Development and Assessment of Snowmelt Models for Flood Forecasting and Warning

Technical Report
W227

Development and Assessment of Snowmelt Models for Flood Forecasting and Warning

R&D Technical Report W227

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Research Contractor:
Institute of Hydrology

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This document describes the findings of R&D Project W5-627, which aimed to develop improved methods for snowmelt forecasting and warning with the benefit of an extended database for snowmelt modelling. The results will be used to improve existing and new Regional flood forecasting systems.

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EXECUTIVE SUMMARY

Snowmelt in the UK can contribute significantly to flooding and to the hydropower potential of upland reservoirs. However, it is unusual for snowmelt models to be included explicitly in forecasting systems used for flood warning and hydropower management. The potential benefits in terms of saving of life and property, cheaper electricity and improved dam safety are clearly apparent. This report aims to develop an appropriate snowmelt model for use in the UK, to assess its performance using field data and to make recommendations for operational use.

A new snowmelt model has been formulated, as a development of the IH PACK model, which can use either a finite number or continuous distribution of elevation zones in a catchment. The elevation-dependent model is suitable for use in high relief areas where changes in temperature with elevation exert an important control on snowmelt. An assumption of the basic form of model is that the snowpack is the same at each contour. Specifically, it is assumed that snow/rain occurrence and melting at any point in the catchment is dependent only on temperature, and in turn is dependent only on elevation through a simple lapse rate relation. The model can simulate the water equivalent of the snowpack and the position of the snowline as well as the release of snowmelt to the catchment. The basic temperature excess melt formulation can be used in extended form to include the effects of wind and rain heating; a full energy-budget melt option allows additional radiation and humidity measurements to be used. Runoff at the catchment outlet is simulated using the snowpack model in conjunction with one of two rainfall-runoff models: the lumped Probability Distributed Moisture (PDM) model or the Simple Distributed Model (SDM). A partial cover curve may be invoked to allow rain to contribute directly to the rainfall-runoff model when snow cover is patchy and not dominated by relief effects, as might be the case for lowland catchments.

The snowmelt model has been run at a 15 minute time-step to simulate flows at the catchment outlet for a number of periods of lying snow. Daily snow survey observations or hourly snow pillow are used to update the model, correcting for the lack of direct snowfall observations. Model performance has been assessed for three study catchments: the Monachyle Burn in Scotland and Trout Beck and Harwood Beck in Northumbria, north-east England. The results of this assessment indicate that use of a snowmelt model invariably leads to improvements in flow simulations when compared to use of a rainfall-runoff model alone. The best snowmelt formulations are shown to use multiple-elevation zones and the extended melt equation or a single-elevation zone and energy-budget melt; it is sufficient to use the simple lumped PDM formulation as the rainfall-runoff model. Based on the encouraging results obtained, an operational trial of the new model is recommended.

KEYWORDS

Snow, Snowmelt, Floods and Flooding, Flood forecasting, Flood warning, Modelling (Hydrological).

1. INTRODUCTION

Although snow is not a major component of the climate of Britain, large snowfalls are not uncommon and their frequency and severity increase with altitude. The melting of snow packs can cause or contribute to flooding especially when combined with rainfall. Periods of lying snow are often terminated by the advection of warm air within North Atlantic weather systems which bring rain and high winds. High melt rates in these conditions will be largely due to turbulent exchange of heat. The contribution of heat due to rain will be small, although rain may improve the conductivity of the snowpack. This dominance of turbulent heat flux contrasts with conditions experienced in North America, Scandinavia and Alpine regions where radiation melt often prevails. There is a large literature on the snowmelt process and its modelling; the majority deal with the aforementioned regions along with significant contributions from Eastern Europe and Japan. Studies undertaken in the UK are limited, with those by Archer and Johnson in north-east England providing good examples (Johnson and Archer, 1972; Archer 1981, 1983). Some work has also been done in the Cairngorms in the Scottish Highlands by Ferguson (1984) and Morris (1982). These local studies are of most relevance to flood forecasting in Britain.

Flow forecasting systems which include rainfall-runoff models without an explicit model for melting snow can prove highly misleading when used as a basis for flood warning in Britain, with consequential implications on flood damage costs. Failure to take account of the snowmelt contribution to floods in the operation of reservoirs for hydroelectric power supply can affect both the safety of the dam and the power output the scheme can sustain. The ephemeral and dynamic nature of snow-cover in Britain, and the occurrence of heavy rain along with melt, means that models need to be formulated at a fine time resolution, typically one hour or less.

Moore *et al.* (1996, 1999) responded to the need for improved snowmelt forecasting methods by establishing a UK Snowmelt Database and investigating alternative methods for snowmelt forecasting. A snowmelt model, 'PACK', was developed which was coupled with two forms of catchment runoff model, the lumped 'Probability Distributed Moisture' model (PDM) and a Simple Distributed Model (SDM) based on saturation excess runoff production and an isochrone-configured kinematic wave routing translation function. The spatial variation of temperature and precipitation across the catchment was incorporated through the use of elevation zones, and was shown to be beneficial for some catchments. The PACK snowmelt module included an extended melt equation incorporating wind and rain heating effects, with the simple temperature excess (or index) method as a special case. The option of a full energy budget melt equation was also included in the model formulation. Initial model assessments were encouraging, showing that significant improvement could be gained in runoff simulation in snowy conditions through the use of a snowmelt model. However, the study highlighted the need for further work in model development, and the need for a longer data record for model assessment and evaluation.

Three years on, the UK Snowmelt Database now includes data from the IH experimental catchments in Balquhidder, the Dove in the Peak District, and additional data from catchments in the Upper Tees, Plynlimon and the Upper Aire. The aim of this report is to present recent work on model development and evaluation using this more comprehensive dataset and to make firmer recommendations for best practice in snowmelt modelling in the UK. Section 2 describes the current formulation of the snowmelt catchment model developed for real-time flood forecasting. It describes how a catchment is sub-divided into elevation zones to represent the change in temperature with altitude and, in turn, the effect of temperature on melt and whether precipitation falls as rain or snow. A hypsometric curve allows for a flexible choice of zone number with a near-continuous distribution of elevation in a catchment being possible. The PACK module used to represent snowmelt in each zone is then described and its coupling to a lumped conceptual rainfall-runoff model, the PDM (Probability Distributed Moisture) and a simple distributed rainfall-runoff model, the SDM. They provide alternative ways to transform the meltwater draining from the snowpack into flow at the basin outlet. Section 4 presents calibration and assessment of the different model formulations with reference to snow water equivalent at the snow survey site and flow at the catchment outlet. A full energy budget melt formulation which uses additional radiation and humidity data is evaluated alongside the simple temperature excess and extended melt equations. Section 5 provides a summary, overall recommendations, and a discussion of prospects for further research.

2. SNOWMELT MODEL FORMULATION

2.1 Introduction

In their 1996 report to the National Rivers Authority, 'Development of Improved Methods for Snowmelt Forecasting' (NRA R&D Note 402), Moore *et al.* reviewed a number of snowmelt models used operationally in the UK. The IH Pack Model was chosen for further development and the new model evaluated on a number of British catchments. Section 2 presents the current model formulation (Bell and Moore, 1999), which is now formulated for use with any number of elevation zones including a near-continuous distribution of zones in a catchment.

2.2 The Elevation-Dependent Snowmelt Model

A simple distributed representation of the snowmelt process can be based on a partitioning of the catchment into elevation zones with a snowmelt 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 and the rain/snow partition, through the use of a temperature lapse rate. The concern here is to formulate a model that can define the number of elevation zones flexibly and can accommodate a near-continuous distribution of elevation in the catchment. This is accomplished using the well-known hypsometric curve (for example, see 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)=dF/dz. 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. By way of illustration, Figure 2.1 shows hypsometric curves for the three study catchments, Monachyle Burn in Scotland and Trout Beck and Harwood Beck in the Upper Tees. The importance of the distribution function, F(z), is that it can be coupled with a temperature-elevation relation 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

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

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 0°C), and T_{aws} and z_{aws} are the temperature and elevation of an automatic weather station (AWS), then the critical elevation below which melt occurs, z_m, is given by

$$z_m = z_{aws} + \alpha^{-1}(T_{aws} - T_m). \tag{2}$$

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,

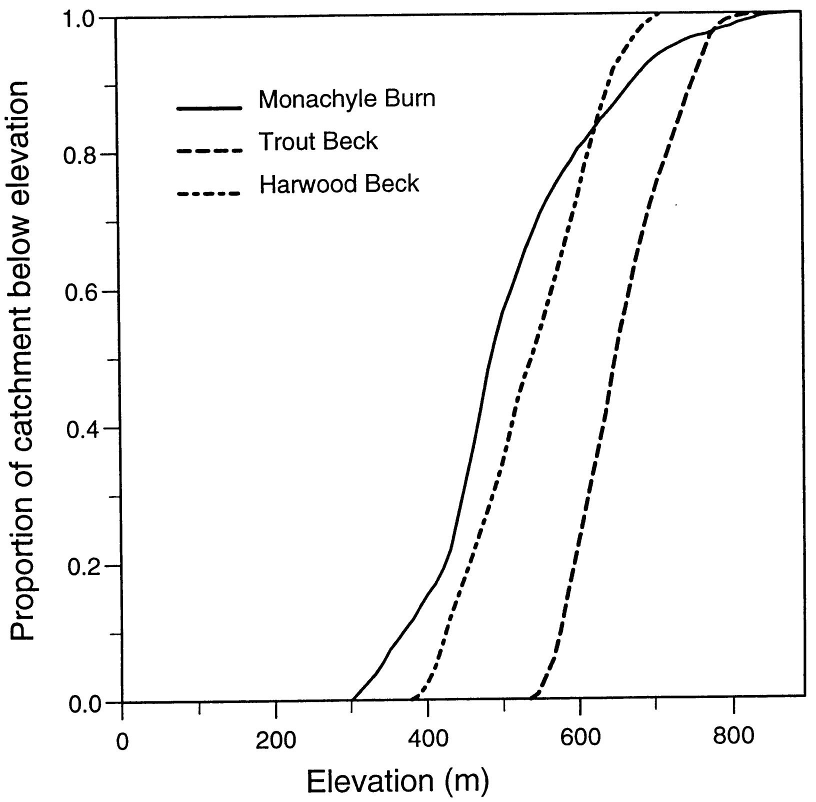


Figure 2.1 Hypsometric curves for Monachyle Burn, Trout Beck and Harwood Beck.

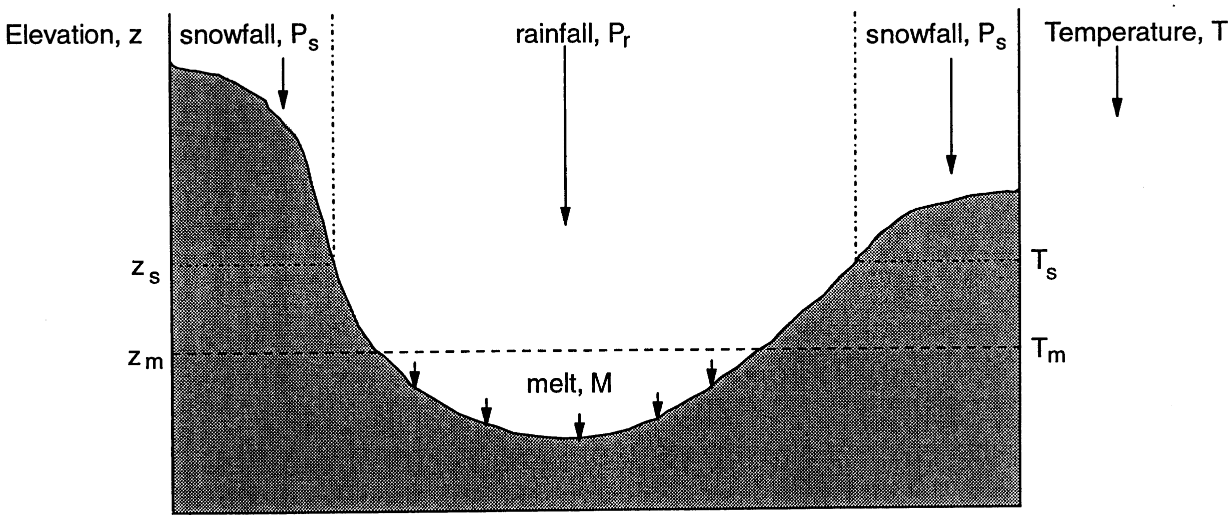


Figure 2.2 Cross-section through a typical catchment showing zones of snowfall and melting.

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 2.2 illustrates the zones of melt and snowfall for a cross-section through a typical catchment. In the application that follows, temperature is taken from one weather station in each catchment and a fixed temperature (wet adiabatic) lapse rate of 0.0059°C m^{-1} is assumed.

2.3 The PACK Snowmelt Module

The PACK snowmelt module conceptualises snow storage to be compartmentalised into "dry" and "wet" snow stores. New snow falling onto the pack contributes to the dry snow store. The wet store receives water directly as rainfall and as melt from the dry store when the temperature is above a melt threshold (usually taken to be 1°C). 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 a rainfall-runoff model. Dry and wet snow water equivalents are denoted by W and S respectively. The overall scheme is depicted in Figure 2.3.

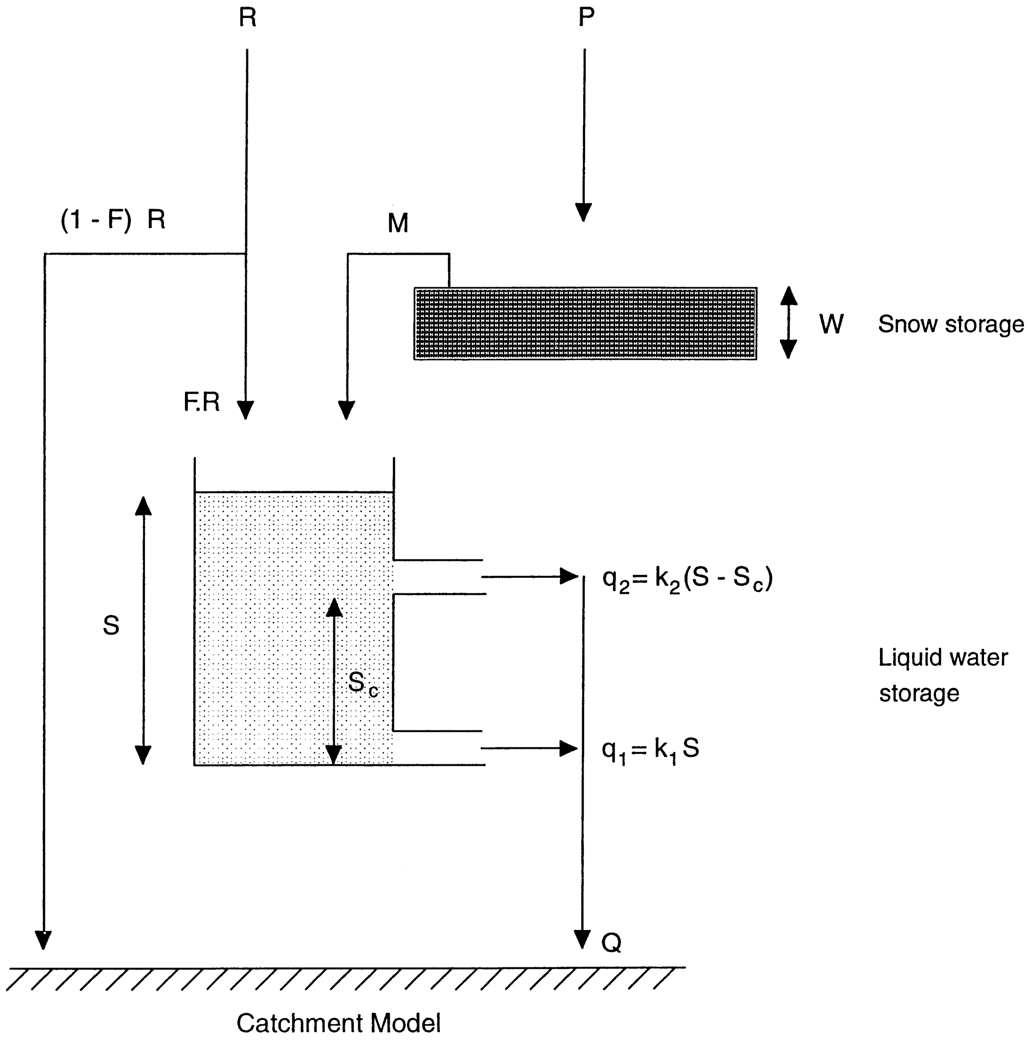


Figure 2.3 The PACK snowmelt module.

Making the assumption that snow/rain occurrence and melting are dependent only on the temperature at a point, and in turn dependent only on elevation through a temperature lapse rate relation, then W and S are also only dependent on z: that is W = W(z) and S = S(z). This also assumes that precipitation is uniform over the catchment, or 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 store

Adopting the model formulation of the PACK module (Moore *et al.*, 1996, 1999), which partitions the snow pack into dry and wet (melted) snow, the following elevation-dependent model can be constructed.

Consider the n'th time interval of duration Δt. The *potential* melt at an elevation z at time n, M_o^n, is given by

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

where β is the melt factor, α is the temperature lapse rate (fixed at 0.0059°C m^{-1}), 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

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

where P_s^n represents the water equivalent of the fresh snow that has fallen in the time interval, and z_m is the critical elevation below which melt occurs. The *actual* melt is given by

$$M^n(z) = \begin{cases} \max\{W^{n-1}(z) - W_o^n(z) - P_s^n, 0\}, & z \le z_m^n \\ 0, & z > z_m^n. \end{cases} \tag{5}$$

Wet snow store

The wet snow water equivalent, S, is updated via

$$S_o^n(z) = S^{n-1}(z) + M^n(z) + P_r^n(z). \tag{6}$$

Here, S_o^n is the initial value of S^n, before drainage-losses are calculated, and $P_r^n(z)$ is the rainfall at z given by

$$P_r^n(z) = \begin{cases} P, & z < z_s, \\ 0, & z \ge z_s, \end{cases} \tag{7}$$

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

If the dry snow component is fully depleted the rainfall bypasses the wet store and contributes directly to the input to the rainfall-runoff model. This direct input is given by

$$I_d^n(z) = \begin{cases} P_r^n(z), & W^n(z) = 0, \\ 0, & W^n(z) > 0. \end{cases} \tag{8}$$

The drainage from the wet pack together with rainfall, forming the total input to the rainfall-runoff model, is given by

$$I^n(z) = I_d^n(z) + k_2 S^*(z)(1 - k_1) + k_1 S_o^n(z) \tag{9}$$

where

$$S^*(z) = \max\{0, S_o^n(z) - S_c^*(S_o^n(z) + W^n(z))\}. \tag{10}$$

The parameter S_c^* is the critical liquid water capacity, expressed as the proportion of the total water content of the pack above which drainage from the pack occurs at a high rate, k_2. When the total water capacity is below S_c^*, drainage occurs at a slower rate, k_1. The storage time constants k_1 and k_2 have units of inverse time. An additional constraint is introduced so that drainage only occurs when the temperature exceeds T_{drel}, usually taken to be the zero degree isotherm. Inhibiting drainage during freezing conditions appears to be appropriate for the shallow, ephemeral snowpacks considered here.

The final value of wet snow water equivalent is obtained as

$$S^n(z) = S_o^n(z) - I_d^n(z). \tag{11}$$

2.4 Total Water Input to the Rainfall-Runoff Model

The total input of water over the catchment from snowpack drainage and rainfall is

$$I = \int_{z_1}^{z_2} I^n(z) f(z) dz. \tag{12}$$

Here $I^n(z)$ is given by equation (9) and $f(z) = dF(z)/dt$ is the frequency function of catchment elevation; F(z) is the hypsometric curve introduced in Section 2.1. The total volume of water produced from a catchment of area A is AI. 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. In practice, calculation of the integral is speeded up by concentrating only on the melt zone of the catchment with z_1 and z_2 defined as

$$\begin{aligned} z_1 &= \max[z_0, z_{min}], \\ z_2 &= \min[z_{max}, \max[z_m, z_{drel}, z_s]]. \end{aligned} \tag{13}$$

Here, z_0 is the "snowline" delimiting the edge of the snowpack, z_m is the elevation delimiting the melt zone, z_{drel} is the elevation corresponding to the threshold temperature for drainage release into the catchment, and z_s is the elevation corresponding to a temperature of T_s above which precipitation falls as snow and not rain; also $z_2 > z_1$.

