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Methods for snowmelt forecasting in upland Britain

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Abstract

Snow, whilst not a dominant feature of Britain's maritime climate, can exert a significant influence on major floods through its contribution as snowmelt. Flood warning systems which fail to take account of melting snow can prove highly misleading. Selected results of a study on methods for improved snowmelt forecasting using trial catchments in upland Britain are presented here. Melt models considered range from a temperature excess formulation, with the option to include wind and rain heating effects, to a full energy budget melt formulation. Storage of melt in the pack is controlled by a store with two outlets, allowing slow release of water followed by rapid release once a critical liquid water content is reached. For shallow snow packs, a partial cover curve determines the proportion of the catchment over which snow extends. The melt, storage and release mechanisms together constitute the PACK snowmelt module which provides inputs to the catchment model. Either a lumped or a distributed catchment model can be used, configured to receive snowmelt inputs from elevation zones within the catchment; a PACK snowmelt module operates independently within each zone and its inputs are controlled by appropriate elevation lapse rates. Measurements of snow depth and/or water equivalent, from snow cores or a snow pillow, are assimilated to correct for a lack of direct snowfall measurements needed to maintain a water balance during snowfall. The updating scheme involves operating a PACK module at the measurement site (the "point model") in parallel to PACK modules in the catchment model, with point model errors being transferred using a proportioning scheme to adjust the snowpack water contents of the catchment model. The results of the assessment of different model variants broadly favour the simpler model formulations. Hourly automatic monitoring of water equivalent using the snow pillow can help in updating the model but preferential melting from the pillow can be a problem. The energy budget melt formulation proves useful in understanding the energy components of melt typical of upland Britain. It reveals that, during the main melt phase, melt can occur in almost equal measure by sensible heat exchange and by latent heat of condensation, as warm air near saturation in cloud condenses on the snowpack; net radiation makes a negligible contribution. This provides a physical explanation for the success of the simple temperature excess approach to snowmelt estimation.

The snowmelt problem

Snow, whilst not a dominant feature of Britain's maritime climate, can exert a significant influence on major floods through its contribution as snowmelt. The catastrophic floodings of the Tay in February 1990 and again in January 1993 (Anderson and Black, 1993) provide recent examples in a Scottish context. Whilst 15% of flood events in England and Wales are associated with snowmelt, this statistic increases to 27% in Scotland (Johnson, 1975). 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, with consequent implications for flood damage costs. Failure to take account of the snowmelt contribution to floods in the operation of reservoirs for hydro-electric 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, mean that models need to be formulated at a fine time resolution, typically one hour or less.

Selected results of a study on methods for improved snowmelt forecasting using catchments in upland Britain are presented in this paper. The paper begins with an outline of the PACK snowmelt module, developed to assess different snowmelt model variants, and its coupling to catchment runoff models for flood forecasting at the catchment scale. Three melt functions of differing complexity and data requirement are considered: a simple temperature excess equation, a form of the latter extended to include wind and rain heating effects and an energy balance formulation. The snowmelt model for the catchment can exist in lumped or distributed form, depending on whether a single PACK module is used or the catchment is subdivided into elevation zones within which separate PACK modules operate. Either a lumped or a distributed rainfall-runoff model can be coupled to the snowmelt model in order to simulate the runoff response at the catchment outlet. A novel method is introduced of incorporating into the model measurements of snow water equivalent, obtained from snow cores or a snow pillow. This serves both to correct for a lack of direct measurements of snowfall and to improve the performance of the model. Results from a selection of the model variants, including one which ignores the presence of snow, are presented for two catchments in the Upper Tees in Northumbria, north-east England and in the Monachyle near Balquhidder in Scotland. The limited data available for model assessment, covering only one snow season for each catchment, precludes strong conclusions being drawn with regard to the relative merits of the different model variants. However, important initial insights are obtained from a review of the model results complemented by a more detailed analysis of the energy balance of the main melt phase for one event. These insights are drawn together in the concluding section of the paper.

