from only two winters has not allowed more explicit model validation, the long periods of lying snow (two months in 1995/96 and four and a half months in 1984) has helped avoid over-fitting of the model giving a falsely optimistic impression of model performance. This problem is further helped by only one parameter being involved. However, continued field monitoring is required to allow testing and validation to be more comprehensive.

Flow evaluation

The new elevation-dependent snowmelt model has been integrated with the PDM "lumped" catchment model in a similar way to the PACK snowmelt module. Hypsometric curves discretised to 1 m are used by the model. This effectively splits the Monachyle Burn and Trout Beck catchments into a maximum of 590 and 307 elevation zones respectively, with the number of zones actually used being readily changed via an input parameter. For a smaller number of zones than the maximum, the data describing the hypsometric curve are aggregated to determine the proportion of the catchment that lies below each elevation zone and the area of each zone.

The model has been assessed on the following four datasets:

Monachyle Burn	9 January to 28 February 1984	
Monachyle Burn	18 December 1995 to 28 February 1996	
Trout Beck	4 to 30 December 1993	daily snow surveys
Trout Beck	4 to 30 December 1993	hourly snowpillow

The main aim of the assessment was to determine how the accuracy of flow simulation varies with number of elevation zones, and whether there is any benefit in using a very large number of zones. With this aim in mind, the model was calibrated for each dataset using a range of elevation zones. The number of zones was chosen to be an integer that was a close multiple of the maximum zones for the catchment considered so as to reduce the error incurred in dividing the catchment into an integer number of zones. In previous work the threshold temperature, T_s, below which precipitation falls in the form of snow has invariably been set to 1°C. The control this parameter now exerts in the new model formulation, in establishing the proportion of the catchment receiving precipitation in the form of snow or rain, has meant that it has featured as an important parameter to be optimised. Two other temperature threshold parameters have also been considered for optimisation. One is the temperature above which melt occurs, T_m, and the temperature below which drainage from the pack to the catchment cannot occur, T_c; these have normally been fixed at 1°C and 0°C respectively.

Monachyle Burn

The flow simulation results for Monachyle Burn are presented in Table 3 and Figure 9. These show how simulation accuracy varies with number of elevation zones for the two events. Figure 9 reveals that while a poor result is obtained using one elevation zone, and a good consistent performance is obtained using more than 20 elevation zones, there is a marked fluctuation in performance between these limits.