The frequency function of catchment elevation, f(z), is computed to a resolution of 1 m using the DTM elevation data. Since this derives from Ordnance Survey contour data with elevation held to 0.1 m, a finer precision hypsometric curve could be calculated if required. If I(z) is calculated at each elevation for this level of precision, an estimate of the average drainage depth across the catchment, I, can be calculated by replacing the integral in (12) with a summation. 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 shape parameters of the distribution inferred by optimisation.

The distributed nature of the new model formulation means that it is more sensitive to the rain/snow temperature threshold which now governs the proportion of the catchment receiving snow (or rain) and not just whether the catchment receives rain or snow. The new formulation allows greater flexibility in the use of either a finite number, or near-continuous distribution, of elevation zones in a catchment, and also permits the use of a probability distribution of zones in cases where a DTM of the catchment is unavailable.

2.5 Partial Cover Curve

A further extension of the model to incorporate the phenomenon that shallow snowpacks may occupy only a fraction, F, of an elevation zone may be important in some instances. The fraction of snow cover may be allowed to vary as a function of the total water equivalent of the pack $\theta=S+W$ ranging from zero when $\theta=0$ to unity when θ exceeds a critical value θ_c and complete snow cover occurs. The functional form for $F\equiv F(\theta)$ adopted here derives from

$$\theta=(\theta_c+1)^{F(\theta)}-1 \qquad (14)$$

suggested by Laramie and Schaake (1972) and used in the US National Weather Service's snowmelt model (Anderson, 1973). In terms of $F(\theta)$ we have

$$F(\theta)=\frac{\log(\theta+1)}{\log(\theta_c+1)}. \qquad (15)$$

Given the current water content of the pack θ the fraction of an elevation zone covered by snow is readily calculated from the above. In the event of a fresh snowfall, $\Delta\theta$, it is assumed temporally that the fraction reverts to 1 until a fraction $(1-\phi)\Delta\theta$ has melted. A linear reversion to the original point on the areal depletion curve (Figure 2.4) occurs in melting the remainder of the new snow, $\phi\Delta\theta$. Normally the proportion, ϕ, is set to 0.25. Any rain falling on the fraction devoid of snow is available immediately for input to the rainfall-runoff model for the basin.

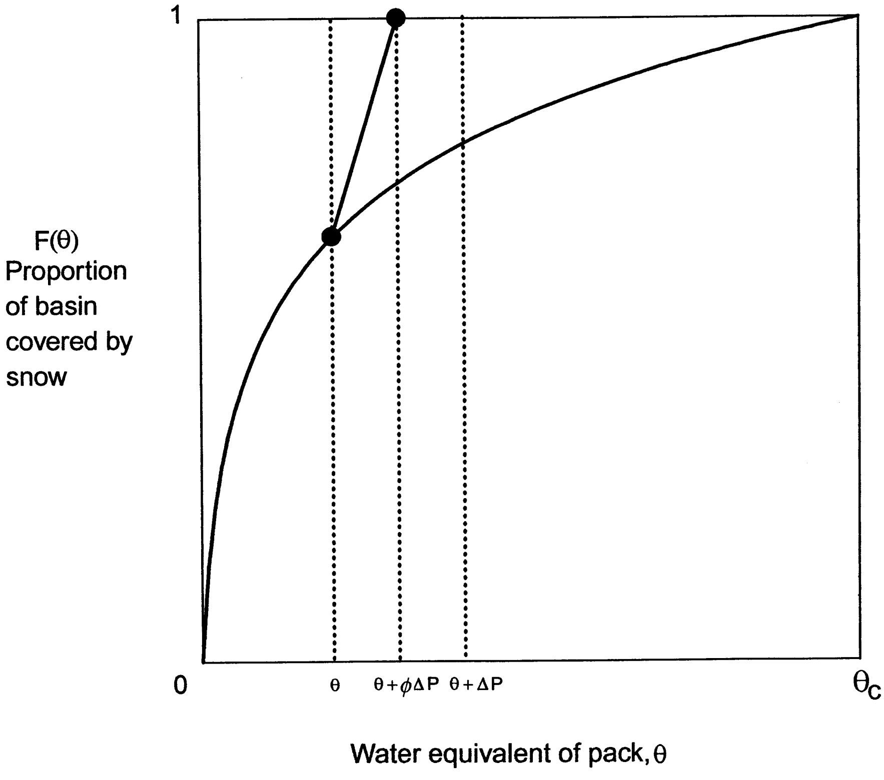


Figure 2.4 **Partial cover curve used in the PACK module.**

2.6 Coupling to Rainfall-Runoff Models

The overall snowmelt model is comprised of PACK snowmelt modules operating within each elevation zone of the catchment. The resulting modelled snowmelt forms part of the input to a rainfall-runoff model which transforms rainfall together with drainage melt from the snowpack into catchment runoff. Two rainfall-runoff models are evaluated here: the PDM (Probability Distributed Moisture) model and the SDM (Simple Distributed Model). Brief descriptions of each are give below.

The PDM (Moore, 1985, 1999; Institute of Hydrology, 1992, 1996) is a conceptual rainfall-runoff model which uses a probability distribution to describe the spatial variation of water storage capacity across a catchment. This allows saturation excess runoff at any point to be integrated over the catchment to yield the total runoff entering fast response pathways (principally stream channels) to the catchment outlet. Groundwater recharge from soil drainage passes through slower subsurface pathways and finally combines with output from the fast response pathways to give the total flow from the catchment. Figure 2.5(a) presents a schematic of the PDM model.

The Simple Distributed Model is a development of the IH Grid Model (Moore *et al.*, 1994; Moore and Bell, 1996; Bell and Moore, 1998a, 1998b) and is presented in schematic form in Figure 2.5(b). The model employs DTM-derived isochrone bands which function as a parallel cascade of kinematic routing reaches transmitting melt, runoff and drainage to the basin outlet. Runoff is generated from the isochrone band area according to saturation excess and storage controlled drainage principles; storage capacity varies as a function of slope as measured from the DTM over the isochrone band.

2.7 Melt Formulations

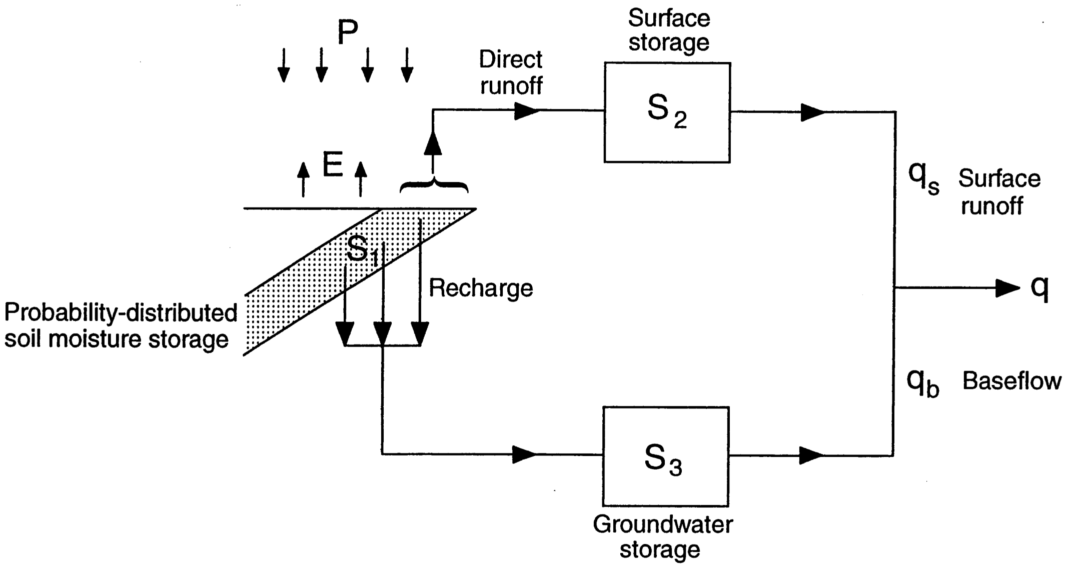
2.7.1 Introduction

Previous sections have provided a description of the basic form of snowmelt model under assessment together with a brief outline of the two rainfall-runoff models which convert snowpack drainage and rainfall to flow at the basin outlet. This development has assumed that a single temperature excess model for melt applies as defined by equation (3). Here, two alternative melt formulations are introduced. The first is a simple extension of the temperature excess model to include the effects of wind and rain on melt. Secondly, a full energy balance formulation is considered.

2.7.2 Extended melt equation

A feature of current operational snowmelt models in the UK is that the surface melt component is approximated by a very simple temperature excess formulation, equation (3), which requires only measurement of temperature. The extended melt equation of Moore *et al.* (1996) incorporates the effects of temperature, wind and rain on melt into a single parameterised expression:

(a) The PDM (Probability Distributed Moisture model)



(b) The SDM (Simple Distributed Model)

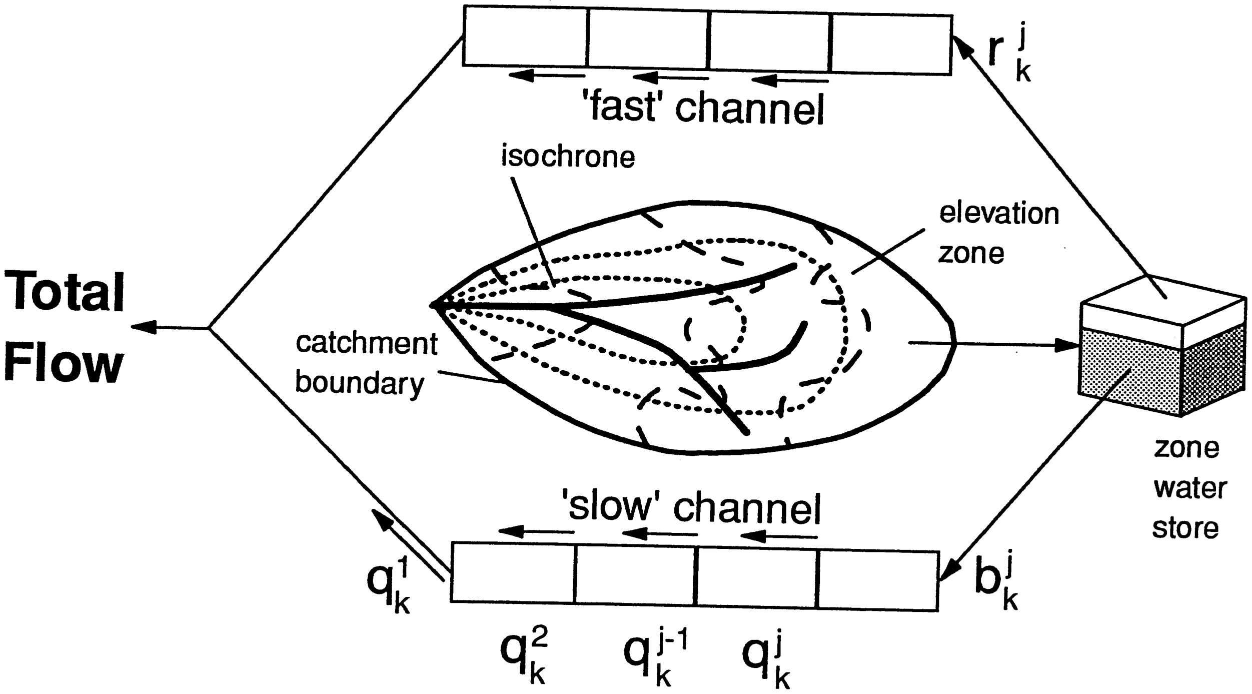


Figure 2.5 Schematic of the lumped and distributed catchment runoff models used with the elevation-dependent snowmelt model.

$$M = \beta(1-\gamma u)(T-T_m)^x + \mu RT, \tag{16}$$

where T_m is the threshold temperature above which melt occurs and β, γ and x are parameters.

The quantity μ is normally defined physically as the reciprocal of the latent heat of fusion, 80 cal g^{-1}. To allow for lack of representativeness in measured values of R and T, μ has been treated as a parameter available for optimisation and is referred to as the rain heating factor. Note that the temperature excess equation (3) is a special case of (16).

2.7.3 Energy budget melt formulation

When measurements of net all-wave radiation and humidity are available in addition to temperature and wind speed, it is then possible to consider the full energy balance approach for melt estimation. In the following section the energy budget approach to melt estimation reviewed in Moore *et al.* (1996) is outlined briefly with specific reference to recent changes. Inclusion of the energy balance approach within the present study provides a formal means of assessing the potential value of additional weather measurements for improved snowmelt forecasting.

The theoretical basis of the energy approach used here derives from the Meteorological Module, MET, and Ground Level Inputs Module, GLI, of the IHDM Snowmelt Model, which together provide a means of calculating an effective rainfall input to a vegetation-covered soil using Automatic Weather Station (AWS) data from a nearby site. The Meteorological Module corrects air temperature and humidity for any difference in altitude between the slope site and the AWS using standard lapse rates and adjusts the radiation input according to the slope angle and aspect. Contained within GLI, along with interception and evaporation components, is a snow component which predicts changes in snow cover and snowmelt from the meteorological inputs, given the initial depth, density and liquid water content of the snow. The snowmelt formulation, described below, is used here in conjunction with the PACK snow storage accounting procedure previously described.

A possible energy budget for a snowpack as a whole may be defined as (Morris, 1982)

$$R_n + Q_c + Q_r + Q_L + Q_s - Q_m = (c_p)_i \frac{dT}{dt} \rho_s Z, \tag{17a}$$

or

$$H - Q_m = (c_p)_i \frac{\partial T}{\partial t} \rho_s Z, \tag{17b}$$

where H = $R_n + Q_c + Q_r + Q_L + Q_s$ is the net heat flux (W m^{-2}) and
R_n = Net radiation-energy flux into the snow surface (W m^{-2}),
Q_c = Heat gained by turbulent convection from the air (W m^{-2}),
Q_r = Advection heat gained from precipitation (W m^{-2}),
Q_L = Heat contributed from condensing vapour (W m^{-2}),
Q_s = Heat conduction exchange between the ground and snow (W m^{-2}),
Q_m = Heat carried away by meltwater (W m^{-2}),
$(c_p)_i$ = Specific heat of ice at constant pressure (J kg^{-1} $^{o}C^{-1}$),
T = Mean temperature of the snowpack (°C),
ρ_s = Mean density of the snowpack (kg m^{-3}),
Z = Depth of the snowpack (m),
t = Time (s).

The inputs of energy per unit time per unit area at the upper boundary of the pack are given by R_n, Q_c, Q_r and Q_L. When Q_L is negative the snow melts and evaporates or sublimes directly into the atmosphere. The exchanges of energy per unit time per unit area at the lower boundary are Q_s and Q_m. A detailed description of the calculation of each term in the energy budget equation is provided by Moore *et al.* (1996).

The right-hand term in equation (17) represents the change in heat stored in the snowpack. Average temperatures of the pack are constrained such that $T \leq 0°C$. It is assumed that the only movement of water across the lower boundary is that of water leaving a melting pack. Hence $Q_m = 0$ when $T < 0°C$, whereas $Q_m \leq 0$ when $T = 0°C$.

Knowing average values for R_n, Q_c, Q_r, Q_L and Q_s over the time interval Δt, the average pack temperature at time t+1, T_{t+1}, can be calculated from the temperature and depth of the pack at time t by assuming that the heat carried away by meltwater $Q_m = 0$. Hence, from equation (17b)

$$T_{t+1} \approx T_t + \frac{\Delta t H}{(c_p)_i \rho_s Z_t} . \qquad (18)$$

For shallow packs ($Z_t \leq 1$ mm), T_{t+1} is set to 0°C, or to the air temperature if this is below freezing. However, if this calculation produces a value of T_{t+1} which is greater than 0°C then this implies that $Q_m > 0$. Then $T_{t+1} = 0°C$ and

$$Q_m = H + (c_p)_i \rho_s \frac{Z_t T_t}{\Delta t} . \qquad (19)$$

The snowmelt rate per unit area per unit time can then be determined from

$$M = \frac{Q_m}{\rho_w (L_w)_i} \qquad (20)$$

where ρ_w is the density of water and $(L_w)_i$ is the latent heat of fusion of ice per unit mass.

The approach so far has been to neglect any calculations of the internal distribution of water and heat, and to treat the snowpack as lumped in the vertical direction. Morris and Godfrey (1978) describe a more detailed formulation of a snowpack in terms of these internal variables. In the current IHDM Snowmelt Model the surface temperature T_o is allowed to vary from the average pack temperature by using an analytical solution for steady-state heat flux at the boundary of a semi-infinite body (Carslaw and Jaeger, 1959). This procedure was found to be unstable for the present application, leading to large oscillatory values for the snow surface temperature. Instead, T_o is set to the average pack temperature, a reasonable assumption for the shallow packs typical of the UK.

The many physical parameters within the energy balance equations can make it a difficult technique to apply. However, for a particular catchment a number of parameters can be set to constant values, such as latitude and longitude, and the zenith and azimuth angles used in radiation calculations. A sensitivity analysis undertaken by Moore *et al.* (1996) suggested that under UK conditions the most critical parameter was the aerodynamic roughness length controlling convective heat loss; the model was found to be only weakly sensitive to the initial pack temperature. As a result, only the roughness length features as a parameter to be optimised in the energy budget melt formulation. This contrasts with two parameters in the simple temperature excess model (the melt factor and threshold temperature).

The energy budget estimate of melt has been incorporated in the PACK module as an alternative to the temperature excess approach. In its current state of development it can be applied to a catchment only when treated as a single elevation zone. Once the snowmelt rate and the net water flux from the surface have been calculated by the energy budget approach, the total melt rate is determined. Finally, changes in the wet and dry snow water equivalent are calculated following the procedures of equations (4) to (11).

The current energy budget formulation is now more robust and has proved to be more stable for the shallow packs experienced under UK conditions. Use of the energy budget approach with multiple elevation zones requires extrapolation across the catchment of meteorological variables, in addition to temperature, such as radiation and wind. This is seen as an opportunity for further research.

2.8 Model Parameters

Table 2.1 provides a summary of the parameters used in the PACK snowmelt module, including those involved in the different melt formulations.

2.9 Updating of the Snowmelt Model

Assimilation of snow measurements into the model in near real-time so as to improve forecast accuracy is accomplished by a novel updating scheme (Moore *et al.*, 1999). This involves operating a "point" PACK model at the snow measurement site in parallel to PACK modules in each elevation zone. Point model errors are transferred using a proportioning scheme to adjust the snowpack water contents of each elevation zone. The scheme can make use of either hourly measurements from a snow pillow (Archer and Stewart, 1995) or measurements from snow cores made once a day.

The correction to the point model ensures that the water equivalent and density of the modelled and measured packs agree, and also establishes the partition between wet and dry pack water storage in the modelled pack. The correction applied to the water equivalent for each elevation zone is in proportion to that applied in the point model. A partition between wet and dry packs is established by maintaining the same density as at the measurement site. The updating scheme is described in more detail below.

Table 2.1 The PACK snowmelt module parameters

Parameter	Description	Typical value	Unit
The basic PACK module:			
c	Precipitation representativeness factor	1	dimensionless
T_s	Temperature threshold below which precipitation is snow	1	°C
T_m	Critical temperature above which melt occurs	0	°C
β	Melt factor	4	mm/day/°C
k_1	Storage time constant: lower outlet	0.15	day^{-1}
k_2	Storage time constant: upper outlet	0.85	day^{-1}
S_c^*	Maximum liquid water content, as a proportion of total	0.1	dimensionless
T_c	Critical temperature below which no drainage occurs	0 (fixed)	°C
Extended melt equation:			
γ	Wind speed factor	0.24	$s\ m^{-1}$
μ	Rain heating factor	0.125	$°C^{-1}$
Partial cover curve:			
θ_c	Critical water content below which only a proportion of the basin is snow-covered	100	mm
ϕ	Fraction of new snow remaining below which snow-covered area starts to revert to partial cover curve	0.25	dimensionless
Energy budget formulation:			
Z_0	Aerodynamic roughness length of snow surface	30	mm

(Note that when the energy budget melt formulation is used, parameters T_m, β, and γ are no longer required.)