Whilst the paper focuses on the development of a snowmelt model for UK conditions, and presents results limited to two small upland catchments in England and Scotland, the general approach adopted here has more widespread relevance. The principles of snow/rain discrimination, melting, storage and release, partial cover, and snow measurement data assimilation are of importance to all regimes experiencing snowfall. Also, the range of model variants incorporated—including various melt formulations, partition of the catchment into elevation zones, and lumped and distributed catchment runoff models—further extend the applicability of the overall modelling approach. The results focus on model performance and which variants are more appropriate for use in upland Britain. Again, the relevance of these specific results is likely to extend to other catchments in humid temperate environments where turbulent energy exchange dominates the melt process. In terms of scale, the results here are relevant to other small, fast responding catchments and the use of data at a time-interval of one hour or less. However, the model formulations are also likely to be appropriate for larger catchments and time-steps; a theoretical basis for adjusting model parameters for a given time-step is included within the paper.

Snowmelt model formulation

The PACK snowmelt module incorporates a range of melt formulations, a storage mechanism based on the critical liquid water concept, and a partial cover model for shallow packs (Moore *et al.*, 1996). The overall scheme is depicted in Fig. 1. The PACK module is coupled to a lumped or distributed catchment model to obtain flood forecasts at the catchment scale. Each component of the overall modelling scheme is described below.

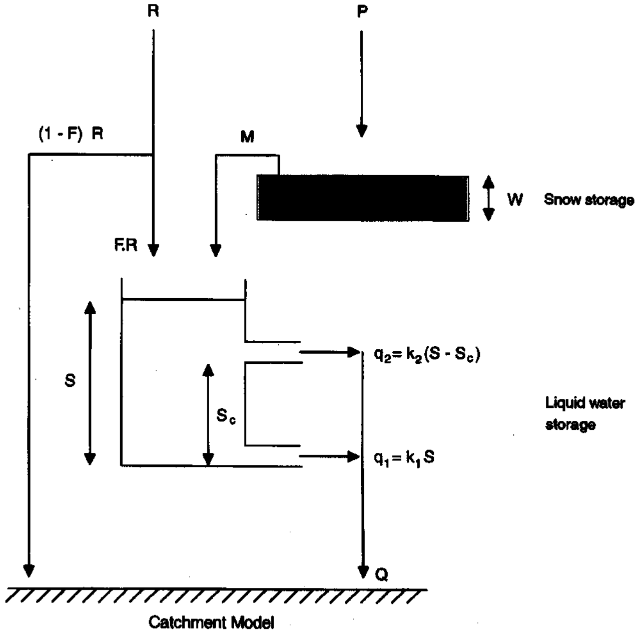


Fig. 1. *The PACK snowmelt module.*

INPUT TRANSFORMATION

Normally only raingauge measurements of precipitation are available. However, there is a need to discriminate between rainfall and snowfall and also to take account of any lack of representativeness of the gauge site. A Raingauge Representativeness Factor, c, is used to scale the precipitation measurement to account for any loss in catch and to compensate for altitude, aspect and other influences. For a given air temperature, T, a temperature threshold, T_S, is then used to discriminate precipitation, p (after correction for representativeness) into rainfall, R, and snowfall, P, such that

$$\begin{array}{ll} \text{For } T \geq T_s & R = p \text{ and } P = 0 \\ \text{otherwise} & R = 0 \text{ and } P = p. \end{array} \qquad (1)$$

A typical value for T_s under UK conditions is 1°C. In practice, when a conventional raingauge is used as a measure of precipitation, then precipitation is assigned as missing if the temperature is below the temperature threshold and there is evidence that snow has fallen.

MELT FORMULATION

Three melt formulations of increasing complexity are accommodated within the PACK module. The simplest is a temperature excess representation where the rate of melt, M, is given by

$$M = \begin{cases} f(T - T_m) & T > T_m \\ 0 & \text{otherwise} \end{cases} \qquad (2)$$

where T_m is the critical temperature above which melt occurs (typically 0°C) and f is a melt factor (mm/day/°C).