Table 3 Flow simulation performance judged using R^2 criterion, Monachyle Burn

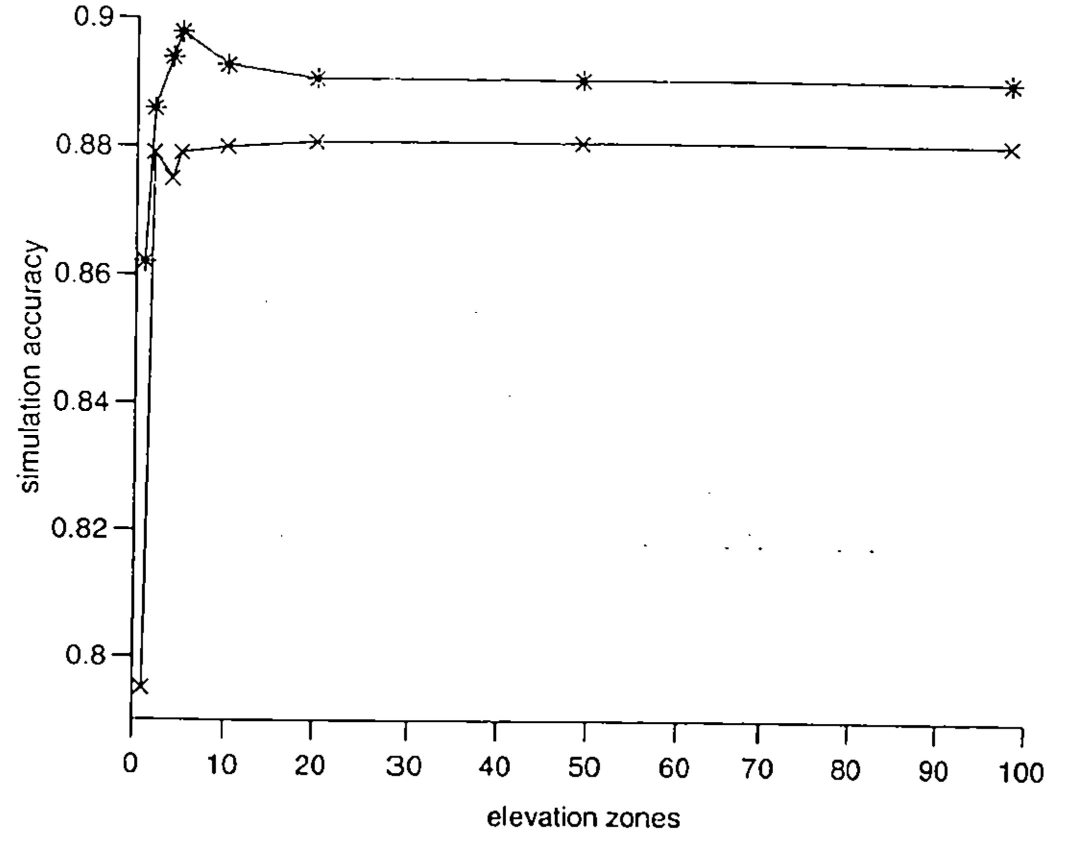
Number of zones	9 January to 28 February 1984		18 Dec 1995 to 28 Feb 1996
	$T_s=1$	T_s optimised	T_s optimised
1	0.795	0.862	0.786
2	0.879	0.886	0.810
4	0.875	0.894	0.777
5	0.879	**0.898**	0.786
10	0.880	0.893	0.797
15	--	--	**0.814**
20	0.881	0.891	0.811
49	0.881	0.891	0.811
98	0.881	0.890	0.810
147	0.881	0.890	--
590	0.881	0.891	0.809

The best result for the 1984 event was obtained using five elevation zones whilst for the 1996 event 15 elevation zones proved best. In both cases the fluctuation in performance ceased beyond around 20 elevation zones, corresponding to an elevation band of 30 m (590/20=30). The optimal value of T_s was in the range -0.1 to 1°C, fluctuating in value for smaller numbers of zones and stabilising to around 0.7°C when more than 10 zones were used. This is not inconsistent with the expected value of around 1°C. For the 1996 event a value of 3°C was optimal, which is unexpectedly large, although some difference might be expected on account of the difference in location of the snow survey site for the two events. Figure 10 presents the results as time-series of snow water equivalent and catchment flow from the best model (15 zones) for the 1996 event. Note that the main melt occurs around day 78 giving rise to two peaks in the hydrograph of circa 5 m^3/s. Note that the performance of the new model using 5 zones for the 1984 event ($R^2=0.898$) is comparable with that obtained using the distributed runoff model presented in Section 3.2 and Figure 1(c).

Trout Beck

Flow simulation results for Trout Beck at Moor House are shown in Table 4 and displayed in graphical form in Figure 11. Three sets of results are shown in Figure 11 one showing the variation in model performance with number of zones when using daily snow survey measurements, and the other two when using hourly snowpillow data. The results using snowpillow data are not as good as those obtained using snow survey observations when only T_s is optimised; however, if T_c and T_m are varied as well, the results are considerably better