The state-correction information computed within the point snowmelt model at the survey site comprises two quantities. The first is the snow correction factor, g, computed as the ratio of the measured water equivalent of the pack, θ_m, to the modelled value, θ; that is

$$g = \theta_m / \theta . \tag{21}$$

The second is the proportion of dry snow in the pack expressed as

$$\lambda = \frac{1-\rho_m}{1-\rho_w} \tag{22}$$

where ρ_m, ρ_w are the measured snow pack density and the density of dry snow, assumed equal to 0.1 g cm^{-3}. The two state variables of the point snowmelt model, W the water equivalent of the dry pack and S the water equivalent of the wet pack, are then updated as follows:

$$W^{\dagger} = \lambda\, \theta_m \tag{23}$$

$$S^{\dagger} = \theta_m - W^{\dagger} = (1-\lambda)\, \theta_m \tag{24}$$

where the superscript dagger is used to denote the updated quantity. It can be seen that this correction ensures that the water equivalent and density of the modelled and measured packs agree; it also establishes the partition between wet and dry pack water storage in the modelled pack.

Transfer of the state correction information, g and λ, to the basin scale model used for snowmelt forecasting proceeds as follows. Firstly, the water equivalent of the model pack, θ=W+S (no change in notation will be introduced as it is clear that reference is to the basin scale model), is factored using the point snow correction factor, g, such that

$$\theta^{\dagger} = g\theta \tag{25}$$

$$W^{\dagger} = \lambda\theta^{\dagger} \tag{26}$$

$$S^{\dagger} = \theta^{\dagger} - W^{\dagger} = (1-\lambda)\theta^{\dagger} . \tag{27}$$

The correction is, thus, in proportion to that applied in the point model, relative to the water equivalent of point and basin packs; it also establishes a partition between wet and dry packs by maintaining the same density. In practice an upper bound has been imposed on the snow correction factor, g, both when applied to the basin scale and the point snow model. In all cases if the factor is unrealistically large, the wet and dry snow water equivalent values are set to 0.1 and 0.9 times the measured value, respectively.

The scheme has been extended to update when only depth measurements are available and depths are increasing, indicating fresh snow has fallen. This situation arises at times when the snow core has not been weighed to obtain water equivalent and density estimates. The water equivalent of the pack is estimated as ρD, where ρ is the most recent measurement of snow density and D is the measured snow depth. This water equivalent is used as an approximation of the missing measurement, θ_m, and the standard updating procedure then followed. More complex schemes have proved less reliable (Moore *et al.*, 1996, 1999).

3. STUDY CATCHMENTS AND MODEL DATABASE

3.1 Introduction

Under this second stage of the project, the Lower Monachyle catchment near Balquhidder in Scotland has been included as a new study site for snowmelt monitoring and use for model development and assessment. Unfortunately, a paucity of historical data and infrequent snowfall over the project period has meant that its usefulness has proved less than originally envisaged. Trout Beck and Harwood Beck in the Upper Tees, north-east England, have been used as additional study catchments as these have proved to be the most valuable for model development. Details of the study catchments are presented below. Data collected from the catchments have been collated in the form of a model database for use in model development and assessment; this is outlined in Section 3.3.

3.2 The Study Catchments

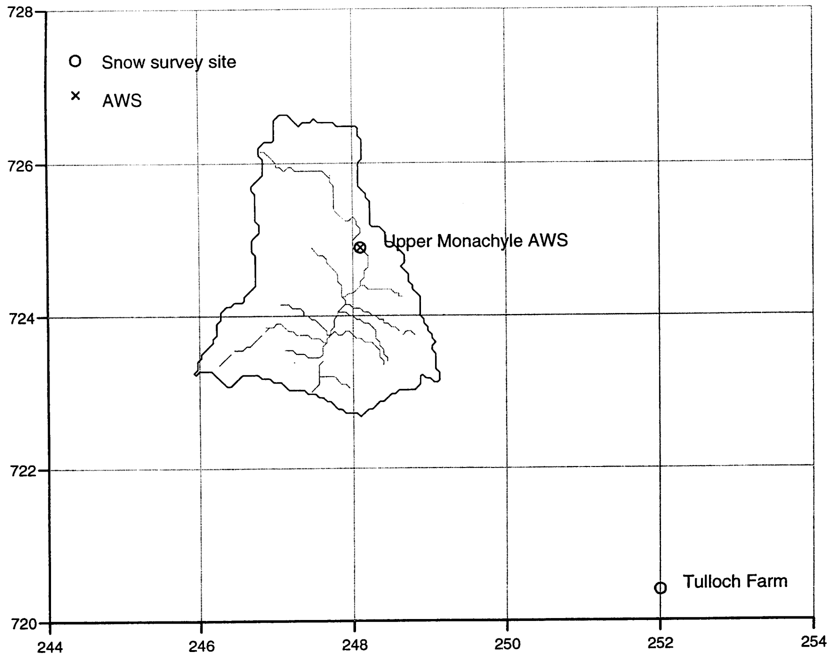
3.2.1 Balquhidder

The Balquhidder experimental catchments, Monachyle and Kirkton Burn, were established in 1981 to study the effects of forestry on water resources. The nature of the Balquhidder catchments is significantly different to other UK experimental catchments, such as Plynlimon, in that they have a more rugged relief and coarser vegetation and experience a higher proportion of annual precipitation falling as snow. Consequently the measurement of snow proves critically important. In this study, modelling work has focussed on the Monachyle Burn catchment, which is the larger of the two catchments and without the added complexity of forestry.

Monachyle Burn, shown in Figure 3.1(a), drains an area of 7.7 km^2 with an elevation range of 302 to 892 metres and natural vegetation of heather, bracken and coarse grass. It has a distinct upper catchment of 2.24 km^2 containing a large undulating peat area with a heather cover. The automatic weather station (AWS) used here is sited near the outlet of this upper catchment in a fairly central location with respect to the catchment as a whole. Measurements from the AWS relate to an hourly time-step, and raingauge values are for a 15 minute time-step. In addition, daily snowcore measurements of depth, density and water equivalent, together with approximate snowline observations are made, but not on a regular basis. An inspection of historical and project period data records revealed only two snow periods, in 1984 and during the project period in 1995/96, as adequate for model development. For the 1984 snow events, daily snow cores were made at Tulloch Farm (elevation 135 m), situated outside the catchment approximately 5 km south-east of the Lower Monachyle gauging station. The snow cores for the 1995/96 period were taken in the vicinity of the Lower Monachyle AWS site which is located at a height of 470 m. Table 3.1 provides a summary of available data in the Balquhidder area.

Water resource studies at Balquhidder have relied upon regular snow pack surveys to determine the inputs of snowfall. The difficulty of this method is the short-lived nature of many snowfall events in Britain, the unknown quantity of snow lost to melt and the redistribution of lying snow by wind. A combination of daily snow surveys and storage gauges would appear to offer a potentially better solution; however, precipitation falling as snow is difficult to measure. The

(a) Lower Monachyle



(b) Trout Beck and Harwood Beck

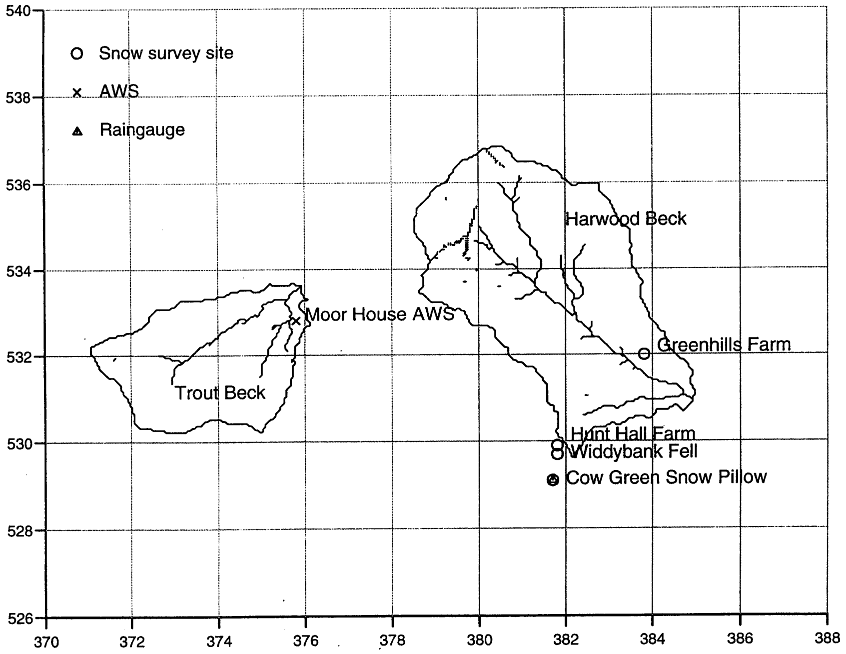


Figure 3.1 **Maps of the study catchments in the Monachyle Glen and the Upper Tees (Trout Beck and Harwood Beck) showing the river network and the position of AWS and snow survey sites (grid coordinates in km).**

large surface to weight ratio of snow makes snowfall vulnerable to wind turbulence. Standard raingauges with gauge rims above the ground surface are known to increase passing wind turbulence, further aggravating snowfall measurement. Also, raingauges used with the rims level to the ground surface, although reducing the effect of wind turbulence on the catch, are vulnerable to drifting snow.

In an attempt to overcome some of these problems the Institute of Hydrology installed a Double Fenced Intercomparison Reference (DFIR) gauge in Monachyle Glen in 1995. This method is regarded by WMO as a reference standard against which all other methods of measurement can be related (Goodison *et al.*, 1989). The DFIR gauge, developed in Russia, comprises a Tretyakov gauge surrounded by two snow fences. During the winter of 1995/96 a field trial of the DFIR in the Balquhidder catchment was carried out to test its performance against existing raingauges. Although initial data suggested that the gauge was effective in reducing the effect of drifting snow on gauge catch, the DFIR was found to be susceptible to extreme conditions and did not survive the 1995/96 winter.

Overall, the field trial of the DFIR showed initial signs of the effectiveness of the gauge but highlighted the impracticality of its design for the measurement of snow in the Scottish Highlands. The installation of the gauge and final results of the trial are reported in Appendix I.

More traditional field monitoring in the form of catchment traverses were also undertaken in Monachyle Glen during the winter of 1998. Depth and water equivalent were measured at forty sampling points in a square starting and finishing at the location of the DFIR. While these traverses have not been used in the present modelling study they might be used in the future to support research into the spatial variability of snowmelt in high relief catchments.

3.2.2 Upper Tees

The Upper Tees catchments, Trout Beck and Harwood Beck, are shown in Figure 3.1(b). Trout Beck drains a heather moorland area of 11.4 km^2 to its gauging station near Moor House with an elevation range of 553 to 857 metres. An automatic weather station (elevation 556 m) is located at Moor House near the catchment outlet whilst a snow-pillow (elevation 500 m) is situated about 8 km to the south-east, near Cow Green Reservoir Dam. The AWS provides hourly rainfall measurements and a recording raingauge (elevation 494 m) near Cow Green reservoir provides 15 minute rainfall data. A snow survey site at Widdibank Fell (elevation 513 m) was closed in December 1995. Since then, an observer has taken daily readings at the nearby Hunt Hall Farm situated about 200 m north of Widdibank Fell.

Harwood Beck is situated approximately 4 km east of Trout Beck and drains an area of 24.7 km^2 with an elevation range of 378 to 713 metres. Rainfall measurements are provided by gauges located at nearby Cow Green Reservoir and at Burnhope Reservoir, situated about 8 km north of the catchment. The nearest AWS is at Moor House in Trout Beck. A snow survey site at Greenhills Farm has snow-survey records dating from 1991.

The snow pillow at Cow Green Reservoir was installed in February 1993 (Archer and Stewart, 1995). It is comprised of a hypalon bladder, 3 m in diameter and 250 mm deep, filled with 50:50 water and antifreeze (ethyl glycol). A manometer arrangement records hourly values of snow water equivalent.

3.3 Model Database

The IH Snowmelt Database was designed to support the development and evaluation of snowmelt models and, potentially, to form the basis for a national archive of snowmelt-related data to support future snowmelt studies (Appendix A, Moore *et al.*, 1996). Modelling has been carried out using the model calibration facilities of the River Flow Forecasting System (RFFS) which previously made use of a specialised, single-platform (VAX/RdB) database. The database component of the Water Information System (WIS), a water-related GIS developed at the Institute of Hydrology in association with ICL, was chosen as the basis of the snowmelt database. Although the graphical front-end of WIS is presently tied to Sun platforms, the underlying Oracle database provides multi-platform support via SQL, with the facility to import data in standard National Transfer Format (NTF).

The snowmelt model variants and associated PDM and SDM rainfall-runoff models require data at regular 15-minute and daily intervals (in principle, other time intervals might be used), some of which may be permitted to be missing. Table 3.1 shows the data requirements of each of the snowmelt model variants. Note that potential evaporation can be in the form of a simple sine curve over the year. Clearly with each level of model complexity more data are required. A summary of data availability for the study catchments is provided in Tables 3.2 and 3.3.

Table 3.1 Data requirements of snowmelt model variants

Model variant **Data**	**Rainfall - runoff model**	**Snowmelt model with temperature excess melt equation**	**Snowmelt model with extended melt equation**	**Snowmelt model with energy-budget melt formulation**
Rainfall	✓	✓	✓	✓
Flow	✓	✓	✓	✓
Potential evaporation	✓	✓	✓	✓
Snow depth		✓	✓	✓
Snow water equivalent		✓	✓	✓
Temperature		✓	✓	✓
Wet bulb temperature				✓
Wind			✓	✓
Net radiation				✓
Incident solar				✓ (optional)
Reflected solar				✓ (optional)
Soil temperature				✓ (optional)
Soil heat flux				✓ (optional)

Table 3.2 Measurement sites for the Monachyle catchments

(a) Flow stations

River	Station	Hydrometric Ref No.	Grid Ref.	Area km^2	Record length
Monachyle Burn	Upper Monachyle	18023	NN480250	2.24	1983 - 1996
Monachyle Burn	Lower Monachyle	18017	NN475230	7.7	1983 -1996

(b) Climate stations

Station Name	Station No.	Grid Ref.	Altitude m AOD	Record length	Sensors
Tulloch Farm	IHCS/019	NN520204	135	1990 – May 1994	Standard
Lower Monachyle	IHCS/012	NN818297	300	1990 – June 1996	Upgraded
Upper Monachyle	IHCS/013	NN758328	470	1987 – June 1996	Upgraded

(c) Snow data

Site Name	Grid Ref.	Altitude m AOD	Period of record for daily snow observations
Daily snow cores			
Tulloch Farm	NN520204	135	Jan/Feb 1984
Upper Monachyle	NN481249	470	1996 – 1998
Daily snowline obs.			
Monachyle	-	-	1981, 1983 - 1997

Table 3.3 Measurement sites in the Upper Tees

(a) Flow stations

River	Station	Hydrometric Ref No.	Grid Ref.	Area km^2	Record length
Trout Beck	Moor House	025003	NY759336	11.4	1957-80, 1991-present
Harwood Beck	Harwood	025012	NY849309	25.1	1969-present

(b) Recording raingauge sites

Station Name		MO No.	Grid Ref.	Altitude m AOD	SAAR mm	Record length
Cow Green Resr. No. 1		026644	NY817291	494	1900 est	1991 - present
Logger Station						1992 - present
Moor House	(a)		NY759336	556	2009	1953-1985
	(b)	026530	NY758328	556		(1961 FMCD)
Burnhope Resr.		021230	NY850391	354	1290 est	1984- present
Logger Station		(021229)	"	354	"	1992

(c) Climate stations

Station Name	Station No.	Grid Ref.	Altitude m AOD	Start of record	Sensors
Moor House		NY758328	556	a)	Standard AWS
				b)	Upgraded AWS
Widdybank Fell		NY818297	513	1969	Manual climate station

(d) Snow survey sites

Site Name	Grid Ref.	Altitude m AOD	Period of record
Greenhills Farm	NY838320	444	1991 - present
Cow Green Reservoir	NY817291	494	1974 - 1984
Widdibank Fell	NY818297	513	1993 – 1995
Hunt Hall Farm	NY818298	368	1996 - present
Cow Green Snow Pillow	NY817298	500	1993 - present

4. MODEL EVALUATION

4.1 Introduction

The aim of this section is to evaluate the different snowmelt model variants outlined in Section 2 on the three study catchments: Monachyle Burn, Harwood Beck and Trout Beck. The snowmelt model has been used in conjunction with two rainfall-runoff models, the lumped PDM (Probability Distributed Moisture) model and the SDM (Simple Distributed Model).

Variants of the snowmelt model allow the following options to be investigated:

(i) Different numbers of elevation zones:
    Single zone
    Multiple zones
    Continuous distribution of zones
(ii) Lumped or distributed rainfall-runoff models
(iii) Different melt formulations:
    Simple temperature excess equation
    Extended melt equation
    Energy-budget approach (used with single elevation zone model only)
(iv) Partial cover curve
(v) Hourly snowpillow data or daily snow survey observations.

Prior to the full model evaluation, the snowmelt model was assessed on two catchments, Trout Beck and Monachyle Burn, to determine the effect of multiple elevation zones on flow simulation. The results of this assessment are presented in Section 4.3 and the best configuration of elevation zones is carried through to the full model evaluation (Section 4.4).

4.2 Evaluation Framework

The models are formulated in such a way that there is a choice of variable for calibration and evaluation. Firstly, the snowmelt model can be applied at a point for which snow survey, or snow pillow data are available, and performance assessed with respect to the model's ability to forecast snow water equivalent. Secondly, the model can be calibrated and assessed at the scale of the catchment with reference to its ability to forecast flow at the basin outlet. The form of objective function used in both cases is the sum of squares of errors. The main criterion used to compare model performance is the R^2 statistic, giving the proportion of the variability in the observations accounted for by the model. This formal statistic is complemented by time series plots of flow and snow water equivalent, as observed and forecast, which provide an informal visual assessment of performance.

The strategy for model calibration adopted first employs a period when snow is absent to calibrate the underlying rainfall-runoff model. Then a snow event is calibrated, fixing the rainfall-runoff parameters, and optimising the parameter of the snowmelt component of the model. The latter is done using flow and water equivalent in turn in forming the objective functions and performance is assessed in terms of both variables.

Since direct measurements of snowfall are not available, the snowpack water equivalent is reset to the observed (snow survey or snow pillow) value on occasions when it is seen to increase. This is accomplished using the updating scheme described in Section 2.9 where a point snowmelt model for the snow survey (or pillow) site is reset using the observed value and the adjustment involved transferred to each elevation zone of the catchment snowmelt model. At other times the snowmelt component is operated in "simulation mode" without updating with reference to observations. Also, the initial assessment of the catchment model component is operated in simulation mode, with no updating using observed flows at the basin outlet. This approach allows the evaluation to focus on the choice of appropriate model dynamics, without the added confusion of the effect of updating. In an operational context the snowpack would be updated with reference to all available snow observations and the rainfall-runoff model updated using observed flows. This would most likely yield a more accurate flow forecast and thus the results presented here might be regarded as conservative in terms of forecast performance.

The strategy for evaluation was restricted to the use of long continuous periods of snow activity for each of the study catchments, each period encompassing a number of snowmelt episodes. This has the advantage of allowing (i) continuous water accounting to be maintained throughout the period and (ii) calibration of a model optimised over the range of conditions experienced. It also avoids the further complication of pooling the objective function across several discrete events to obtain a single parameter set, or the disadvantage of obtaining several model parameter sets for each event calibrated separately. Use of a long period containing several snowmelt episodes avoids the danger of overfitting and lessens the need for independent validation using records not used for model calibration. The strategy was also practical since the number of snow events well-suited to model evaluation were rather restricted, particularly in the case of Monachyle Burn where only two snowy periods were available.

In view of the large number of model variants available for assessment, once the optimal number of elevation zones was determined (Section 4.3) the strategy adopted was to test all model variants on the Harwood Beck catchment, for which particularly extensive snow records are available. Then the most successful model variants were carried forward for assessment on Trout Beck and Monachyle Burn. The similarity in relief and catchment area of all three catchments means that it is reasonable to generalise about likely model performance in this way; for larger, low relief catchments it would be preferable to assess the complete set of model variants again.