Intermediate in complexity is the extended melt equation which incorporates the effects of temperature, T, wind speed, u, and heating by rain, R, in a single parameterised expression

$$M = f^* (1 + \beta u)(T - T_m)^x + cRT. \tag{3}$$

Here, T_m is the threshold temperature above which melt occurs and f^*, β, x and c are parameters. The fixed values $x = 1$ and $c = 1/80$ (the ratio of the specific heat of water to its latent heat of melting) have been used, leaving f^* and β to be optimised. Third, and most complex, is the energy budget melt formulation based on an extensive recoding and integration of the MET and GLI codes of the IHDM (Institute of Hydrology Distributed Model). The energy components involved are net radiation, turbulent heat transfer via latent heat and sensible heat, heating by rainfall and heating from the ground; further details can be found in Morris and Harding (1991) and Moore *et al.* (1996). Turbulent heat exchange is dominant during the main melt phase in the uplands of the UK. At such times, melt is usually associated with a warm, moist and windy airstream, with cloudy conditions reducing radiation melt. Heating by rain has a minor influence on melt: for example, 16 mm of rain at 5°C produces only 1 mm of melt; groundmelt is even smaller at about 0.5 mm day^{-1}. Thus, temperature is expected to be the dominant control on melt, supporting the use of the simple temperature excess equation, with wind also an important variable.

Whilst the cumulative effect of radiation melt can exert an influence on the water and energy budget of the pack at times of longer lying snow, such conditions are less likely to coincide with, or be followed by, flood flows. Longer lying snow is more commonly a feature of the deeper snow packs experienced in the Scottish Highlands at higher altitudes. Errors in accounting properly for radiation melt as the pack ages can also be compensated for by updating the modelled snowpack using measurements of lying snow; this issue is addressed in detail later.

SNOWPACK STORAGE AND DRAINAGE

The model distinguishes between dry snow that has yet to melt and wet snow which has melted but is still held in the snowpack. Water accounting within the snowpack uses the concept of dry and wet stores. New snow falls on the pack contributing to the dry store. Water continuity gives

$$\frac{dW}{dt} = P - M \tag{4}$$

where W is the water equivalent of snow in the dry store, P is the snowfall addition and M is the melt loss.

The wet pack water equivalent, S, is given by continuity as

$$\frac{dS}{dt} = R + M - Q \tag{5}$$

where R is rainfall, M is melt from the dry store and Q is the drainage to the catchment.

CRITICAL WATER CAPACITY DRAINAGE CONCEPT

Storage of snowmelt within the pack is represented by a store with two drainage outlets having outflows q_1 and q_2. The bottom outlet allows the pack to drain slowly, except under freezing conditions when no drainage can occur. Above a critical storage, S_c, release of water occurs at a faster rate with the pack breaking up and draining away completely. Specifically, the total drainage to the catchment is given by:

$$Q = q_1 + q_2 = \begin{cases} k_1 S & S \le S_c \\ k_1 S + k_2(S - S_c) & S > S_c. \end{cases} \tag{6}$$

Here, k_1 and k_2 are the storage constants (units of inverse time) controlling the rate of release via the lower and upper outlets. The level of the upper outlet, S_c, varies dynamically according to the relation

$$S_c = S_c^*(S + W) \tag{7}$$

where S_c^* denotes the maximum liquid water content (expressed as a proportion of the pack water content), a fixed parameter of the model. This formulation is similar to that used in the Japanese Tank Model (Sugawara *et al.*, 1984). Note that, once the upper outlet has been activated by the wet storage exceeding the critical liquid water content, S_c, the critical level reduces as the pack drains allowing it to empty completely. If rain is allowed to be added to a pack containing only wet snow, the pack can persist because of the control on drainage rate. This is overcome by adding the rain directly to the drainage, thereby bypassing the pack at times when only wet snow remains. As much as 20% of the pack can be meltwater in storage.

DISCRETE-TIME MODEL FORMULATION

The model representation is formulated as a set of discrete-time equations for computational purposes and incorporates a procedure to adjust the storage time constants to the time-step adopted for modelling. Specifically, for a time interval $(t - 1, t)$ of duration Δt,

$$\begin{aligned} W_t &= W_{t-1} + (P_t - M_t)\Delta t \\ S_t' &= S_{t-1} + (R_t + M_t)\Delta t \\ S_c &= S_c^*(S_t' + W_t) \end{aligned} \tag{8}$$

$$Q_t = \begin{cases} k_1 S_t' & S_t' \le S_c \\ k_1 S_t' + k_2(S_t' - S_c) & S_t' > S_c \end{cases} \tag{9}$$