1984 period



1996 period

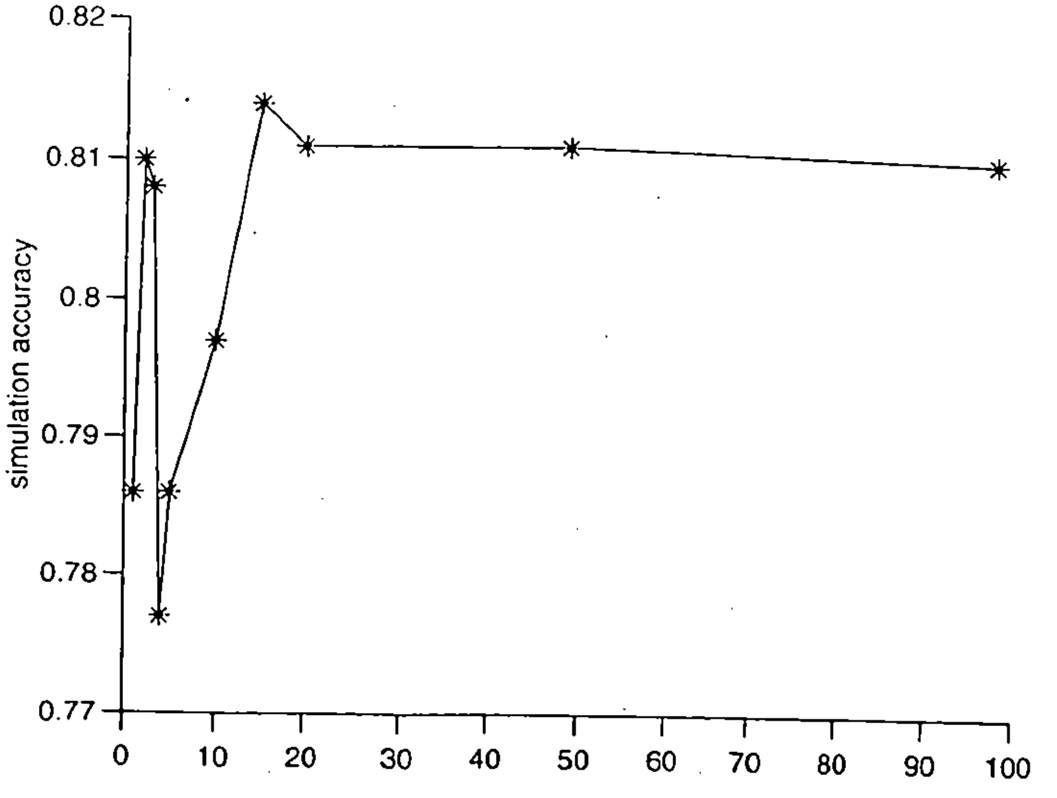
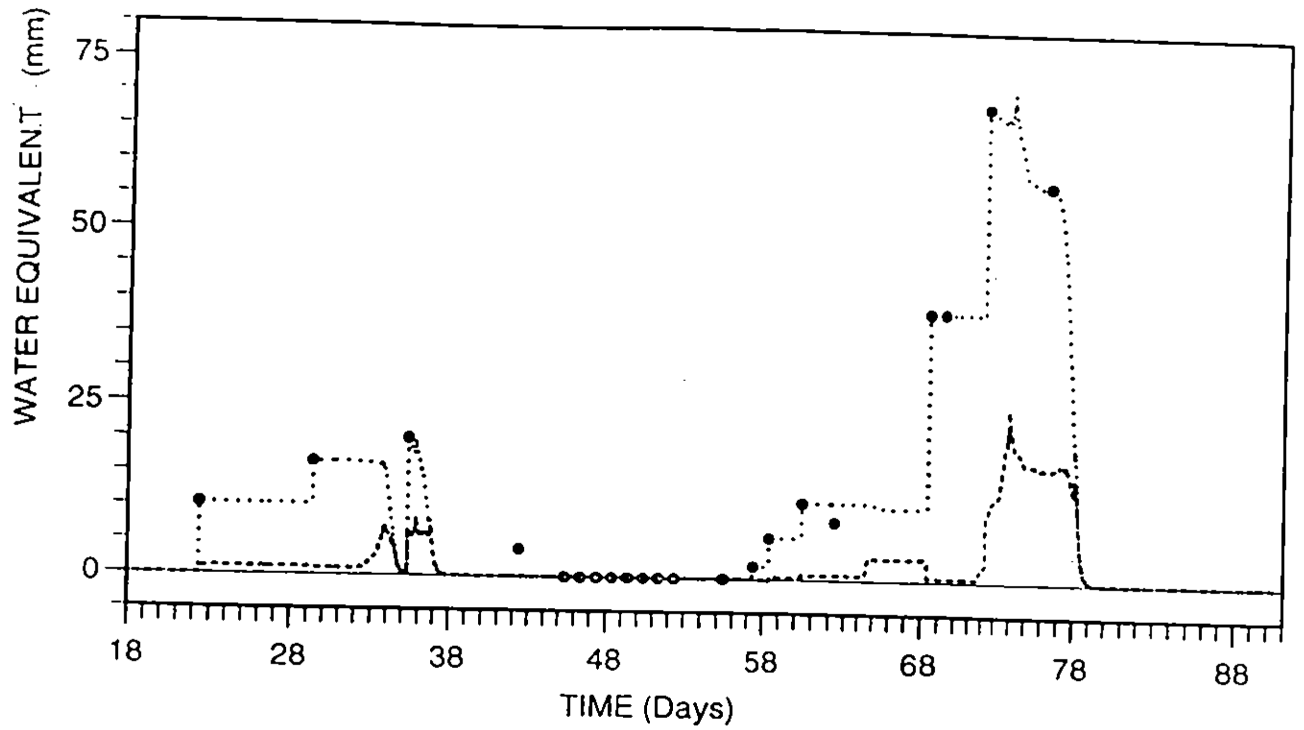