4.3 Trials on Choice of Number of Elevation Zones

To determine the number of elevation zones that yields the optimal model performance, the snowmelt model used in conjunction with the PDM rainfall-runoff model has been assessed on two datasets:

(i)	Monachyle Burn	9 January to 28 February 1984 and 18 December 1995 to 28 February 1996
(ii)	Trout Beck	4 to 30 December 1993 (daily snow surveys)

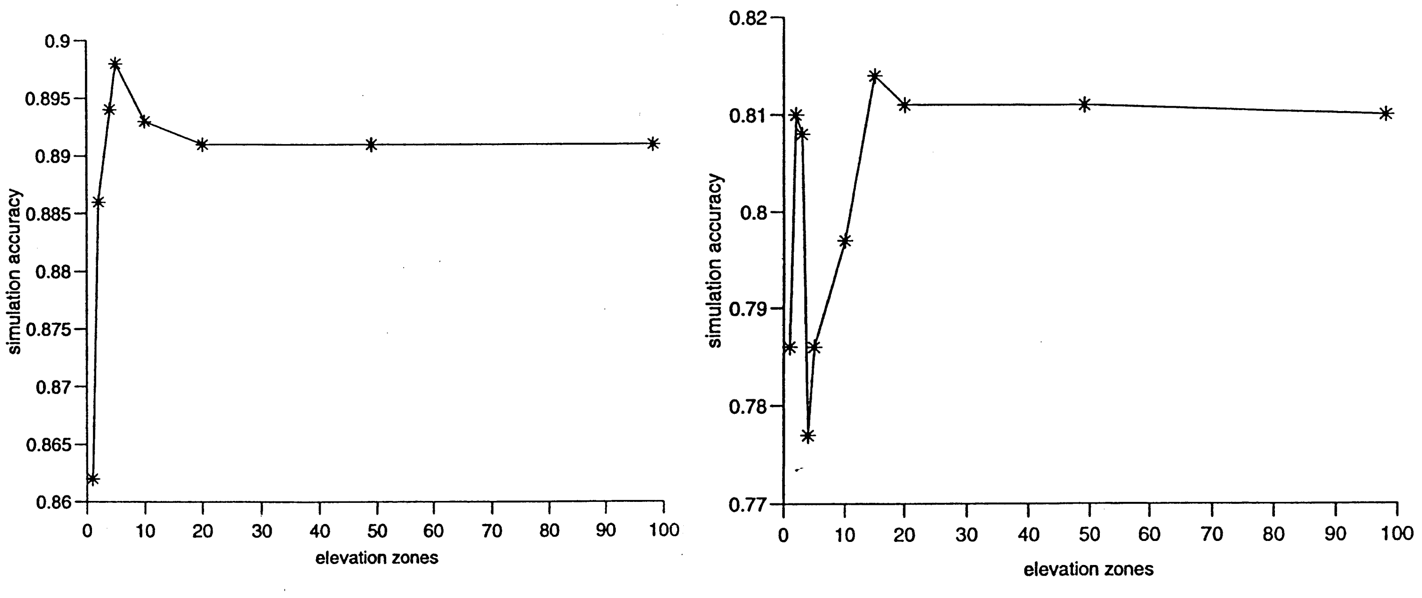
Flow measurements used for model calibration and assessment were for a 15 minute time interval, the same as the model time-step adopted here. The procedure outlined in Section 4.2 was followed for model calibration.

Use by the model of hypsometric curves, discretised to 1 metre, means that the Monachyle Burn and Trout Beck catchments are effectively split into a maximum of 590 and 304 elevation zones respectively, with the zones actually used being readily changed in number. For a smaller number of zones the data describing the hypsometric curve are aggregated to determine the proportion of the catchment that lies below each elevation zone together with the area of each zone.

Model performance has been 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.

4.3.1 Monachyle Burn

Figure 4.1 shows how simulation accuracy varies with number of elevation zones in the Monachyle catchment for the two periods, 1984 and 1995/96. The figure 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.



(a) 1984 period

(b) 1995/96 period

Figure 4.1 **Sensitivity of model performance (R^2 statistic for flow) to the number of elevation zones used: Monachyle Burn.**

The best result for the 1984 period was obtained using five elevation zones and the fluctuation in performance ceases beyond around 20 elevation zones, corresponding to an elevation band of 30 m (590/20 ≅ 30). The optimal value of the rain/snow temperature threshold, T_S, was in the range -0.1 to 1°C, fluctuating in value for smaller numbers of zones and stabilising at around 0.7°C when more than 10 zones were used. This is not inconsistent with the value of around 1°C commonly used by others.

4.3.2 Trout Beck

Figure 4.2 shows how model performance varies with number of elevation zones for the Trout Beck catchment. The highest R^2 value of 0.916 was obtained using 2 elevation zones. 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 range for a zone of 30 to 12 m.

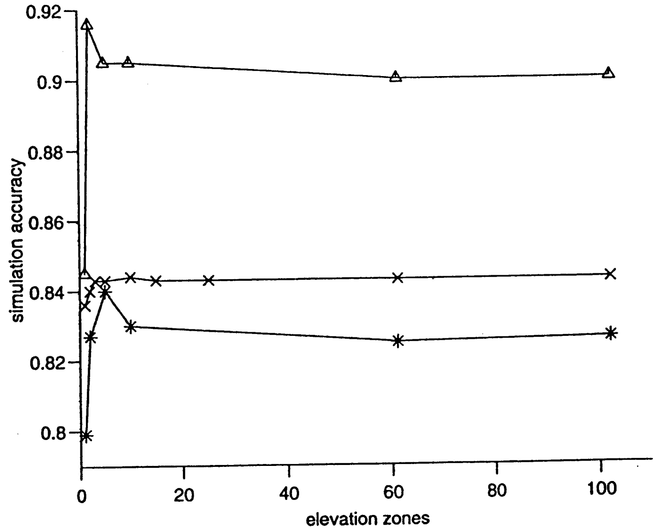


Figure 4.2 **Sensitivity of model performance (R^2 statistic for flow) to the number of elevation zones used: Trout Beck. Cross:- snow survey data with snow/rain parameter (T_s) optimised, star:- snow pillow data with snow/rain parameter (T_s) optimised, triangle:- snow pillow data with snow/rain, melt and release temperature parameters (T_s, T_m, T_c) optimised.**

4.3.3 Discussion

The model was calibrated for each choice of number of elevation zones which resulted in a slightly different set of parameters 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 for the number of elevation zones were used with the same set of model parameters (for, say, 5 elevation zones) to see how model performance was affected. The results showed that although there were slight differences in model performance, the variation in model performance with zone number remained unchanged. For example, the set of parameters calibrated for a 5 zone model when applied to a 20 zone model gave similar flow performance to that obtained from a calibrated 20 zone model. That the variation in model performance is also little affected by a change of parameter set confirms that the observed variation is not due to insufficient calibration but reflects sensitivity to zone number.

Overall the results suggest that more than one elevation zone is optimal, with performance varying 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 regions. 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 15 to 20, placing the model in the region where it is relatively insensitive to changes in the number of zones. However, for the work described here, 10 zones have been used in Monachyle Burn and Trout Beck and 15 zones in Harwood Beck; these numbers achieve good model performance while minimising computational time during model calibration and evaluation.

4.4 Model Assessment

Table 4.1 presents a summary of the hydrometric stations used for model calibration and assessment, giving the names of the stations measuring flow, rainfall, snow and climate variables, such as temperature and wind speed. Potential evaporation used in the rainfall-runoff model is approximated by a sine curve over a year with a mean value of 1.4 mm day^{-1}.

Table 4.1 Hydrometric stations used for model calibration

Catchment	Flow station	Rainfall station	Snow station altitude, m	Climate station altitude, m
Harwood Beck	Harwood	Cow Green	Greenhills Farm 444	Moor House 556
Trout Beck	Moor House	Cow Green	Widdybank Fell (1993 – 1995) 513	
		or AWS 31	Hunt Hall Farm (1996 – present) 368	Moor House 556
Monachyle Burn	Lower Monachyle	Upper Monachyle AWS	Tulloch Farm (1994) 135 Lower Monachyle (1996) 470	Upper Monachyle 470

Following initial trials on the choice of number of elevation zones to use (Section 4.3), the model assessment described here aims to establish the benefit of using each of the following model variants:

(i) Lumped or distributed rainfall-runoff model
(ii) Different melt formulations:
    Simple temperature excess equation
    Extended melt equation
    Energy-budget approach (used with single zone model only)
(iii) Partial cover curve
(iv) Hourly snowpillow data or daily snow survey observations.

As mentioned in Section 4.2, the strategy adopted was to test all model variants on the Harwood Beck catchment, for which particularly extensive snow records are available. The most promising model variants were then carried forward for assessment on the Trout Beck and Monachyle Burn catchments. Detailed model results now follow for each catchment.

4.4.1 Harwood Beck

Tables 4.2 to 4.4 present the assessment of model performance in terms of the R^2 statistic for flow and snow water equivalent for a number of model variants. Different parameters sets exist depending on whether flow or snow water equivalent has been used in forming the objective function to be minimised. The rainfall-runoff models were calibrated on the snow-free period 1 October 1992 to 1 January 1993. Once an optimal set of parameters was obtained, the snowmelt module was introduced and the overall model applied to the snowy period 1 January to 6 March 1994 in order to calibrate the snowmelt module parameters using the water equivalent and flow objective functions in turn. Four snowy periods have been used for independent model evaluation on the previously calibrated models. These are:

(i) 1 January – 1 February 1993
(ii) 27 December 1994 – 6 February 1995
(iii) 27 December 1994 – 30 January 1995
(iv) 2 December 1997 – 6 March 1998.

The second of these periods includes an isolated flow peak of 63 m^3s^{-1} on 31 January 1995. This peak is one of the largest recorded flows in the catchment, with a return period of around 40 years. This flood peak was caused in part by melting snow and has proved particularly difficult to simulate. Because of the limited number of snowy periods available for modelling, and the fact that this peak overshadows smaller flow peaks caused by melting snow, the winter period has been used twice, excluding and including the high flow peak.

Table 4.2 compares model results in terms of the R^2 statistic obtained using two different rainfall-runoff models, the 'lumped' PDM (Probability Distributed Moisture) model and the SDM (Simple Distributed Model) for the calibration period 1 January 1994 to 6 March 1994. The results suggest that when both models are calibrated to give the best possible results for flow simulation, the PDM generally performs slightly better than the SDM except when the snowmelt component of the flow is ignored. Based on this set of results, and the better computational efficiency of the 'lumped' PDM model formulation, the latter has been used in preference to the SDM. The distributed nature of the SDM is likely to be of greater benefit for larger catchments where spatial and topological effects on runoff production become more important (Moore *et al.*, 1994, Bell and Moore, 1998a,b).

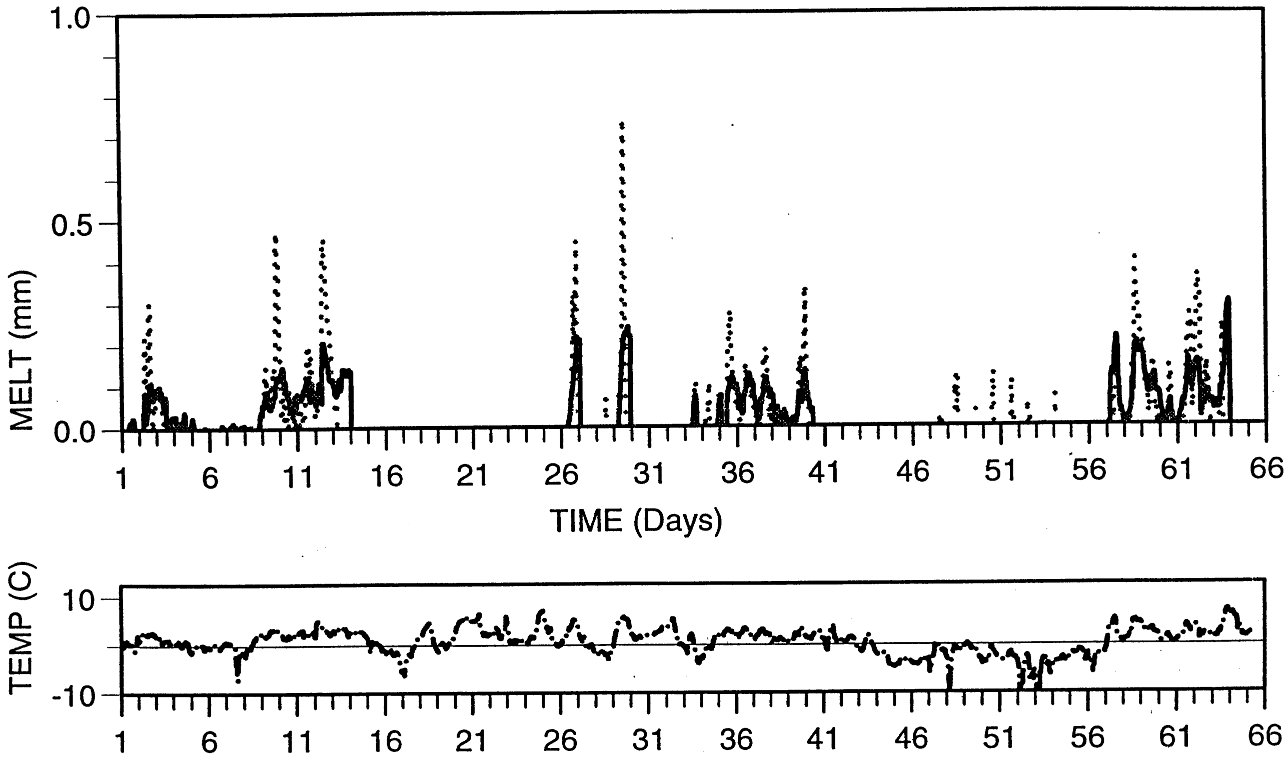
Both the simple temperature excess melt formulation and the extended melt equation are evaluated in Table 4.2. Results suggest that there is some slight benefit to be gained by the use of the extended melt formulation, equation (14), which introduces the effect of wind and rain on snowmelt. Figure 4.3 compares simulated melt (mm/15 minute time-step) from these two melt formulations alongside the melt obtained using the energy-budget. Figure 4.3(a) shows a time series of melt from the simple temperature excess melt formulation alongside the energy-budget approach. The time-series illustrate the dependence of the temperature excess melt on air temperature, which is displayed below, and shows how the magnitude of the melt is often 50% below that obtained using the energy-budget melt formulation, and sometimes misses the melt 'peaks' altogether (for example days 39 and days 47 to 54). When the effect of rain and wind is introduced in Figure 4.3(b) the melt is increased dramatically, often leading to a higher melt rate than that obtained from the energy formulation. The melt 'peak' of day 39 is similar to that obtained from the energy-budget method, though there are large differences in melt simulation in the first ten days of the calibration period.

Table 4.2 Assessment of model performance using temperature excess and extended melt formulations with lumped (PDM) or distributed (SDM) rainfall-runoff models; calibration period 1 January to 6 March 1994

		PDM		SDM	
Melt formulation	**Objective function**	**Flow R^2**	**W.E. R^2**	**Flow R^2**	**W.E. R^2**
Snow ignored	Flow	0.528	-	**0.549**	-
Snow included + temperature excess	W.E.	-	0.995	-	0.998
Snow included + temperature excess	Flow	**0.668**	0.973	0.652	0.820
Temperature excess + rain	Flow	**0.714**	0.951	0.700	0.956
Temperature excess + wind	Flow	**0.670**	0.967	0.653	0.803
Temperature excess + rain and wind	Flow	**0.714**	0.951	0.700	0.958

The partial cover curve, introduced in Section 2.5, is used to reduce the effective area of a shallow snow pack to reflect patchy snow cover conditions. As a consequence of using this function, any rain falling on the part of the catchment that is free from snow is immediately available for input to the rainfall-runoff model without passing through the wet snow store, leading to a more rapid runoff response. Initial investigations into its use with a 15 elevation zone model suggested that there was little to be gained through its use. However, further work summarised in Table 4.3 suggested that the use of the partial cover curve could improve flow performance for a model with one elevation zone, with its beneficial effect decreasing with increasing number of elevation zones. This result is not surprising since the use of multiple elevation zones allows for the possibility that lower parts of the catchment will be subject to warmer temperatures, and will be more likely to be free from snow cover. These results suggest that use of a partial cover curve is only likely to be of benefit for models configured to use a small number of elevation zones. More generally, a partial cover curve may be of value where partial cover conditions can predominate and are not adequately represented by elevation zoning, as might be the case for lowland catchments.

(a) Simple temperature excess (bold line) and energy-budget (dotted line) melt



(b) Extended melt equation (bold line) and energy-budget (dotted line) melt

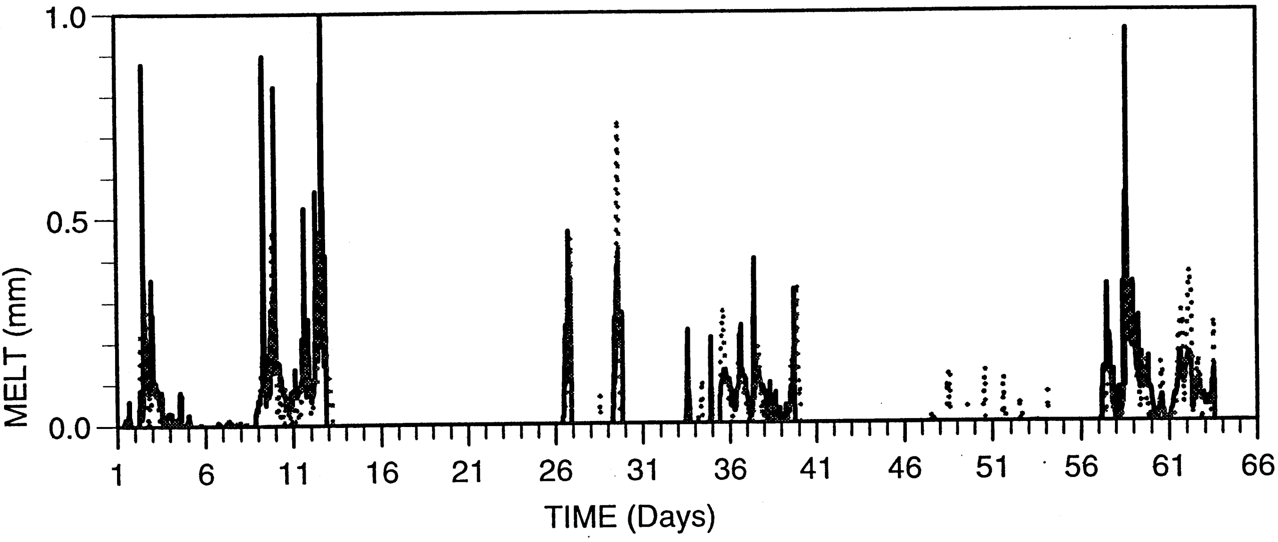


Figure 4.3 **Comparison of simulated melt from the snowmelt model using different melt formulations.**

Table 4.3 **Assessment of model performance incorporating partial cover curve and using different numbers of (PDM) elevation zones for lumped and distributed (SDM) rainfall-runoff models; calibration period 1 January to 6 March 1994**

	PDM		SDM	
Elevation zones	**Full cover**	**Partial cover**	**Full cover**	**Partial cover**
1	0.625	0.637	0.661	0.673
5	0.712	0.713	0.646	0.653
9	0.712	0.713	0.700	0.701
15	0.714	0.714	-	-

Building on these exploratory results, Table 4.4 presents the main snowmelt model evaluation in terms of the R^2 statistic for flow and snow water equivalent. Four snowy periods not used in model calibration are simulated using the snowmelt model coupled with the PDM rainfall-runoff model. Two forms of the snowmelt model are evaluated. The left hand side of Table 4.4 presents results obtained using the extended melt equation with 15 elevation zones, while the right hand side displays results obtained using the energy-budget melt formulation and representation of the catchment by a single elevation zone (multiple zones are not available for use with the energy-budget melt formulation). For each period the model is evaluated in three ways:

(i) ignoring the presence of snow with no additional calibration (PDM only).
(ii) including snow observations, using parameters obtained by calibration from the January 1994 period with no additional calibration; and
(iii) including snow observations and recalibrating to achieve the best possible flow result for that period.

In the third way of evaluation, the optimal model performance achieved using recalibration provides a benchmark against which evaluation (ii) can be compared. This may be used to determine how robust the snowmelt parameter set is when applied to different events.