$$S_t = S_t' - Q_t \Delta t. \tag{10}$$

The storage time constants, k_1 and k_2, depend on the time-step used for modelling. Typical values for these parameters are available in the literature for daily and three hourly time steps (e.g. Sugawara *et al.*, 1984) and these require adjustment to the 15 minute model time-step used here. The form of adjustment can be worked out by considering that the volume of output from a linear reservoir over an interval (t, $t + \Delta t$) is related to the storage at the start of the interval, S_t, by

$$V_{t+\Delta t} = K_{\Delta t} S_t \qquad (11)$$

where $K_{\Delta t}$ is a dimensionless time constant with the suffix Δt emphasising the dependence of the time constant on the time-step Δt. Continuity gives

$$S_{t+\Delta t} = S_t - V_{t+\Delta t} = (1 - K_{\Delta t})S_t. \qquad (12)$$

Consider two time-steps, one longer $\Delta t_1 \equiv \tau_1$, and one shorter $\Delta t_2 \equiv \tau_2$, such that $\tau_1 = n\tau_2$ where n is a positive integer. Using the above equation over n recursions for time-step τ_2 gives the result

$$S_{t+n\tau_2} = (1 - K_{\tau_2})^{\tau_1/\tau_2} S_t, \qquad (13)$$

whilst a direct storage update using the coarser time-step τ_1 gives

$$S_{t+\tau_1} = (1 - K_{\tau_1})S_t. \qquad (14)$$

The following relation between the two dimensionless time constants is thus implied:

$$K_{\tau_2} = 1 - (1 - K_{\tau_1})^{\tau_2/\tau_1}. \qquad (15)$$

This result has been given in a different context by Nalbantis (1995). Published daily values for the reservoir time constants of 0.15 and 0.85 therefore approximate to 0.0017 and 0.02 in dimensionless form ($Q_t\Delta t$ replaced by V_t and k_1 and k_2 replaced by $K_1 = k_1\Delta t$ and $K_2 = k_2\Delta t$ in equation (8) with $t = 1$).

PARTIAL COVER CURVE

Patchy snow typical of a shallow snowpack at the catchment scale can be represented by a partial cover (or areal depletion) curve concept. Shallow snowpacks can be made to occupy only a fraction of the basin, F, which varies with the total water equivalent of the pack, $\theta = S + W$, below a critical value, θ_c, corresponding to complete snow cover. The underlying form of relation used is

$$\theta = (\theta_c + 1)^{F(\theta)} - 1 \qquad (16)$$

so that the partial cover fraction is given by

$$F(\theta) = \frac{\log(\theta + 1)}{\log(\theta_c + 1)} \qquad (17)$$

for $0 \leq \theta \leq \theta_c$. This parameterisation was suggested by Laramie and Schaake (1972) and adopted for use in the US National Weather Service's snowmelt model (Anderson, 1973). Figure 2 depicts the partial cover curve and shows how for fresh snowfall, $\Delta\theta$, the partial cover fraction is defined so as to revert to 1 until a fraction $(1 - \alpha)\Delta\theta$ has melted. A linear reversion to the original point on the partial cover curve occurs in melting the remainder of the new snow, $\alpha\Delta\theta$; typically α 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 catchment. This feature can be of particular importance for rain-on-snow events.

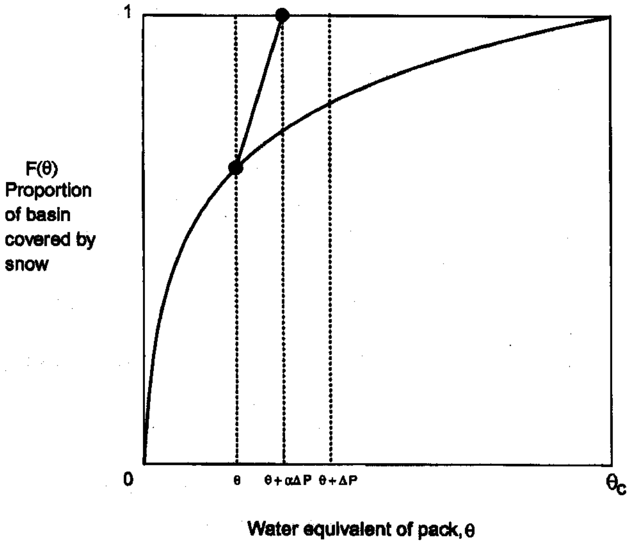


Fig. 2. *Partial cover curve used in the PACK module.*

Table 1 provides a summary of the model parameters involved in the basic form of the PACK snowmelt module that employs the simple temperature excess melt equation.