Figure 9 Model performance (R^2 statistic for flow) as affected by the number of elevation zones used, Monachyle Burn; cross: snow/rain temperature threshold parameter fixed, star: snow/rain threshold parameter optimised

Snow water equivalent



Flow

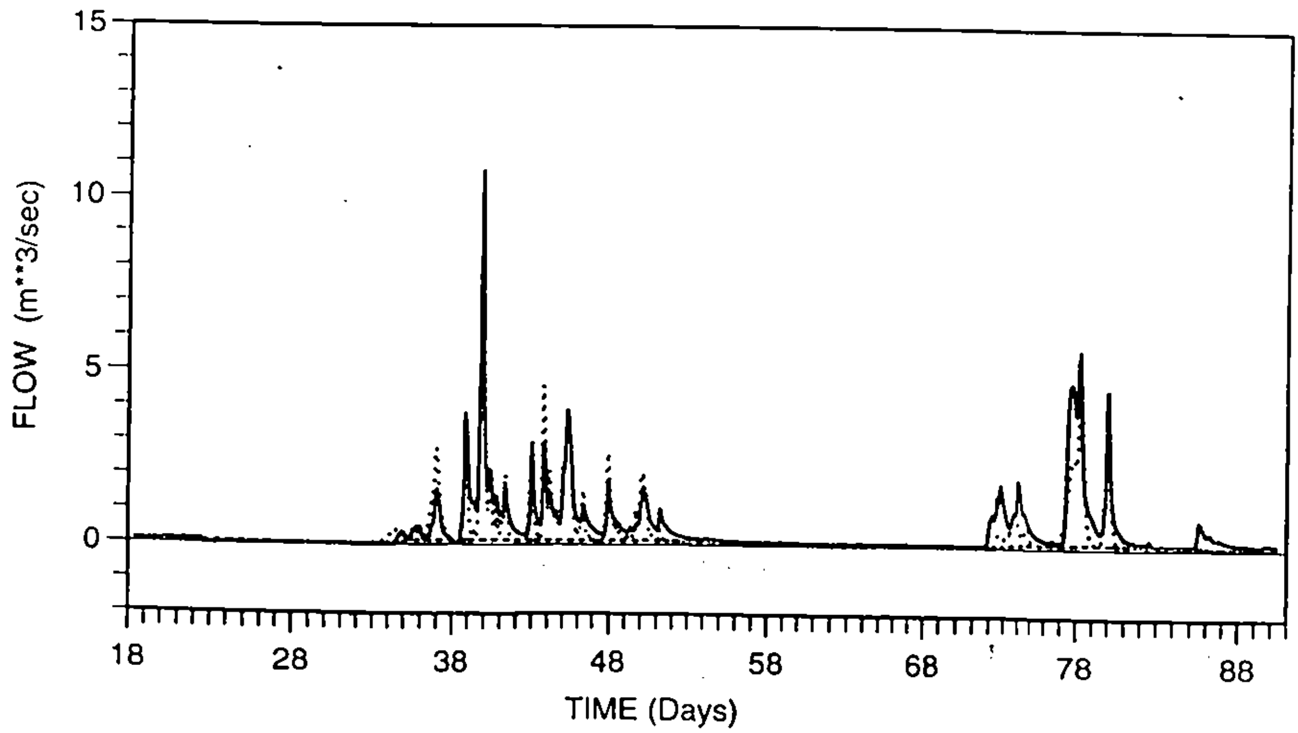


Figure 10 Model predictions of snow water equivalent and flow from the 15 elevation zone model; Monachyle Burn, 18 December 1995 to 28 February 1996. Snow water equivalent:- measured: large dots, predicted: dotted line. Flow:- measured: bold line, predicted: dotted line

Table 4 Flow simulation performance judged using R^2 criterion, Trout Beck, 4 to 30 December 1993

	Snow survey	Snow pillow	
Number of zones	$T_s=1$	T_s optimised	T_s, T_m, T_c optimised
1	0.836	0.799	0.845
2	0.840	0.827	**0.916**
3	0.843	--	--
5	0.843	**0.840**	0.905
10	**0.844**	0.830	0.905
25	0.843	--	--
61	0.843	0.825	0.900
102	0.843	0.826	0.900
307	0.843	0.825	0.900

using snow pillow data. Varying T_c and T_m made little or no difference to the results obtained using snow survey measurements. Again, there is considerable variation in model performance when only a few elevation zones are used, with the performance stabilising at around 10 to 25 zones, corresponding to an elevation band of 12 to 30 m. The optimal values of T_s were around 0.8 when using snow survey measurements and around 0.1 when using snowpillow data. Figure 12 presents the predicted and observed hydrographs obtained using the two elevation zone model in combination with snow pillow data. The R^2 performance statistic obtained for the new model of 0.916 represents a considerable improvement on the value of 0.747 obtained using the five zone model (with standard values for the threshold temperature parameters) presented in Section 3.2, Table 2 and Figure 2(c).

Discussion

Overall the results suggest that more than one elevation zone is optimal, with performance varying erratically between one and 20 zones. One reason may be that the model is simply very sensitive to the use of a small number of zones which split the catchment into a few very large zones. This may introduce errors in partitioning the catchment into areas experiencing melt and receiving precipitation as rain rather than snow. In certain cases these errors may be beneficial leading to improvement in model performance whilst for other numbers of zones model performance could suffer. The results suggest that a conservative selection for the number of zones to use might be a number around $z_{max}/30$, placing the model in the region where it is relatively insensitive to changes in the number of zones.