Table 4.4 **Model performance with extended melt and energy-budget melt formulations using PDM rainfall-runoff model and snow survey measurements: Harwood Beck**

		Extended melt		**Energy-budget**	
Period	**Model**	**Flow R^2**	**W.E. R^2**	**Flow R^2**	**W.E. R^2**
Calibration					
1 Jan- 6 Mar 1994	Snow ignored	0.528	-	0.528	-
	Flow calibration	0.714	0.951	0.640	0.978
Assessment					
1 Jan – 1 Feb 1993	Snow ignored	0.362	-	0.362	-
	Snow included	0.440	0.900	**0.543**	0.737
	and recalibrate	0.528	0.789	**0.614**	0.686
27 Dec 1994 – 6 Feb 1995	Snow ignored	-0.072	-	-0.072	-
	Snow included	0.054	0.414	**0.228**	0.424
	and recalibrate	**0.935**	0.762	0.786	0.263
27 Dec 1994 – 30 Jan 1995	Snow ignored	0.350	-	0.350	-
	Snow included	0.581	0.414	**0.619**	0.424
	and recalibrate	0.705	0.808	**0.709**	0.739
2 Dec 1997 – 6 Mar 1998	Snow ignored	0.663	-	0.663	-
	Snow included	**0.751**	1.0	0.742	0.999
	and recalibrate	0.776	1.0	-	-

Table 4.5 **Model performance with extended melt and energy-budget melt formulations using PDM rainfall-runoff model and snow pillow measurements: Harwood Beck**

		Extended melt		**Energy-budget**	
Event	**Obj. Function**	**Flow R^2**	**W.E. R^2**	**Flow R^2**	**W.E R^2**
Calibration					
1 Jan- 6 Mar 1994	W.E.	-4.75	0.903	0.031	0.903
	Flow	**0.546**	0.758	0.518	0.770
Assessment					
27 Dec 1994 – 6 Feb 1995	No recalibration	-0.037	0.774	-0.074	0.850
	Flow	**0.066**	0.849	-0.008	-

Overall, Table 4.4 reveals that for the events tested, the snowmelt model

- always improves on flow results obtained using a rainfall-runoff model without a snowmelt model component;
- is often improved through the use of a full energy-budget melt formulation; and
- has a robust parameter set which gives reasonable results when applied to different periods of snowmelt.

The use of hourly snow pillow measurements of snow water equivalent in place of daily snow core readings taken by an observer is assessed in Table 4.5. For the two snowy periods modelled in Harwood Beck, it is seen that the daily snow cores provide superior measurements of snow water equivalent for modelling purposes.

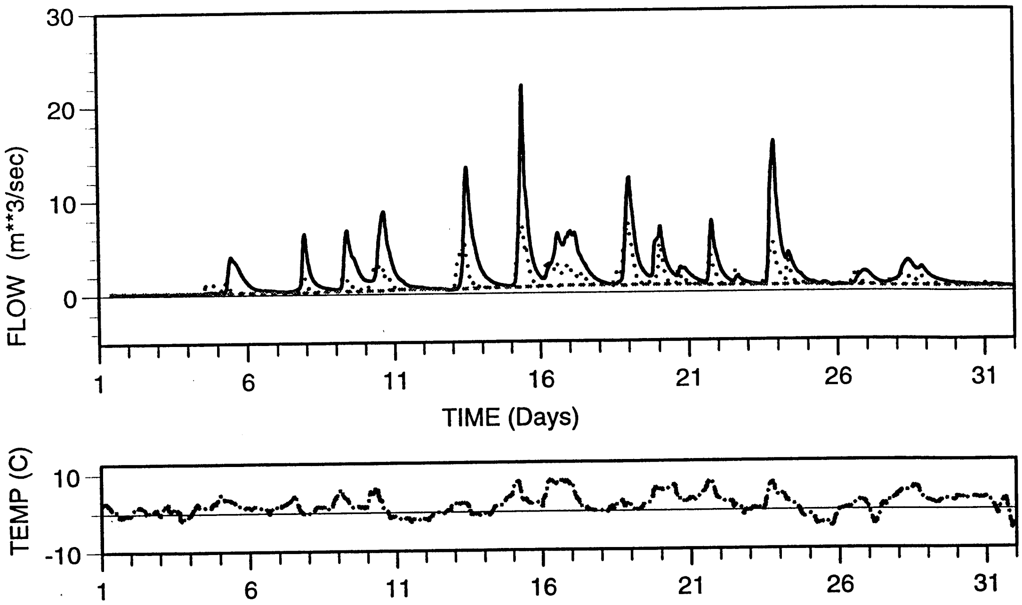
Whilst the tabulated results in terms of R^2 provide a quantitative overview of model performance, a more qualitative discussion of model performance on each snowmelt period now follows based on time-series plots of observed and predicted quantities.

1 January to 1 February 1993

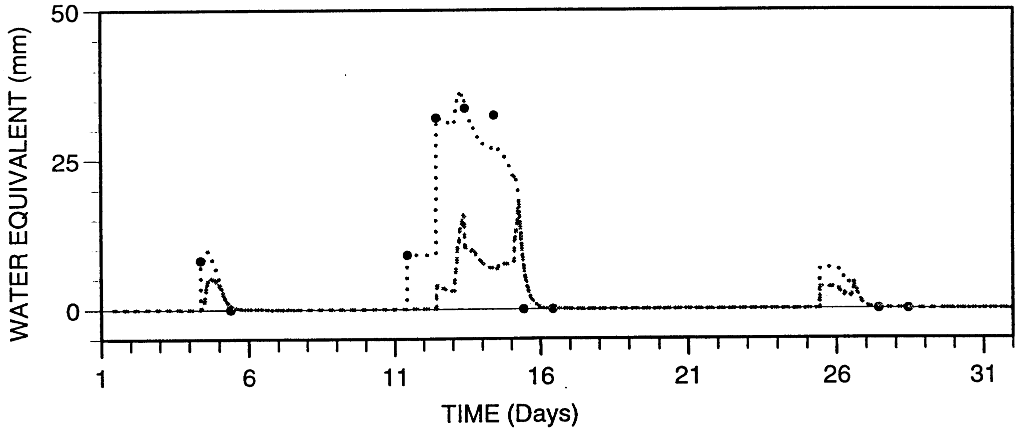
Figure 4.4 presents time-series plots for this period, showing flow hydrographs for the PDM (no snowmelt model component), the single zone model with energy-budget melt formulation, and the 15 zone model with an extended melt equation. Time-series of snow water equivalent and energy flux (Wm^{-2}) are also displayed. The snow observer measured lying snow at Greenhills Farm on seven days. The main period of lying snow was 11-14 January, when snow water equivalent reached a maximum of 34 mm. The snow melted when the air temperature increased on 14 January and combined with rainfall to give a flow peak of 22 m^3s^{-1}.

Figure 4.4(a) shows the flow hydrograph obtained using the PDM rainfall-runoff model, omitting the effect of snowmelt. The hydrograph reveals that the main flow peak of 22 m^3s^{-1} is underestimated by the model, which predicts a value of 7 m^3s^{-1}. Figure 4.4(b) shows the observed and simulated snow water equivalent, and Figures 4.4(c) and (d) show the flow hydrographs obtained using the snowmelt model with the extended melt equation and the energy-budget melt formulation respectively. These two hydrographs, which were obtained without model calibration over the period, show that the inclusion of a snowmelt model formulation improves simulation of the flow peak, which is estimated to be 19 and 24 m^3s^{-1} by the energy-budget and extended melt equation formulations respectively. The improvement in R^2 gained through the use of an energy-budget formulation appears to be due mainly to the model simulating the timing of the falling limb of the flow peak more accurately. Figure 4.4(e) shows the components of the energy-budget melt formulation in January, and reveals that the dominant processes influencing melt are sensible heat transfer and the latent heat of condensation. These two components increase on 15 January, and again on 17-18 January partly in response to an increase in air temperature on those days. Figure 4.4(f) compares the potential melt rates of the energy-budget and the extended melt formulation which are seen to be very similar, though the extended melt formulation yields a higher melt total on day 13. Both formulations result in similar quantities of melt on 15 January, which yielded a measured flow peak of 23 m^3s^{-1}; the energy-budget yielded a modelled melt rate of 48 mm d^{-1}, while the extended temperature index melt formulation resulted in a melt rate of 125 mm d^{-1} and a larger modelled flow peak of 24 m^3s^{-1}.

(a) Flow: snow ignored



(b) Snow water equivalent: extended melt equation



(c) Flow: extended melt equation

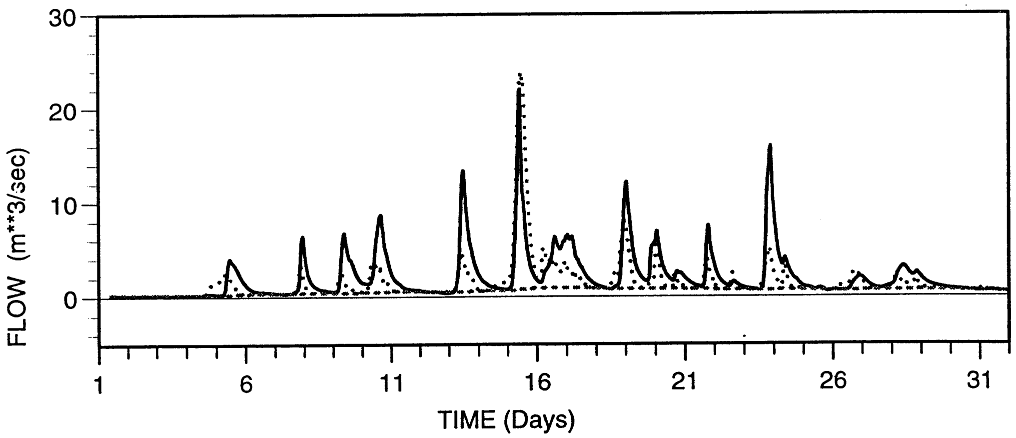
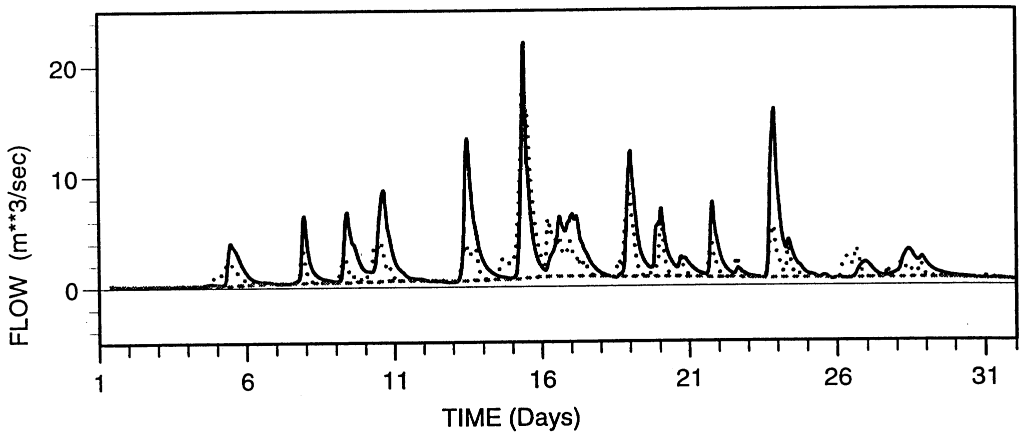
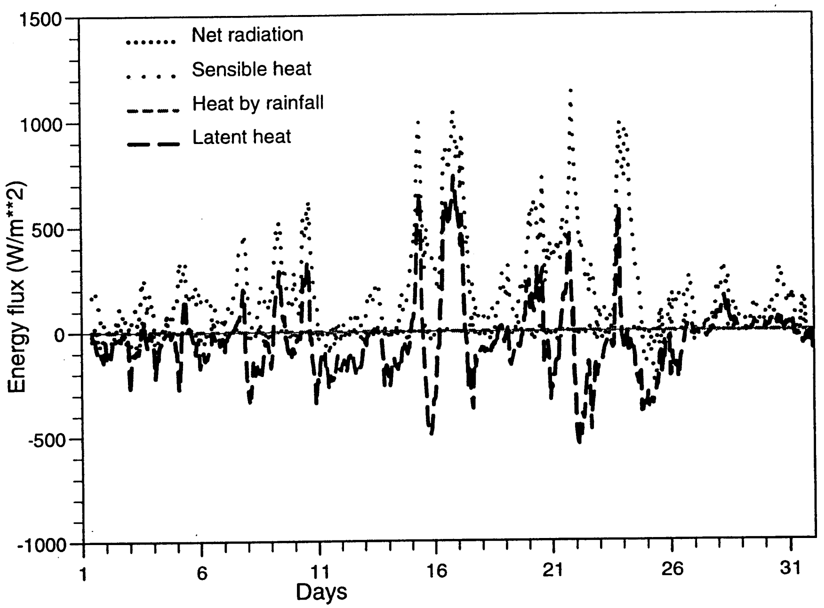


Figure 4.4 Time-series of flow and water equivalent: Harwood Beck. Snow water equivalent:- measured: large dots, predicted total snow: dotted line, predicted wet snow: dashed line. Flow:- observed flow: bold line, predicted total flow: dotted line, predicted baseflow: dashed line.

(d) Flow: energy-budget melt formulation



(e) Components of the energy-budget



(f) Comparison of melt from the extended melt equation (bold line) and energy-budget melt formulation (dotted line).

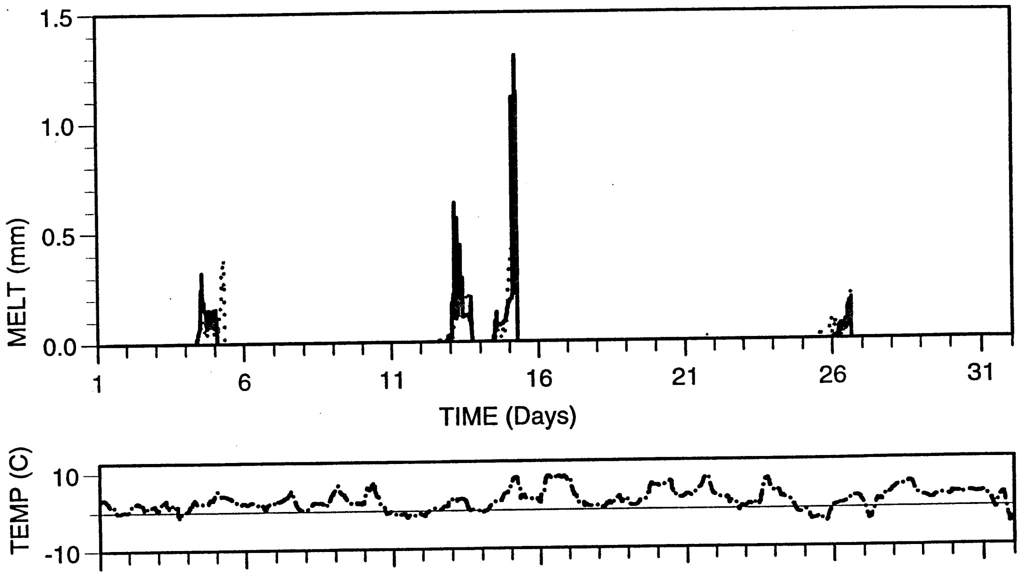


Figure 4.4 (cont...) Time-series of flow and water equivalent: Harwood Beck.

27 December 1994 to 6 February 1995

On 31 January 1995 a flow peak of 64 m^3s^{-1} was recorded for Harwood Beck. This flow is one of the highest recorded in the catchment, with an estimated return period of approximately 40 years. Lying snow was recorded at Greenhills Farm between 31 December 1994 and 5 January and 16–31 January 1995. The most significant melt periods were 23–25 January, when temperatures rose to around 2°C, and 26–31 January when temperatures varied but peaked at 7°C. When snow was not taken into account, the PDM model R^2 was negative (-0.07), and flow peaks after 20 January were not simulated, suggesting that they are due primarily to melting snow. Including snow yielded a slight improvement in R^2; the model performed better on the small peaks after 20 January, but the 63 m^3s^{-1} peak was poorly simulated. The snowmelt model using temperature excess melt simulated this peak as 2 m^3s^{-1} whilst using energy-budget melt performance was slightly better with a simulated peak of 10 m^3s^{-1}. Both models were improved significantly after further calibration over the period of record. However, the R^2 of 0.935 obtained using the temperature excess melt formulation required a very high melt factor, f, of 90 $mm^{-1}\ day^{-1}{}^{o}C^{-1}$ (a typical value is 4). Similarly, reasonable results were achieved using the energy-budget melt formulation, but only by using an unusually high roughness length, Z_0, of 0.28 m as opposed to the more usual 0.03 m. It is possible that underestimation of rainfall and sleet during the main melt period is the principal cause of the poor model simulation.

Table 4.5 presents the snowmelt model results obtained using hourly snow pillow measurements in place of daily snow survey observations. When compared to Table 4.4, which shows model performance using snow survey observations, it is apparent that model performance is worsened by the use of snow pillow data. For the calibration period 1 January to 6 March 1994 the best R^2 of 0.714 is obtained using daily snow core observations whilst the use of snow pillow data results in an R^2 of 0.546. The main reasons for the difference in performance appear to be the preferential rate of melt from the pillow causing some peaks to occur too soon, and an underestimation in measured water equivalent from the snow pillow compared to snow core measurements, which affects some days more than others. Similar results are obtained for the period 27 December 1994 to 6 February 1994 and the change from snow core to snow pillow observations did not improve simulation of the high flow peak on 31 January 1995.

27 December 1994 – 30 January 1995

Excluding the 64 m^3s^{-1} flow peak, the snowmelt model variants perform reasonably well over this period. Without taking snow into account, the PDM model R^2 is only 0.35; when snow is included in the formulation R^2 improves to 0.62 (energy-budget melt) and 0.58 (extended melt equation). Calibration over this period reveals that an R^2 of 0.71 is the best that can be obtained, suggesting that while there may be some room for improvement in the model calibration, the parameter set used for both model variants is reasonably robust.

2 December 1997 to 6 March 1998

Snow was absent for much of this period, with lying snow recorded for only 18 days. All but four of the snow observations were only available as depth measurements rather than snow water equivalent. Meltwater contributed to the flow peaks on 6 December, 5 and 7 January (35 m^3s^{-1}) and 3 March. Taking snowmelt into account improved the overall R^2 from 0.66 to

0.75 (temperature excess melt formulation) and 0.74 (energy-budget). Without the snowmelt component, the PDM underestimated the observed 35 m^3s^{-1} flow peak on 7 January as 15 m^3s^{-1}. When the snowmelt component was incorporated the estimates rose to 22 m^3s^{-1} (temperature excess melt) and 19 m^3s^{-1} (energy-budget melt). The high R^2 values for the water equivalent in Table 4.4 are due to only two values of non-increasing water equivalent being incorporated into the performance statistic.

4.4.2 Trout Beck

The snowmelt model evaluation for Harwood Beck indicated that the most promising model variants were the PDM 'lumped' rainfall-runoff model with either multiple elevation zones and an extended melt equation, or the energy-budget melt formulation (available only for use with a single elevation zone). These model variants have therefore been carried forward for evaluation on Trout Beck at Moor House, located approximately 3 km to the west of Harwood Beck and having an area of 11.4 km^2. In addition to the raingauge at Cow Green Reservoir, AWS 31 is situated within the catchment boundary and provides hourly rainfall data. Daily snow cores were taken at Widdybank Fell, approximately 6 km south east of the catchment, until December 1995 when the station closed. Since then, an observer has taken daily readings at Hunt Hall Farm, situated 10 km south-east of Trout Beck.

Table 4.6 shows calibration and assessment results for Trout Beck using the PDM and a snowmelt component incorporating the extended melt equation or the energy-budget melt formulation. Best results are highlighted in a bold typeface. The period 1 January to 6 March 1994 has been used for calibration of the snowmelt model parameters, and snow core measurements from Widdybank Fell have also been used. Four additional periods affected by snow have been used to assess model performance. These are:

(i) 4 December - 30 December 1993
(ii) 1 March – 15 April 1995
(iii) 26 February – 16 April 1996
(iv) 18 November 1996 – 6 February 1997.

For the first two periods snow core data are from the Widdybank Fell site, whilst for the last two periods, data are from Hunt Hall Farm. Because of the change in location of the snow survey site the snowmelt component was recalibrated for periods (iii) and (iv).