COUPLING TO CATCHMENT MODELS

The PACK snowmelt module has been integrated with two catchment models which transform snowmelt drainage, or rainfall, to catchment runoff. The first is a simple lumped conceptual model, called the PDM or Probability Distributed Moisture model (Moore, 1985, 1993), whilst the second is the Simple Distributed Model or SDM specifically tailored for snowmelt applications (Moore *et al.*, 1996). Figure 3(a) presents a schematic of the PDM model. Runoff production in the PDM model is controlled by saturation excess and storage-controlled drainage principles. The variation of storage capacity over the catchment is represented by a probability density function, such as Pareto, and analytical expressions derived giving the runoff response integrated over the catchment. Routing functions in parallel are used to represent the transmission of runoff and drainage to the basin outlet, respectively, with their sum giving the total basin flow. Coupling of the PACK snowmelt module to this catchment model is straightforward, with the snowmelt drainage forming the input to the lumped 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

Table 1. Parameters of the PACK snowmelt module

Parameter	Meaning	Typical value	Unit
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
f	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
θ_c	Critical water content below which only a proportion of the basin is snow-covered	100	mm
α	Fraction of new snow remaining below which snow-covered area starts to revert to areal depletion curve	0.25	dimensionless

schematic form in Fig. 3(b). The model employs DTM-derived isochrone bands which function as a cascade of kinematic routing reaches transmitting melt and runoff 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.

ELEVATION ZONES

The above outline of coupling PACK and catchment models together assumes that a single PACK module functions as a lumped catchment scale model of the snowmelt process. A simple distributed representation of the snowmelt process can be based on a partitioning of the catchment into elevation zones with a PACK module operating in each zone. Incorporation of elevation zones provides a way of taking account of variations in temperature with elevation, and its effect on melt, into the snowmelt model formulation through the use of temperature lapse rates. Melt from each zone is added to give the total input to the lumped PDM rainfall-runoff model.

In contrast for the Simple Distributed Model, melt from each elevation zone contributes to the coincident isochrone band and its corresponding kinematic routing reach. The development from the original IH Grid Model, originally configured on the radar grid to make use of grid square radar data, is the simple substitution of the grid configuration by an elevation zone configuration for this snowmelt application. For both models, a catchment is divided into n (say 5) elevation zones each with equal elevation range and the average elevation and area occupied by each calculated from the Digital Terrain Model for the catchment. The temperature for each average elevation is estimated from climate stations in the vicinity using an assumed temperature lapse rate. As a consequence, the difference in temperature between adjacent elevation zones in the model is the same for all zones at a given time.

Specifically, the area, a_i, covered by elevation band i at a median elevation, h_i, is calculated for each of the n elevation bands. Given m temperature stations in the vicinity, with station j recording temperature, T_j, at a given time, a simple lapse rate model is used to extrapolate to obtain the temperature, T_i, of elevation band i at elevation h_i. Thus,

$$T_i = T_j - \alpha(h_i - h_j) \qquad (18)$$

where α is the lapse rate taken to be .59°C/100 m, equal to the saturated adiabatic lapse rate at 5°C and roughly equivalent to the environmental lapse rate during the main melt phase in the UK. (Use of a higher rate—the dry adiabatic rate—under radiation-dominant melt conditions, is not invoked because of the emphasis on modelling the main melt phase and the ability to use snow measurements to correct the modelled pack prior to the onset of flooding.) For m temperature stations, there are m estimates of T_i, and an elevation-weighted average is obtained as