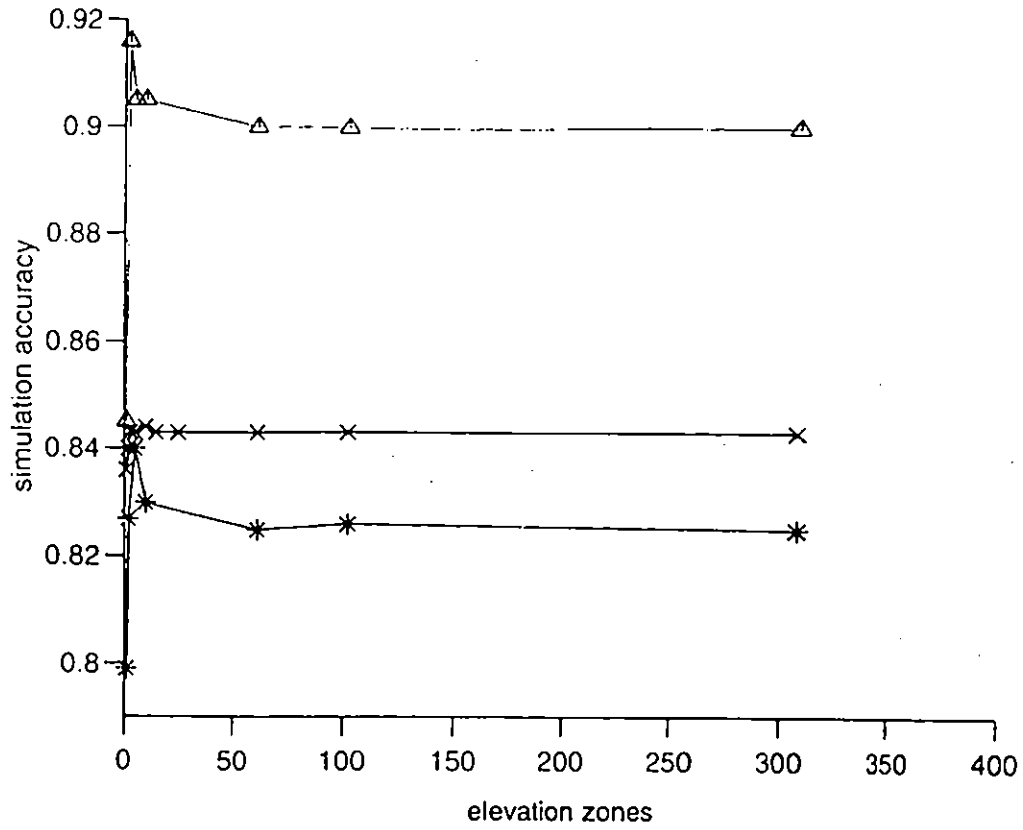


Figure 11 Model performance (R^2 statistic for flow) as affected by the number of elevation zones used, Trout Beck; cross: snow survey data with snow/rain parameter optimised, star: snow pillow data with snow/rain parameter optimised, triangle: snow pillow data with snow/rain, melt and release temperature parameters optimised