Overall the results show an improvement in flow simulation with the use of a snowmelt component, compared to results obtained using a rainfall-runoff model alone. Figures 4.5 and 4.6 present time-series plots obtained for the first two periods respectively. The modelled flow hydrograph shown in Figure 4.5(a), which takes no account of snow, is clearly poor, giving an R^2 of 0.216. This result is improved with the use of a snowmelt component (Figure 4.5(b)) when R^2 increases to 0.409 using the energy-budget melt formulation and to 0.531 using the extended melt equation. After recalibration, the best flow simulation is obtained using the energy-budget formulation, with an R^2 of 0.675. When the snowmelt component is not used, the PDM is unable to simulate the flow peak on day 11, and overestimates the peak on day 17. The temperature excess formulation improves simulation of the day 11 flow peak (8 m^3s^{-1}), estimating the peak at 4.5 m^3s^{-1}, and reduces the overestimation of the 3.5 m^3s^{-1}

Table 4.6 Model performance using the extended melt and energy-budget melt formulations with the PDM rainfall-runoff model: Trout Beck

		Extended melt		**Energy-budget**	
Period	**Model**	**Flow R^2**	**W.E. R^2**	**Flow R^2**	**W.E. R^2**
(a) Widdybank Fell snow survey site					
Calibration					
1 Jan 1994 – 6 Mar 1994	Snow ignored	0.250	-	0.250	-
	Snow included				
	Flow calibration	**0.589**	0.919	0.560	**0.939**
	W.E. calibration	0.262	0.946	**0.540**	**0.950**
Assessment					
4 Dec 1993 – 30 Dec 1993	Snow ignored	0.398	-	0.398	-
	Snow included	0.559	0.954	**0.656**	**0.994**
	and recalibrate	0.737	**0.997**	**0.911**	0.982
1 Mar 1995 – 15 Apr 1995	Snow ignored	0.216	-	0.216	-
	Snow included	**0.531**	-0.476	0.409	**0.238**
	and recalibrate	0.672	-0.587	**0.675**	**0.035**
(b) Hunt Hall Farm snow survey site					
Assessment					
18 Nov 1996 – 6 Feb 1997	Snow ignored	0.356	-	0.356	
	Snow included	-	-	-	-
	and recalibrate	0.637	0.535	**0.679**	**0.766**
Recalibration					
26 Feb 1996 – 16 Apr 1996	Snow ignored	-0.449	-	-0.449	-
	Snow included	-9.999	**-1.084**	-9.999	-3.501
	and recalibrate	0.241	-0.024	-	-

peak on day 17 from 8 to 7 m^3s^{-1}. Further calibration achieves a near-perfect simulation of the peak (Figure 4.5(c)). Figure 4.6 presents a similar set of time-series plots for the period 4 December to 30 December 1993. The hydrograph obtained using the PDM with no snowmelt model component (R^2 = 0.398) is shown in Figure 4.6(a), and the flow result achieved using the energy-budget melt formulation (R^2 = 0.656) is shown in Figure 4.6(b). The corresponding components of the energy-budget are presented in Figure 4.6(c), which shows the increase in sensible heat and latent heat of condensation over the main melt period (days 14 to 17).

To take account of the move of the snow survey site to Hunt Hall Farm from January 1996 onwards, the snowmelt component was recalibrated. Recalibration was undertaken over the period 18 November 1996 to 6 February 1997: the resulting R^2 was over 0.6 for both types of melt formulation. The period 26 February to 16 April 1996 used for assessment should have provided a good test of the snowmelt component as almost all the flow peaks were predominantly due to melting snow. However, as the results in Table 4.6 suggest the period proved very difficult to model, with negative values of R^2 except when using the extended melt equation after recalibration. This is partly because there were no water equivalent measurements over the main melt period (1–6 April 1996, days 36 to 41 on the hydrographs), only depth measurements, and partly because the flow was very low over this period. During this period melt occurred primarily in response to diurnal temperature fluctuations causing an almost oscillatory flow hydrograph.

Table 4.7 compares flow simulation results for Trout Beck obtained using the Cow Green raingauge (elevation 494 m) and the Moor House AWS raingauge (elevation 556 m) for a mixture of snowy and snow-free periods. The PDM was calibrated on the snow-free period 1 October to 31 December 1991 and then the parameters used to evaluate model performance for two other snow-free events. These results show that flow simulation during snow-free events is significantly improved in Trout Beck by using hourly rainfall data from the Moor House AWS as opposed to the Cow Green raingauge, which is 50 km away, and at a much lower elevation. However, when snow is present in the catchment, the situation is reversed and superior flow simulation results are obtained using the Cow Green raingauge. Figures 4.7(a) and (b) present the modelled flow hydrographs obtained using rainfall from AWS 31 and the Cow Green raingauge. The time-series plots show an overestimation in the hydrograph when AWS 31 rainfall is used as input to the snowmelt model. This overestimation is probably caused by snow collecting in the raingauge funnel and melting when the air temperature increases or when rain falls. Hence snow may be being input into the model twice, from both snow survey observations and raingauge catches. Figure 4.7(c) presents the flow hydrograph obtained using AWS 31 raingauge values alone, and shows a slight improvement in flow simulation. The spurious peak on day 13 is no longer apparent, and the overestimation in other peaks is not so pronounced as when snow survey data were incorporated, but the overall model fit is still very poor ($R^2 = -5.8$).

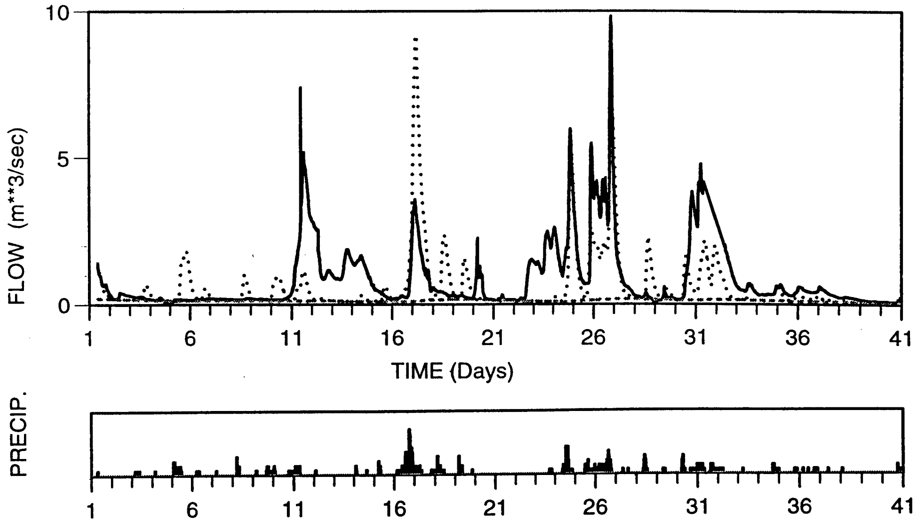
The AWS 31 raingauge, therefore, does not seem to be an adequate substitute for snow survey measurements taken by an observer. The raingauge catch may be affected by drifting snow which will inflate the quantity of melt measured by the gauge. Also the snow in the gauge will not generally melt at the same time and rate as the snow pack on the surrounding ground.

These results suggest that using the Cow Green raingauge which is situated at a distance from the catchment and at a lower altitude, together with snow survey measurements, can provide superior flow forecasting capability during snowy events than the AWS 31 gauge inside the catchment. Clearly a raingauge situated at a significantly lower altitude will not provide as good rainfall estimates as a raingauge placed in the catchment, but during snow and freezing conditions it is less likely to be blocked with snow.

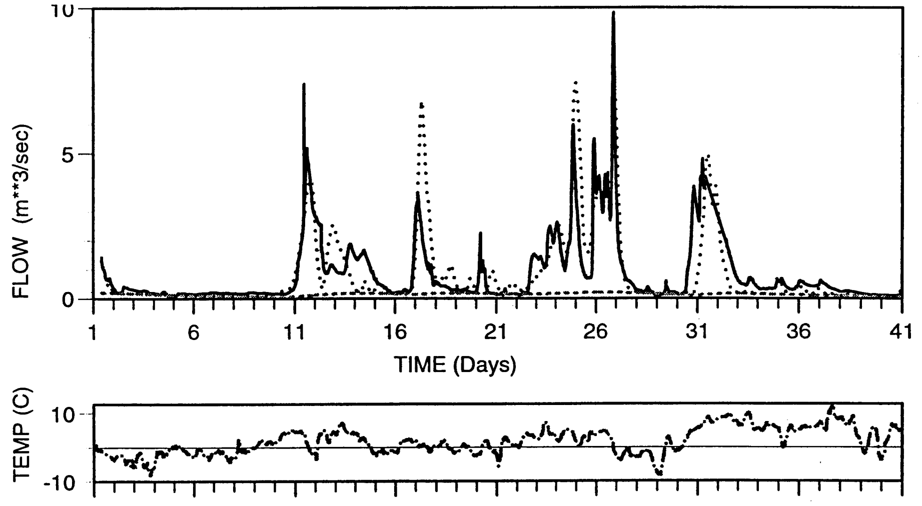
Table 4.7 **Model performance (R^2) using Cow Green raingauge (494 m) and Moor House AWS raingauge (556 m) as alternative rainfall inputs: Trout Beck**

Period	Model	Cow Green raingauge Flow R^2	Cow Green raingauge W.E. R^2	Moor House raingauge Flow R^2	Moor House raingauge W.E R^2
Snow-free periods					
1 Oct 1991 – 31 Dec 1991	PDM	0.687	-	**0.839**	-
1 Jul 1992 – 1 Oct 1992	PDM	0.540	-	**0.763**	-
1 Apr 1997 – 30 Jun 1997	PDM	0.564	-	**0.622**	-
Snow-present periods					
4 Dec 1993 – 30 Dec 1993	Snow ignored	**0.398**	-	-3.001	-
	Snow included	**0.559**	0.954	0.415	0.999
	and recalibration	**0.737**	0.997	0.479	0.961
1 Mar 1995 – 15 Apr 1995	Snow ignored	**0.216**	-	-5.815	-
	Snow included	**0.531**	-0.476	-7.593	0.767
	and recalibrated	**0.672**	-0.587	-5.514	-

(a) Flow hydrograph: no snowmelt component



(b) Flow hydrograph: snowmelt model with extended melt formulation



(c) Flow hydrograph: extended melt equation and recalibration

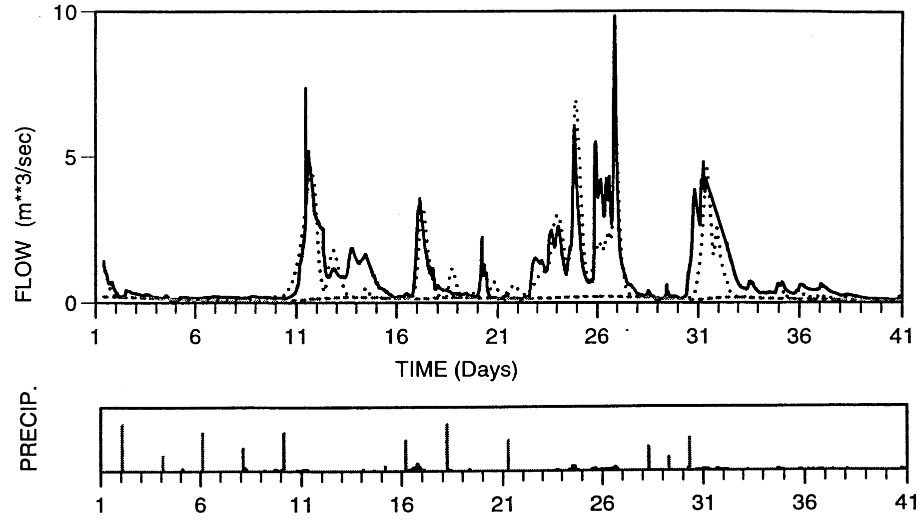
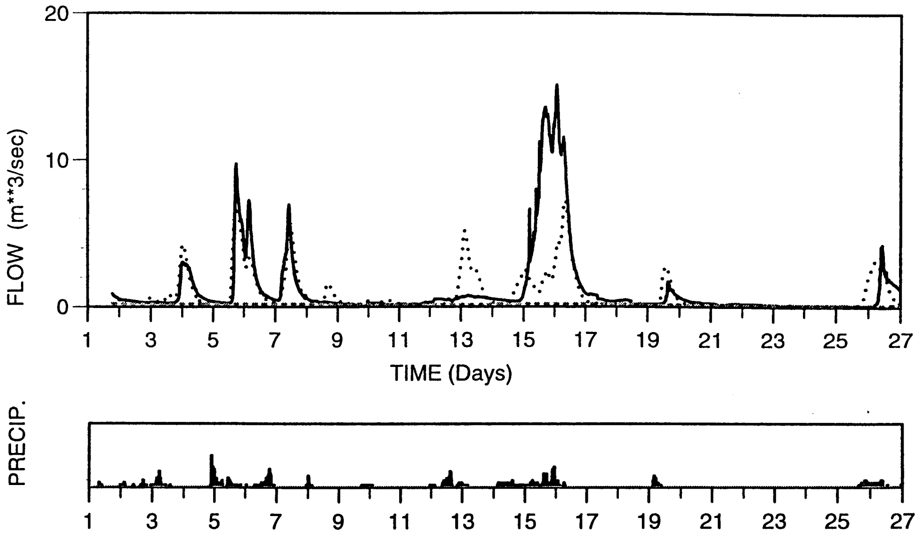
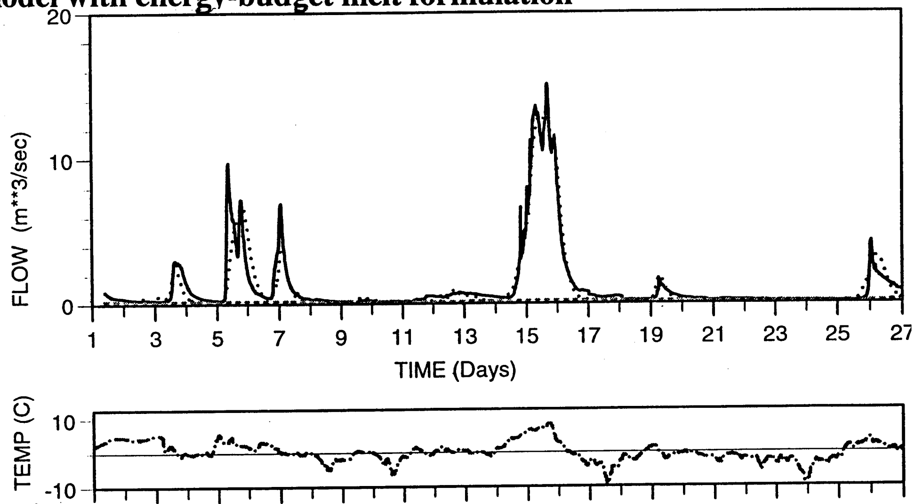


Figure 4.5 **Flow hydrographs for Trout Beck obtained using different model variants. Observed flow: bold line, predicted total flow: dotted line.**

(a) Flow hydrograph: no snowmelt component



(b) Flow hydrograph: snowmelt model with energy-budget melt formulation



(c) Components of the energy-budget

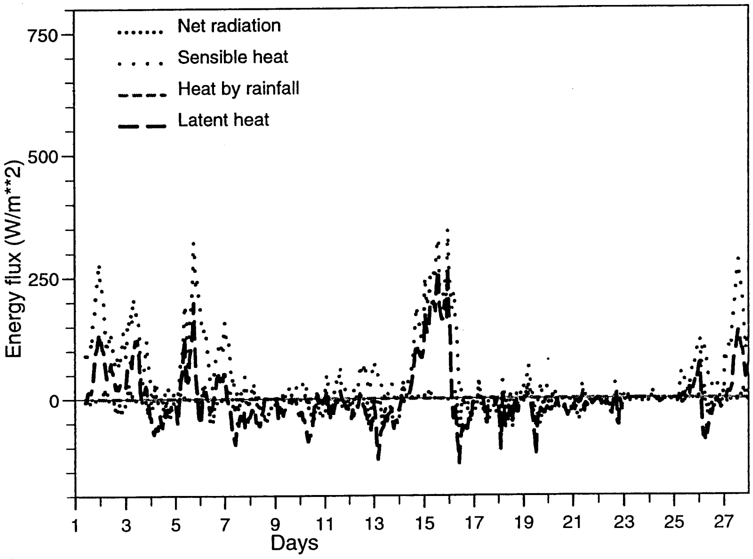
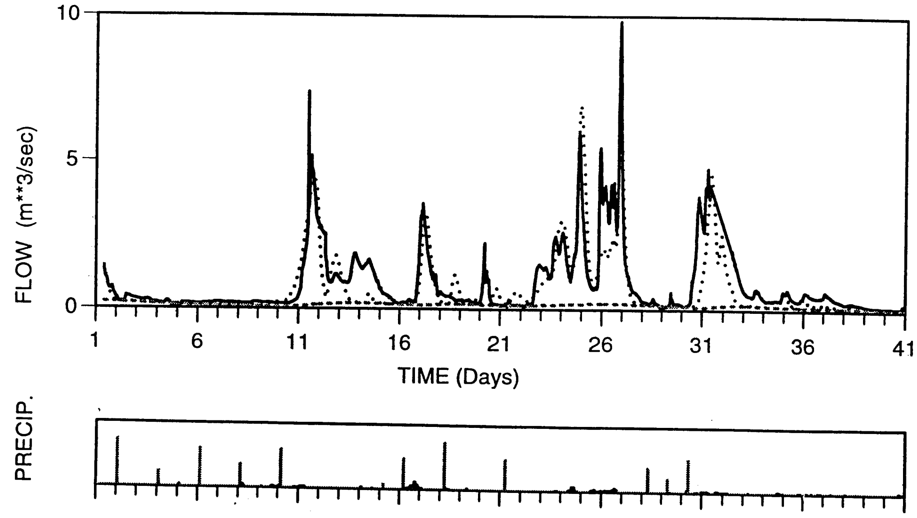
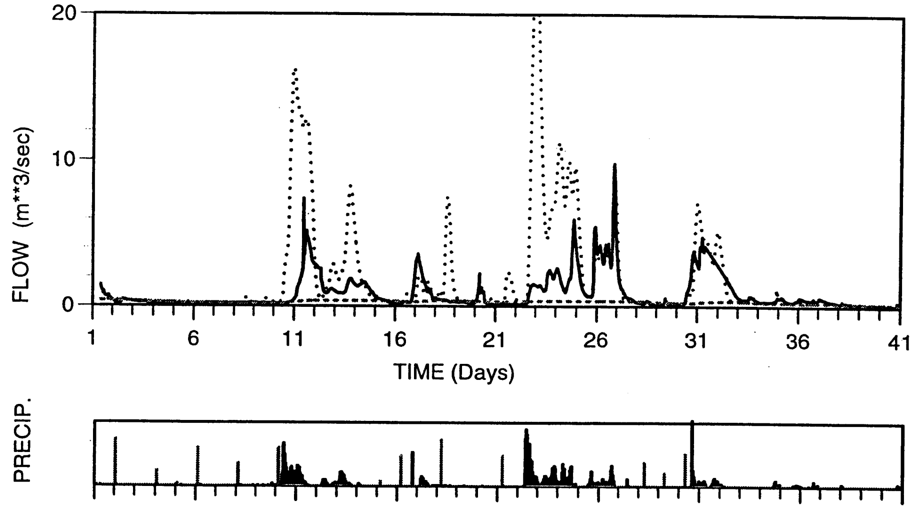


Figure 4.6 Time-series of flow and energy-budget melt components: Trout Beck Observed flow: bold line, predicted total flow: dotted line.

(a) Cow Green raingauge



(b) AWS 31 raingauge



(c) AWS 31 raingauge and no snow survey data

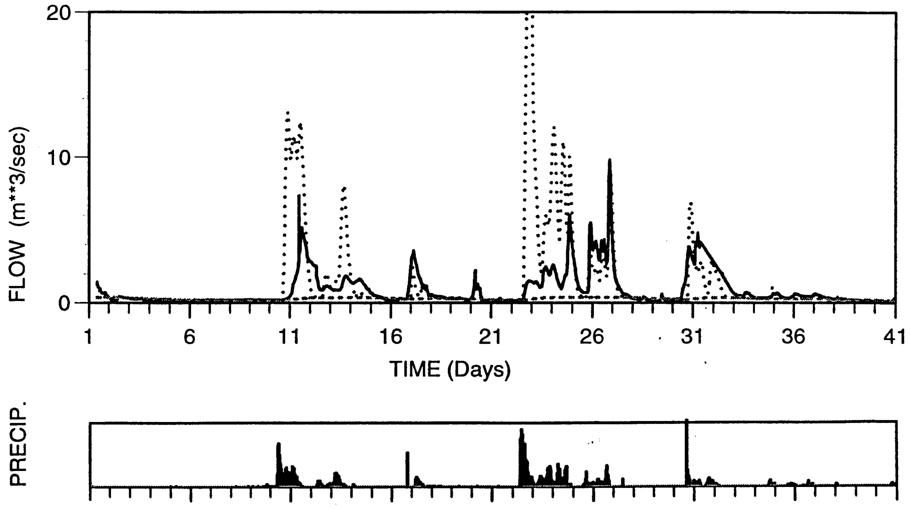


Figure 4.7 **Comparison of flow hydrographs obtained using rainfall from different raingauges as model input: Trout Beck. Observed flow: bold line, predicted total flow: dotted line.**

4.4.3 Monachyle Burn

Although a special field monitoring programme has been in place in the Monachyle Burn catchment from winter 1995 to spring 1998, very little daily snow data have been collected. Winters have been mild in recent years and combined with difficulties of access, have led to only two sets of data, one for winter 1995/96 and five observations of water equivalent in March 1998 (insufficient for snowmelt model assessment). Only two snow periods are suitable for modelling:

(i) 8 January 1984 – 28 February 1984
(ii) 18 December 1995 – 28 February 1996.