$$\overline{T}_i = \sum_{j=1}^{m} w_j\{T_j - \alpha(h_i - h_j)\} \qquad (19)$$

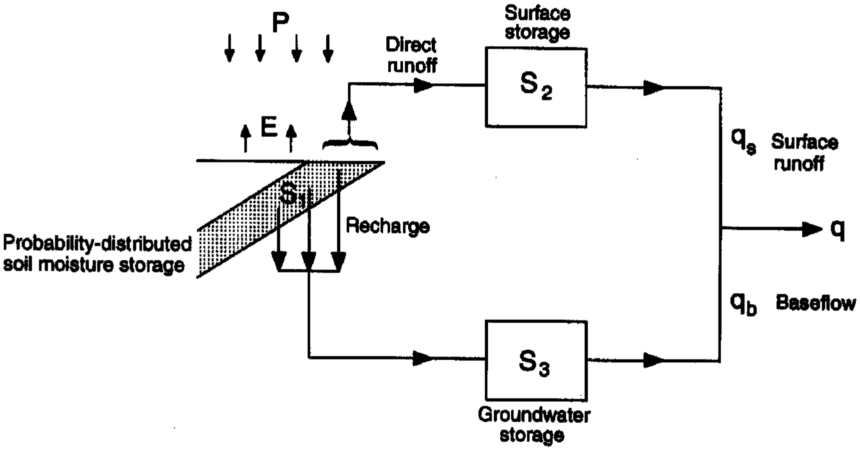
with the weight

$$w_j = d_j^{-1}/(d_1^{-1} + d_2^{-1} + \ldots + d_m^{-1}) \qquad (20)$$

where d_j is the elevation difference $h_i - h_j, j = 1, 2, \ldots, m$.

The model options considered here are restricted in two main areas. First, the topographic parameters controlling the energy budget melt option in the PACK module, other than altitude used in lapse rate calculations, are assumed to relate to weather station location and not to average conditions within an elevation zone. Second, the energy balance melt option is presently only available for use with the PDM catchment model.

(a) PDM model



(b) Simple Distributed Model

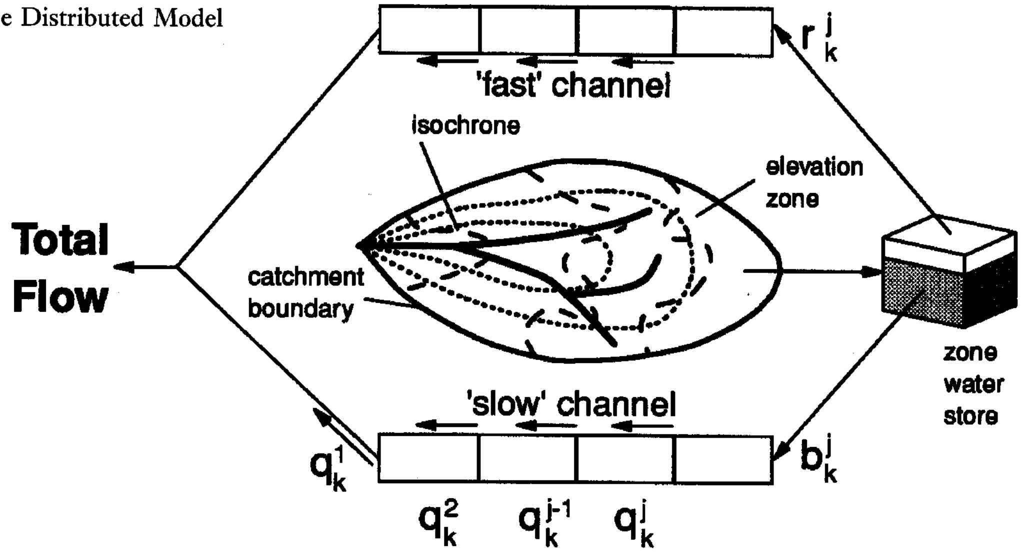


Fig. 3. *Lumped and distributed catchment runoff models used with the PACK snowmelt module.*

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. 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.