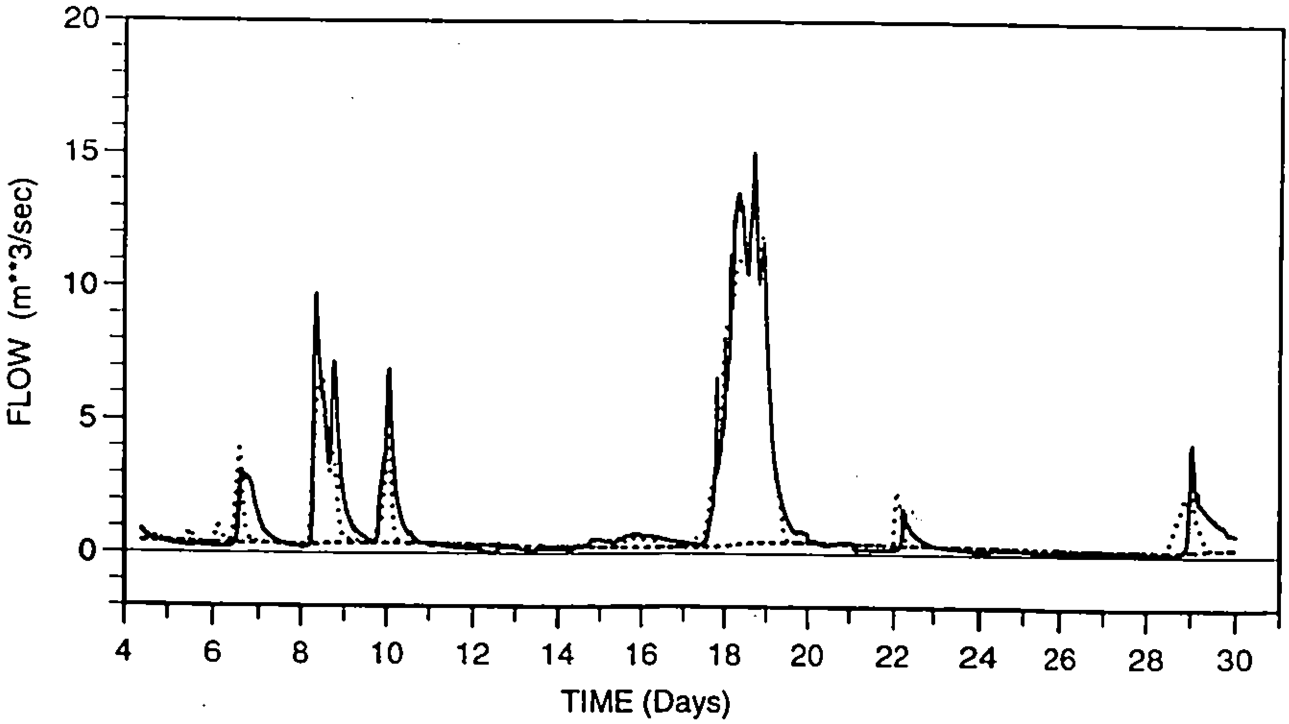


Figure 12 Observed (bold line) and predicted flow (dotted line) using the two elevation zone model in combination with snow pillow data. Trout Beck, 4 to 30 December 1993

In order to ascertain the optimal number of elevation zones, the model was calibrated for each elevation zone and a slightly different set of parameters obtained for each. This raises the question of how sensitive the model is to the parameter sets obtained in this way. To answer this question a range of values of zone number were subjected to one set of model parameters (for, say, zone number equal to 5) to see how well the model performed. The results showed that although there were slight differences in model performance, the *variation* in model performance with zone number remained unchanged, and that, for example, the set of parameters obtained through calibration for 5 zones would yield flow results for 20 zones not dissimilar to those that would be obtained by calibration. That the variation in flow simulation performance is also unchanged by a change of parameter set confirms that the observed variation is not just a result of insufficient calibration for some values of zone number.

3.3.3 Summary and conclusions

An elevation-dependent snowmelt model has been developed for use in high relief areas where changes in temperature with elevation exert an important control on snowmelt. The model is entirely elevation dependent and assumes that the structure of the snowpack is the same at each contour. The model can be used in two ways:

(i) to produce a profile of the dry snow water equivalent with elevation at each time-step enabling the position of the snowline to be determined; and

(ii) to model flow in a catchment during periods of lying snow by dividing the catchment into any number of elevation zones, or even to use a near-continuous distribution of elevation in a catchment.