Data from both periods have had to be used for calibration of the snowmelt model parameters because the position of the snow survey site changed from Tulloch Farm (elevation 135 m) in 1984 to sites in the vicinity of the Lower Monachyle AWS (elevation 300 m) in 1995. Table 4.8 compares flow and water equivalent obtained using the snowmelt model with the extended melt equation and the energy-budget melt formulation. Ignoring snow, the PDM yields R^2 values of 0.57 (in 1984) and 0.42 (in 1995). The snowmelt model parameters have been calibrated to give the optimal model fit for both flow and water equivalent for each period. The results are therefore reasonably good: when a snowmelt component is used with the PDM the R^2 for flow rises to above 0.8 for all models and events. Model performance using the two types of melt equation is very similar, with the extended melt equation performing better in 1984 and the energy-budget model working better in 1995. More events are needed in this catchment to better evaluate model performance.

Table 4.8 Model performance with extended melt and energy-budget melt formulations using the PDM rainfall-runoff model: Monachyle Burn

		Extended melt		Energy-budget	
Period	**Model**	**Flow R^2**	**W.E. R^2**	**Flow R^2**	**W.E. R^2**
Calibration only					
8 Jan 1984 – 28 Feb 1984	Snow ignored	0.566	-	0.566	-
	Snow included + flow calibration	**0.886**	0.916	0.856	0.963
	W.E. calibration	-	-	0.793	0.983
18 Dec 1995 – 28 Feb 1996	Snow ignored	0.415	-	0.415	
	Snow included + flow calibration	0.806	0.957	**0.832**	0.963
	W.E. calibration	-	-	0.652	0.994

4.4.4 Snowline position assessment for Monachyle Burn

Two periods of lying snow in the Monachyle Burn catchment, 12 years apart, have been used to evaluate the snowmelt model's ability to predict snowline elevation: these are 14 January to 30 May 1984 and 22 December 1995 to 28 February 1996. The main difference in the two datasets is the location of the snow survey site as previously discussed. Daily visual estimates of the snowline were used for model assessment. The snowline was recorded to the nearest

100 m with a maximum recorded elevation of 1000 m corresponding to a catchment free from snow cover.

The model representation for dry snow (equations (3) to (5)) is used to determine the variation with elevation of W resulting from temporal changes in temperature and fresh snowfall. At each time-step, the snowline elevation, z_0, at which $W(z_0) = 0$, and $W(z) > 0$, for $z > z_0$ is identified. The snowline is conventionally defined as the minimum elevation above which lying snow is present. It is interpreted here as the elevation above which dry snow (visible white snow) is present and thus relates directly to W and not to wet snow, S. 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 a single snowline elevation for the catchment exists and 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. Snowline observations ranged in value from 200 to 1000 m, the latter indicating a snow-free catchment. 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 were not available after the end of February; however, the snowline records showed only one fresh snow event after this time on 23 March and the absence of these data was considered unlikely to significantly affect the analysis.

The model was initialised on the fresh fall of snow on 14 January 1984. At each hourly time-step of the model a profile of the dry snow water equivalent with elevation was calculated and the position of the snowline, z_0, identified and compared with the daily catchment observations. Other than the temperature thresholds, T_s and T_m, only one model parameter affects the modelled snowline. This is the melt factor in equation (3), β, which determines the amount of melt associated with each unit of temperature increase. This parameter was adjusted to achieve the best model fit, using R^2 and visual judgement as guides to assess performance. The final model gave an R^2 of 0.72 using a melt factor of 2.2 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. The value of 4.4 previously obtained for the flow calibration (Section 4) gave a poor R^2 of -0.1 when used for snowline prediction.

Figure 4.8 compares time-series of observed and calculated snowline positions from 14 January onwards using a melt factor of 2.2. 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 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 300 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 snowline observations over this period ranged from 0 (implying snow down to sea level) to 1000 m (a snow-free catchment).

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 4.9 which reveals a fairly good model simulation of the snowline position. Figure 4.10 shows the time-lapse (daily) profiles of dry snow water equivalent, W(z), against elevation for the first 30 days and shows the pack melting in the lower elevation areas first, then receding to the higher elevations after 30 days. Note that fewer than 30 profiles are apparent because on very cold days there is no melt and the snow profile does not change. The R^2 statistic for this simulation was 0.655, obtained after manually adjusting the melt factor to an optimum value of 4.4. Setting the melt factor to 0.54, the optimum value obtained for the flow assessment, a reasonable R^2 value of 0.65 was obtained for the snowline simulation. The snowfall on the 30th day of the model run (21 January), when the snowline fell from 1000 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 was adjusted to achieve the best snowline model fit, obtaining significantly different values for the two periods: 2.2 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. For flow simulation the smaller volumes of melt are compensated for by adjustments to the parameters of the rainfall-runoff model. A shallower snow pack will melt away faster than a deeper one resulting in a faster moving snowline. The 1995/96 optimal 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 a more extensive model assessment, 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 an optimistic impression of model performance. This problem is further helped by only one parameter, the melt factor, being involved. The dominance of different melt mechanisms (radiation, turbulent heat exchange) will affect the stability of the melt factor value. Investigation of the energy balance

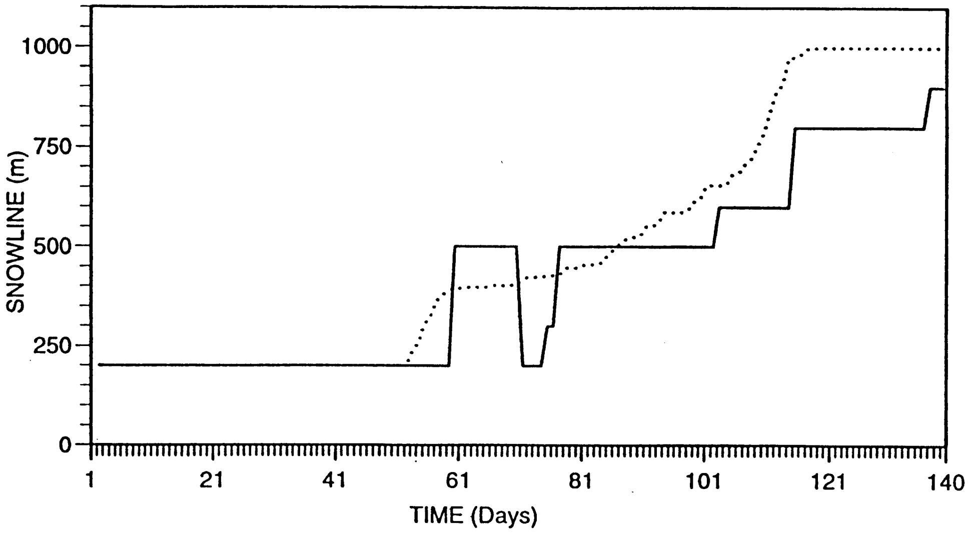


Figure 4.8 Comparison of observed (continuous line) and model simulated (dotted line) snowline elevation, Monachyle Burn, 14 January to 30 May 1984. Time in days from 14 January 1984.

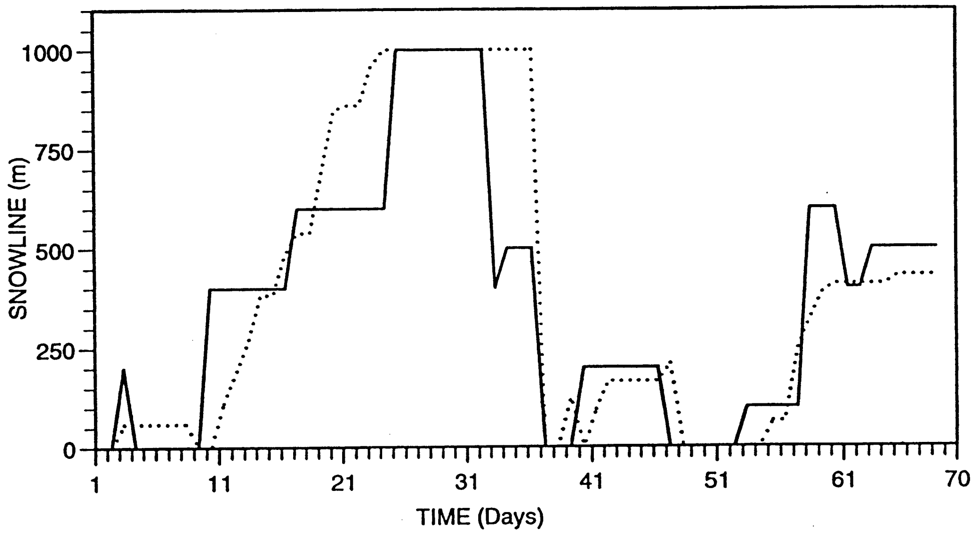


Figure 4.9 Comparison of observed (continuous line) and model simulated (dotted line) snowline elevation, Monachyle Burn, 2 December 1995 - 28 February 1996. Time in days from 2 December 1995.

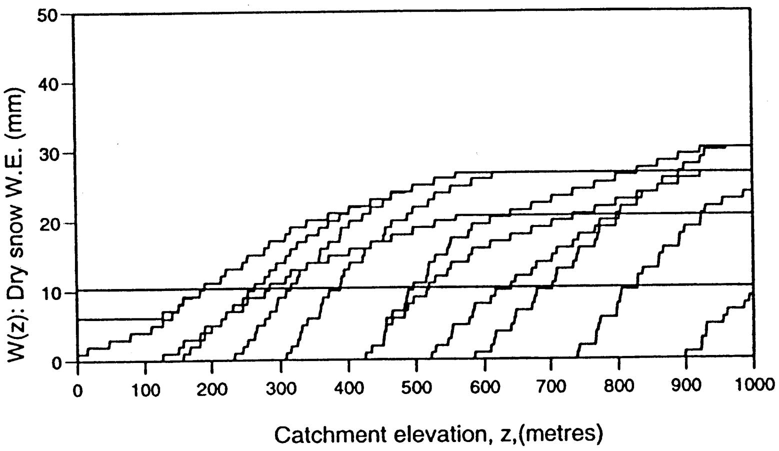


Figure 4.10 **Time-lapse (daily) profiles of dry snow water equivalent with changing elevation.**

of a melting snowpack has shown that, under typical melt conditions experienced in upland Britain, melt is dominated by sensible and latent heat transfer mechanisms that are strongly influenced by temperature (Moore *et al.*, 1996). This similarity of melt conditions might be expected to lead to stable values for the melt factor in the simple temperature excess melt formulation used here. However, continued field monitoring is required to allow testing and validation to be more comprehensive and to establish the stability of the estimated model parameters.

4.5 Intercomparison of Model Performance Across all Catchments

Initial testing of model variants on Harwood Beck established that the most successful model for simulating river flow during snowy events was the PDM with the snowmelt module coupled with one of two melt formulations, the extended melt equation (16) and the energy-budget melt formulation. The tests on Harwood Beck indicated that the use of multiple elevation zones rather than just a single zone lead to improved flow simulation, and an optimum number of zones was determined for each study catchment. The option of multiple elevation zones is not currently available for use with the energy-budget melt formulation, so this melt model has only been evaluated within a single elevation zone catchment model.

Two main model variants have therefore been evaluated across the three study catchments: the extended melt equation with multiple elevation zones and the energy-budget melt formulation with a single elevation zone. In all cases the use of a snowmelt component during snowy weather conditions improved model performance when compared to a rainfall-runoff model with no snowmelt component. Judging model performance across all catchments in terms of flow simulation, both model variants gave reasonable results prior to additional calibration. Typically, R^2 values improved from 0.35 without a snowmelt model component to 0.55 when one is used. Additional calibration on each period of record showed that the best model performance that could be obtained gave R^2 values of about 0.7. No one model variant could be relied upon to outperform the other. However, the energy-budget melt formulation tended to be slightly better, particularly after additional calibration on each period. This is an encouraging result as there is still work to be done on the energy-budget model formulation, particularly in extending it for use with multiple elevation zones, which has nearly always resulted in an improved model performance. Comparing model variants in terms of their ability to simulate snow water equivalent, it becomes apparent that there is often very little to choose between them. On Harwood Beck both model variants give similar results, with R^2 values ranging from 0.4 to 0.9, while in Trout Beck and Monachyle Burn the energy-budget melt model gave a slightly better performance than the simpler extended melt equation.

Overall, simulation results across different catchments are encouraging, and suggest that the model parameters are reasonably robust across periods of lying snow. A summary of the calibrated model parameters across the three catchments are presented in Table 4.9. It is clear that some parameters are taking on effective values to compensate for inadequate sources of data. Given good quality snow survey data, temperature data and raingauge data, river flow can be modelled with a fair degree of success. However, when the raingauge is situated at too high an altitude (as shown with the AWS 31 raingauge in the Trout Beck catchment), the gauge can be blocked with snow, or suffer from drifting snow, leading to poor model performance. A raingauge situated at lower elevation can be of more use in such situations, as it is less likely to be blocked with snow and may give a better indication of recent rainfall. If AWS measurements of wet bulb temperature and radiation are available, a full energy-budget seems to provide slightly more robust estimates of melt water, and can lead to improved flow simulation in some cases.

As expected, there was a drop in simulation accuracy in the Trout Beck catchment following the closure of the Widdybank Fell snow survey site and transfer of monitoring to Hunt Hall Farm, which is at a much lower elevation, and further away from the catchment.

Table 4.9 PACK snowmelt module parameters: summary of calibrated parameters

Parameter	Description	Unit	Harwood Beck		Trout Beck		Monachyle Burn 1984		Monachyle Burn 1995/96	
			Extended Melt	Energy Budget	Extended Melt	Energy Budget	Extended Melt	Energy Budget	Extended Melt	Energy Budget
The basic PACK module:										
c	Precipitation representativeness factor	dimensionless	0.883	0.925	1.358	1.358	2.16	2.01	1.194	1.118
T_s	Temperature threshold below which precipitation is snow	°C	-0.228	0.537	-3.603	-0.641	0.750	-0.1	3.041	2.566
T_m	Critical temperature above which melt occurs	°C	0.538	-	0.123	-	-0.113	0.0	0.186	-
β	Melt factor	mm/day/°C	4.341	-	4.49	-	4.428	-	5.974	-
k_1	Storage time constant: lower outlet	day^{-1}	0.468	0.731	0.275	0.731	0.0184	0.450	0.470	0.655
k_2	Storage time constant: upper outlet	day^{-1}	0.999	0.980	0.999	0.999	0.974	0.996	0.999	0.999
S_c^*	Maximum liquid water content, as a proportion of total	dimensionless	0.280	0.209	0.392	0.390	0.266	0.282	0.108	0.0046
T_c	Critical temperature below which no drainage occurs	°C	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Extended melt equation:										
γ	Wind speed factor	$s\,m^{-1}$	0.979	-	0.101	-	0.003	-	0.399	-
μ	Rain heating factor	$°C^{-1}$	0.157	-	0.0	-	0.036	-	0.097	-
Partial cover curve:										
θ_c	Critical water content below which only a proportion of the basin is snow-covered	mm	not used	45.2	not used	0.0	100.0	100.0	100.0	100.0
ϕ	Fraction of new snow remaining below which snow-covered area starts to revert to partial cover curve	dimensionless	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Energy budget formulation:										
Z_0	Aerodynamic roughness length of snow surface	mm	-	0.0026	-	0.0026	-	0.0087	-	-

5. SUMMARY, CONCLUSIONS AND OPPORTUNITIES FOR FURTHER WORK

5.1 Summary

The 1996 report to the National Rivers Authority (now the Environment Agency), entitled 'Development of Improved Methods of Snowmelt Forecasting' (NRA R&D Note 402), investigated how snowmelt forecasting in the UK could be improved through new developments in modelling and measurement, and established a UK Snowmelt Database. Following a review of models currently available, the IH PACK model was developed further to include a facility for use with multiple elevation zones within a catchment, and an extended melt equation which incorporated the effect of wind and rain. An energy-budget formulation was also considered, and analysis revealed the dominance of the sensible and latent heat terms in the snowmelt events studied, providing an explanation for the success of the simple temperature excess melt approach. While initial results were encouraging, the report concluded that more data were needed for model evaluation in order to provide firmer operational guidance on the choice of model and the extent of measurements required.

The purpose of the present study is to report on data collection and model development since the 1996 report. The Monachyle Burn catchment in Balquhidder has been the focus of much study, and although snowfall has been limited over the project period, recent monitoring together with historical records have provided two good periods of record for investigation. During the winter of 1995/6 a field trial of the WMO Double Fenced Intercomparison Reference (DFIR) precipitation gauge was carried out in the Monachyle Glen to test its performance against existing raingauges. Two catchments in the Upper Tees, Northumbria, have also been used in model development and assessment. Trout Beck and Harwood Beck are small upland catchments for which a long record of snow survey observations exists together with AWS and snow pillow measurements.

Section 2 reported on recent modelling developments and introduced a new snowmelt model formulation which can use either a finite number or continuous distribution of elevation zones in a catchment. Two different melt formulations can be used with the new model. These are the extended melt equation, which uses measurements of temperature, wind and rainfall to determine the potential melt experienced by the snow pack, and the energy-budget melt formulation which requires additional AWS data in the form of radiation and wet bulb temperature.

Section 3 presented a description of the study catchments and the database used for model evaluation. The section also describes the field trial of the DFIR gauge, which lasted just one winter in the harsh Scottish climate before collapsing. The new snowmelt model and variants are evaluated in Section 4 on the three upland catchments: Monachyle Burn, Harwood Beck and Trout Beck. An initial evaluation assessed the value of single, multiple or a continuous distribution of elevation zones in a catchment. This established that for the purposes of flow modelling, between 10 and 20 elevation zones generally gave the best model performance, with performance varying erratically with smaller numbers of zones. To limit the scope of the assessment overall, most model variants were tested on Harwood Beck, which contained the longest record of lying snow. The added complexity of the distributed SDM rainfall-runoff model was found not to be beneficial in the small upland catchments used in the study. Only the lumped PDM rainfall-runoff model was carried forward for further assessment. Two types of snowmelt model were found to be promising, the extended melt equation used with multiple elevation zones and the energy-budget melt formulation used with a single elevation zone. The partial cover curve, which is used to allow for patchy snow cover for shallow packs, was found to be mainly of use when a single elevation zone is used. When multiple elevation zones are used in a catchment, the differential rates of melt with elevation are accounted for, and any error in snow coverage in a few zones having a shallow pack is likely to be small. The partial cover curve is currently of most use with the energy-budget melt formulation, which is only available for use with a single elevation zone. It may also be of value in larger lowland catchments at times when patchy snow cover exists and elevation effects on snow cover are less influential.

Overall, when the snowmelt model was assessed alongside a rainfall-runoff model with no snowmelt model component, the use of a snowmelt model typically resulted in an improvement in R^2 values from 0.35 to 0.55 for flow simulation.

5.2 Achievements

The main achievements arising from the study are set down below.

(i) Development of a new elevation-dependent snowmelt model formulation which can use a finite number or continuous distribution of elevation zones in a catchment (Bell and Moore, 1999).

(ii) Incorporation of snowmelt data from Balquhidder and recent data from the Upper Tees catchments into the IH UK snowmelt database.

(iii) Installation and field trial of the WMO Double Fenced Intercomparison Reference (DFIR) precipitation gauge at Balquhidder.

(iv) Further development of the energy-budget melt formulation to remove sources of instability, and its incorporation, as an option, into the snowmelt model.

(v) Revision and assessment of the partial cover curve model code and its operational implementation in EA North East.

(vi) Use of the new IH Digital Terrain model for Scotland to derive topographic features and the hypsometric curve for snowmelt modelling in Monachyle Burn.