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

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

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

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

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:

$$W^{\dagger} = \beta\theta_m \tag{23}$$

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

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, f and β, to the basin scale model used for snowmelt forecasting proceeds as follows. Firstly, the water equivalent of the model pack, $\theta = W + S$ (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, f, such that

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

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

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

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, f, 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. Updating of the depth in each elevation zone is such that the depth for all zones is reset to that measured, whilst the original ratio of wet to dry pack is preserved in each. This has the benefit of preventing the pack depth in some zones becoming unrealistically high. Specifically, for a point depth measurement D_m and model values S and W for the wet and dry pack components in a specific elevation zone, then updating in the zone follows the procedure

$$S^{\dagger} = \begin{cases} \dfrac{D_m}{S + W\rho_w^{-1}} & S + W > 0 \\ 0 & S + W = 0 \end{cases} \tag{28a}$$

$$W^{\dagger} = \begin{cases} (D_m - S^{\dagger})\rho_w & S + W > 0 \\ D_m\rho_w & S + W = 0 \end{cases} \tag{28b}$$

where ρ_w is the density of dry snow and the superscript dagger is used to denote the updated quantity. This state adjustment is such that $D_m = S^{\dagger} + W^{\dagger}\rho_w^{-1}$ so that the snow depth is reset to the measured depth in each elevation zone whilst the proportion of wet to dry snow remains unchanged. An alternative, simpler, scheme is to update the pack when an increase in depth from one day to the next, ΔD, shows that new snow has fallen and its water equivalent is estimated as $\Delta W = \rho\Delta D$, where ρ is the most recent measurement of snow density. The results reported later are based on equations (28a) and (28b) although more recent work has suggested some benefit in using the simpler scheme.