The performance of the model has been assessed for periods of lying snow in two catchments: the Monachyle Burn in Scotland and Trout Beck in Northumbria. When the model was tested against snowline observations for two periods in Monachyle Burn it performed well in each case, considering the approximate nature of the snowline observations; R^2 performance statistics of 0.74 and 0.66 were obtained for events in 1984 and 1995/96 respectively. The melt factor model parameter was adjusted manually for each event because the snow survey observations were not comparable between them, and a different parameter value was required for each. Whilst additional data are needed to support further model assessment the initial results outlined here appear promising.

The model has also been used to simulate flows at the catchment outlet for a number of events, using both snow survey observations and hourly snowpillow data. An analysis of model performance against number of elevation zones used by the model suggests that for elevations bands greater than around 30 m model performance fluctuates. To ensure good model performance a choice of zone number greater than $z_{max}/30$, where z_{max} is the maximum elevation in the catchment, appears appropriate. In general, a model employing multiple elevation zones has always proved superior to one based on a single elevation zone.

A comparison of the use of snowpillow data versus snow survey measurements has shown that if used carefully, snowpillow data can lead to as good or better flow simulation for a catchment. However, it should be noted that snow appears to melt preferentially from the pillow compared to the surrounding vegetation.

4. LIAISON

A seminar on 'The Snow Resources of Scotland' was held at Bridge of Allan, Scotland on 19 March 1997 at which progress on the project was reported. The seminar was jointly sponsored by the Scottish Snow Group, the Scottish Hydrological Group, British Hydrological Society and Scottish Natural Heritage. The meeting brought together representatives from the full range of snow-interests in Scotland, and included both scientists and representatives from the skiing industry.

On 20 March 1997 two project staff based at Wallingford were shown the field installations in the Monachyle Glen by one of the field observers to the project. This provided a valuable opportunity to discuss the practical difficulties of snow monitoring and the model requirements for snow data.

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