(vii) Assessment of the different model variants, using continuous records encompassing several periods of melt, for catchments in Balquhidder and in the Upper Tees.

(viii) Participation and presentation of new research at the Scottish Snow conference, Bridge of Allen, 1997 (Moore *et al.*, 1999)

5.3 Conclusions

This study builds on the preliminary work of Moore *et al.* (1996) which developed a range of model variants and a snowmelt database to support future research relating to snowmelt in the UK. The present study has expanded the database to include snowmelt data from Balquhidder in Scotland. A new elevation-dependent snowmelt model has been formulated and evaluated in Monachyle Burn near Balquhidder and two catchments in the Upper Tees, Harwood Beck and Trout Beck. Based on extensive model calibration and assessment on the larger dataset, the main conclusions of the study are summarised below.

(i) *Value of a snowmelt model.* During periods of snowmelt, use of a snowmelt model component improves upon the accuracy of flow forecasts obtained using a rainfall-runoff model alone.

(ii) *Lumped or distributed rainfall-runoff model.* For the small upland catchments used for assessment, a simple distributed rainfall-runoff model - the SDM - gave a similar performance to the "lumped" PDM model. As a result the simpler PDM has been used primarily in the assessments of snowmelt model variants, and may be preferred for operational implementation if the choice is to be restricted to one model. For larger catchments with greater spatial variability, the use of the SDM may prove beneficial.

(iii) *Choice of snowmelt model formulation.*

- No one snowmelt model variant provided consistently the best results.
- The energy-budget melt formulation used with the single zone snowmelt model can give very good performance but is the most complex and demanding of data.
- Use of the simple temperature excess melt equation with multiple elevation zones can give as good performance as the energy budget, is simple and has small data requirements. It is this formulation which is recommended for operational use at the present time.
- A sensitivity analysis of the snowmelt model to the number of elevation zones employed suggests that the use of multiple elevation zones in upland catchments can improve model performance during periods of melting snow.
- Developing the energy balance melt formulation for multiple zones is seen as a fruitful avenue for future research.
- Inclusion of rain and wind heating terms in an extended temperature melt equation was found to provide some benefit in model performance.
- The partial cover curve, defining the fraction of the catchment (or elevation zone) covered by snow, was found to be of some benefit to model performance when the catchment was represented as a single elevation zone. However the use of multiple elevation zones seems to render this model variant largely unnecessary for upland catchments where elevation exerts a strong control on ablation. For larger, lowland catchments the partial cover curve may still be of value.

(iv) *Precipitation measurement using raingauges.* Precipitation measurement in the uplands during periods of snow and rain can be difficult due to blocking of raingauges by snow. Use of a gauge at a lower elevation less affected by snowfall can improve model forecasts, given the model takes account of the changing form of precipitation with elevation through a temperature lapse rate and rain/snow temperature threshold. There is clearly a trade-off with representativeness of the precipitation at the raingauge site with respect to that of the catchment.

(v) *Measurement of lying snow.* While Cow Green snow pillow in the Upper Tees was found to be of value to modelling, comparisons with daily snow core measurements suggested that use of the hourly snow pillow data could not easily improve on flow modelling results obtained using daily snow core observations.

5.4 Operational Recommendations

This section aims to provide recommendations for each Environment Agency Region aimed at achieving pull-through of the research reported here into operational practice.

North East Region

The North East Region currently operates the River Flow Forecasting System, or RFFS, in support of flood warning across the rivers of Yorkshire. Plans are in hand to extend its coverage to include the Tees and rivers of Northumbria. The Yorkshire RFFS includes the original PACK snowmelt model linked to the PDM rainfall-runoff model for forecasting runoff from headwater catchments. It has been possible within the two phases of this project to make some improvements to the PACK model in operational use. These relate to the parameter values appropriate for use at a 15 minute model time-step and coding improvements to the partial cover curve and the way the pack disappears in the final phases of melt. A more extensive revision of the models to accommodate elevation zoning is recommended here. This will involve development of new and revised Model Algorithms used by the operational RFFS's to incorporate the new model features which exist in the off-line calibration version of the code. The task is eased by the RFFS's generic and modular design which can readily accommodate any model structure through its Information Control Algorithm (ICA) Model Interface. The work needed will also involve the derivation from the Digital Terrain Model of the elevation zones to be used for each catchment. Prior to an extensive revision to the existing RFFS Model Network for the rivers of Yorkshire, it is recommended that the new snowmelt model be developed and trialled as part of the planned extension of the RFFS to the River Tees. This would make immediate use of the calibrated model for Trout Beck in the Upper Tees.

Anglian Region

The Anglian Region employs the PACK snowmelt model, together with the PDM rainfall-runoff model, within the Lincoln Flood Alleviation Model or LFAM. This model is configured without the benefit of the RFFS ICA generic model framework and has not been revised in the way described for the Yorkshire RFFS. The ongoing development of the AFFMS (Anglian Flow Forecasting and Modelling System) could provide a shell environment within which the RFFS ICA "forecast engine" operates, facilitating a way of making the revised PACK model available for use across the whole of the Anglian Region, including that part currently served by LFAM. Direct model insertion within such proprietary systems as MIKE-11FF and ISIS model environments is less straightforward on account of their lack of generic, multi-model interfaces suitable for real-time updating.

Model developments relating to elevation zoning will be of little benefit to the low-lying Anglian Region but improvements to the partial cover curve and better specification of model parameters will be of benefit and need to be implemented.

Thames Region

Thames Region are currently implementing the RFFS ICA forecast engine within their CASCADE system and will be able to make immediate use of the existing PACK snowmelt module if configured into their RFFS Thames Model Network. A network of snow observer stations, using snow cores to measure snow depth and water equivalent, would need to be initiated. Temperature measurements would also be needed on telemetry. It might be judged that snowmelt-induced flooding is infrequent and of low priority in the Thames Region, and not deserving of investment. Elevation zoning will be of limited benefit.

Southern Region

Snowmelt-induced flooding may be judged infrequent and low priority for Southern Region and not deserving of investment. Where forecasting systems exist, these are not designed to readily accommodate snowmelt models without specific, detailed re-coding.

Midlands Region

The Midlands Flood Forecasting System (MFFS) employs the Midlands Catchment Runoff Model (MCRM) for forecasting runoff from headwater catchments. Coded within this model is a snowmelt model which was reviewed in the First Phase Report (NRA R&D Note 402). This was based on an earlier review by Harding and Moore (1988), commissioned by the NRA Severn-Trent Region, which led to the development of the prototype form of the PACK model. To implement the present development of the PACK model within the MCRM would require detailed re-coding of parts of the model and some modifications to the MFFS environment. Also the procedure used for updating, based on running separate point and catchment snowmelt models, with transfer of information between them, would not be straightforward to implement within the present system. A replacement for the MFFS is currently being sought. If the replacement is based on the RFFS ICA forecast engine then pull-through of research into practice would be eased. An RFFS calibration form of the MCRM already exists and it would be relatively straightforward to develop a Model Algorithm form from this which could be linked to PACK Snowmelt Model Algorithms for operational use.

South West Region

Snowmelt-induced flooding is infrequent and may be judged as low priority and not deserving of investment. The software implementation issues are similar to those faced in North West Region.

North West Region

Snowmelt-induced flooding can be important in North West Region but at present provision does not exist for either monitoring or modelling snowmelt. It is recommended that consideration be given to setting up a snow observing network based on daily snow core measurements and providing telemetered measurements of temperature, at a minimum. The WRIP system is employed for flood forecasting and this uses simple transfer function models without snowmelt being explicitly taken into account. Specific coding would be required to incorporate the development of the PACK model described here. The region would benefit from the new elevation zone formulation due to the varied relief and its influence on temperature and melt. Pull-through of research into practice would be eased by the adoption of a forecast engine having a generic model algorithm interface architecture.

For regions without a generic model algorithm interface it is likely that inclusion of the new snowmelt model would be easiest to achieve as a precipitation preprocessor, in a similar structural way to computation of areal average rainfall. This might be relatively simple to achieve in simulation-mode but is likely to present more problems in updating-mode, especially in relation to the transfer of information from point to catchment forms of snowmelt model.

5.5 Opportunities for Further Work

(i) Assessment of the snowmelt model in a simulated real-time context with full updating.

(ii) Explore the viability of the snowmelt model variants and data requirements in an operational situation.

(iii) Improved application of the energy-budget melt formulation for use with multiple elevation zones to accommodate topographic controls on melt at the catchment scale, supported by the IH Digital Terrain Model.

(iv) Further examination of the use of snow pillow data to improve forecast performance.

(v) This study has focussed on datasets from the Upper Tees and Balquhidder as these have been found to be most useful for model development and assessment. There is scope for further work using other historical records from the Snowmelt Database, particularly those for Pynlimon. There is also a need to extend the database through inclusion of more recent data and widening its coverage to include lowland sites.

(vi) The current model formulation assumes uniform precipitation over the catchment. An extension to include a precipitation lapse rate which is solely elevation dependent is straightforward.

(vii) Drifting snow and the accumulation of snow in hollows are not represented. Combining the elevation-dependent model with a topographic snow cover index, of the type developed by Bloschl *et al.* (1991), might allow the effects of slope, curvature and aspect on snow accumulation to be introduced.

(viii) Explore the use of satellite remote sensing of snow cover in the formulation and application of snowmelt models. This would need to take account of the progress made by Moore *et al.* (1996) in the first stage of the project, ongoing work under the Scottish Snow Cover Project involving the universities of Dundee and Cambridge, and the future availability of new sources of remotely-sensed data over Britain.

(ix) Explore alternative extended melt equations incorporating the effects of humidity and aspect. A parameterised form of the melt equation used by Hough and Hollis (1995), which incorporates humidity, provided results which were broadly intermediate between the extended melt and energy-budget formulations. Whilst these results have not been reported here, they do provide the basis of further work of relevance to both forecasting and design applications of snowmelt models.

(x) A fundamental problem is the difficulty of reliable snowmelt measurement. An exploratory study of the use of Met. Office Numerical Weather Prediction (NWP) model estimates of snowfall, for both past and forecast amounts, as input to the snowmelt model would be of value. This might extend to include NWP estimates of other quantities involved in snowmelt forecasting, particularly temperature and wind.

(xi) Implement the new snowmelt model as a Model Algorithm within the River Flow Forecasting System (RFFS) for operational use (Moore and Jones, 1991; Moore *et al.*, 1994). The RFFS which supports the Environment Agency's flood warning service in North East Region could be used for operational trials. Planned extension of the system from the rivers of Yorkshire to the Tees would allow immediate operational use of the snowmelt model calibrated here for the Trout Beck catchment.

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APPENDIX I: FIELD TRIAL OF THE WMO DOUBLE FENCED INTERCOMPARISON REFERENCE PRECIPITATION GAUGE

A.1 Introduction

The Balquhidder experimental catchments were established in 1981 to study the effects of upland afforestation on water resources in Highland Scotland. The nature of the Balquhidder catchments is significantly different to other UK experimental catchments, such as Plynlimon, in that they have a more rugged relief and coarser vegetation and experience a high proportion of annual precipitation falling as snow. Consequently the measurement of snow proves critically important.

Precipitation falling as snow is difficult to measure in the catchments. The large surface to weight ratio of snow makes snowfall vulnerable to wind turbulence. Standard raingauges with gauge rims above the ground surface are known to increase passing wind turbulence, further aggravating snowfall measurement. Also, raingauges used with the rims level to the ground surface, although reducing the effect of wind turbulence on the catch, are vulnerable to drifting snow.

The water balance study at Balquhidder has relied upon regular snow pack surveys to determine the inputs of snowfall. The difficulty of this method is the short-lived nature of many snowfall events in Britain, the unknown quantity of snow lost to melt and the redistribution of lying snow by wind. Consequently, the combination of snowpack surveys and storage gauges offers a potentially better solution.

In 1985 the WMO initiated an intercomparison of international methods of solid precipitation measurement (Goodison *et al.*, 1989). The work noted that it was possible to incur significant differences in precipitation measurement arising from variations in measurement technique. The WMO intercomparison set out to determine a reference standard to which all measurement techniques could be related. The gauge decided upon, developed in Russia, was the Double Fence Intercomparison Reference (DFIR) comprising a Tretyakov gauge surrounded by two snow fences. After testing in numerous locations, specifications were set for the gauge design and siting. The results of the intercomparison over the period 1986 to 1993 at 11 stations in Canada, the USA, Russia, Germany, Finland, Romania and Coatia are reported in Yang *et al.* (1995).

During the winter of 1995/96 a field trial of the DFIR in the Balquhidder catchment was carried out to test its performance against existing raingauges. The installation of the gauge and final results of the trial are reported below.

A.2 WMO Double Fenced Intercomparison Reference (DFIR) Gauge

The DFIR gauge consists of a Tretyakov storage gauge, mounted on a 3 metre high vertical post, surrounded by two octagonal fences, 4 and 12 m in diameter, providing the wind shield (Figure A.1). The design specification for the gauge requires 300 metres of surrounding level ground for

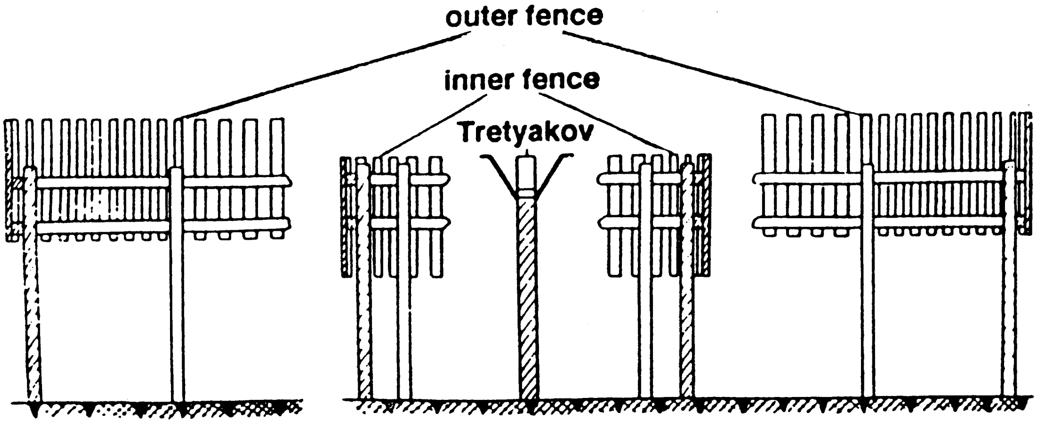

Figure A.1 WMO Double Fenced Intercomparison Reference (DFIR) Gauge.

its siting. This excludes many sites in Highland Scotland where snow inputs are significant. A site in the Monachyle glen at Balquhidder was chosen as the location for the gauge. To allow for easy access during the winter months, the gauge was sited on a river terrace in the glen bottom. This had the added benefit of being situated near to existing raingauges and an automatic weather station.

Installation of the gauge proved difficult. Lack of ease of installation is one cause that would inhibit its widespread use. Also, although additional bracing was added to the construction over and above that required by the specification, the gauge did not survive the winter. The design of the DFIR makes it susceptible to extreme conditions, such as those experienced in the Highlands of Scotland. Even when managed under experimental catchment conditions, as is the case with Balquhidder, the gauge proved impractical to maintain.

A.3 Performance of the DFIR

Although the DFIR gauge did not survive the entire 1995/96 winter, it did experience some heavy snowfall periods which allowed for comparison with existing gauges, with wind speed data from a weather station being available to support the interpretation of results. The DFIR gauge performance was judged against the catch of the existing Meteorological Office Mk II gauge. This gauge had previously provided the standard method for precipitation measurement in the catchments (Johnson, 1989).

The DFIR gauge was measured at the same time as the Meteorological Office Mk II gauge on frequent visits to the catchment. Figure A.2 shows the relationship between the two gauges when displayed as a scatter plot. Whilst a good relationship exists between the two gauge measurements, the Mk. II gauge consistently records the greater amount. A regression analysis,

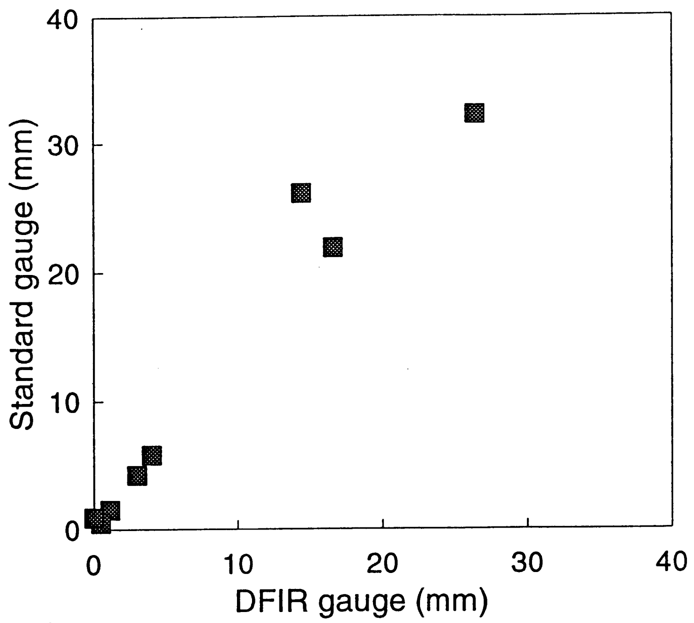

Figure A.2 **Comparison of DFIR and Met Office Mk II gauge measurements of precipitation.**

with the line constrained to pass through the origin, yielded a slope of 0.72 and a squared correlation coefficient of 0.95. Thus factoring Mk II gauge values by 0.72 provides good agreement with the DFIR gauge values. The higher catch from the Mk II gauge might imply that it is more susceptible to drifting snow at ground level. This was certainly evident in one of the comparisons, when the Mk II gauge measured 0.9 mm while the DFIR gauge for the same period failed to measure any precipitation. This highlights the advantage of the DFIR collector being 3 metres above ground level.

A major design feature of the DFIR is reduction of the effect of wind on the catch through the use of two wind shields. To assess its effectiveness, the ratio of measurements from the two types of gauge was plotted with respect to wind speed and the result is shown in Figure A.3. No clear relationship is evident from the limited data set covering only a restricted range of wind speeds.

A.4 Conclusion

The field trial of the DFIR snow gauge in Balquhidder aimed to assess the effectiveness of this WMO standard snow precipitation gauge for use in Highland Scotland. The trial reached the following conclusions:

(i) the installation of the DFIR is not practical for snow precipitation measurement in the Highlands of Scotland and is susceptible to extreme conditions;

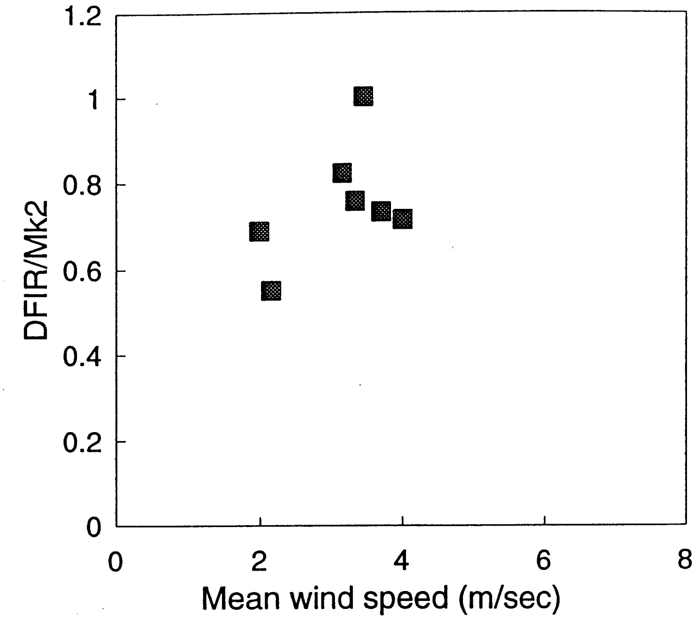

Figure A.3 Wind speed dependence of the ratio of DFIR to Met Office Mk II gauge measurements of precipitation.

(ii) the DFIR catch was on average 0.72 of the Met Office Mk II gauge catch, possibly implying that the design of the gauge, being 3 m above ground level, is effective in reducing the effect of drifting snow on gauge catch; and

(iii) the limited data collected over the trial period was insufficient to establish a clear relationship between wind speed and standard gauge catch, using the DFIR gauge as a reference.

Overall, the field trial of the DFIR showed initial signs of the effectiveness of the gauge but highlighted the impracticality of its design for the measurement of snow in the Scottish Highlands.