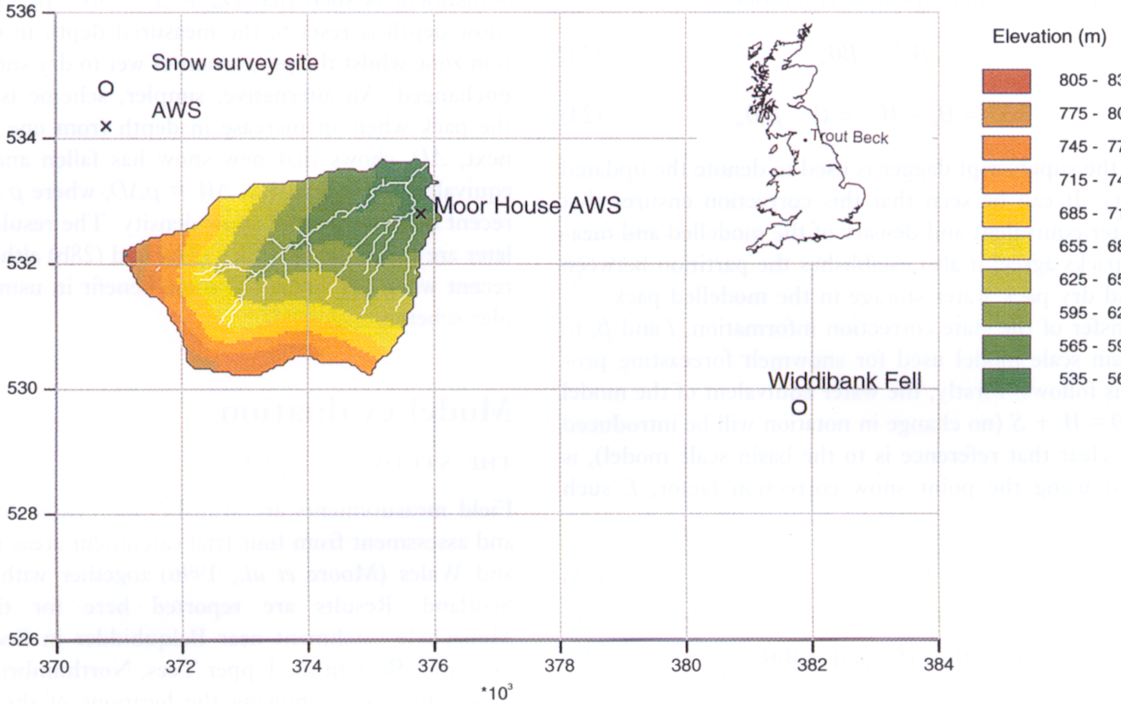
Model evaluation

THE STUDY CATCHMENTS

Field measurements are available for model development and assessment from four trial catchment areas in England and Wales (Moore *et al.*, 1996) together with a fifth in Scotland. Results are reported here for the Lower Monachyle catchment near Balquhidder in Scotland and for Trout Beck in the Upper Tees, Northumbria. Maps of these catchments showing the locations of the automatic weather stations and snow survey sites are shown in Fig. 4. The Monachyle drains an area of 7.7 km^2 with an elevation range from 302 to 892 m 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 used here is sited near the outlet of this upper catchment in a fairly central location with respect to the catchment as a whole. Daily snow cores were made at Tulloch Farm, about 5 km southeast of the gauging station at a lower elevation of 135 m, for the 1984 snowmelt period considered here. The Trout Beck catchment drains a heather moorland area of 11.4 km^2 with an elevation range of 553 to 857 metres. An automatic weather station is located at Moor House near the catchment outlet whilst a snow pillow is situated about 8 km to the southeast (elevation 505 m), close to Cow Green Reservoir Dam and near the snow survey site at Widdibank Fell (elevation 513 m).

SCOPE OF EVALUATION

The snowmelt catchment model presented in the previous section encompasses a number of variants, including three melt functions, two rainfall-runoff models and the choice of one or more elevation zones. It is also possible to run the rainfall-runoff models without a snowmelt component, thereby ignoring the presence of snow. An exhaustive evaluation of the different model variants will not be attempted here; instead, a subset of the variants that are judged to be of greatest interest and relevance is selected for assessment. Trials using the extended form of the (a)Monachyle Burn



(b)Trout Beck

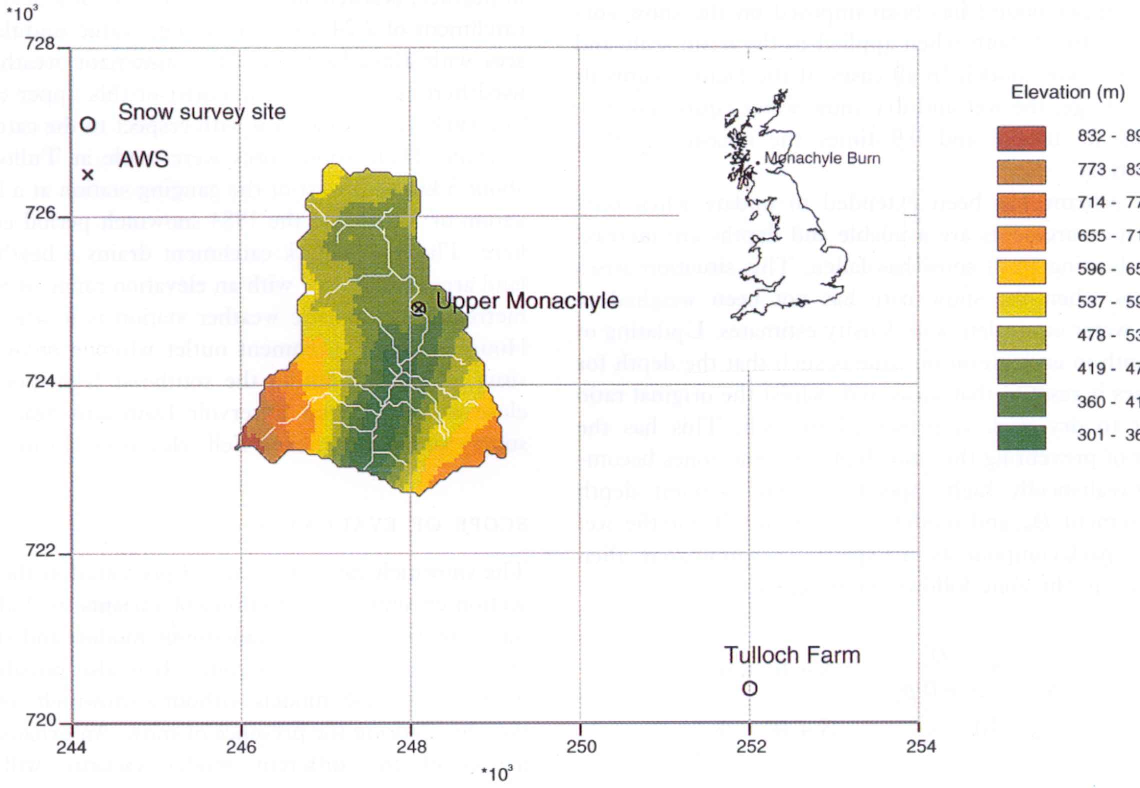
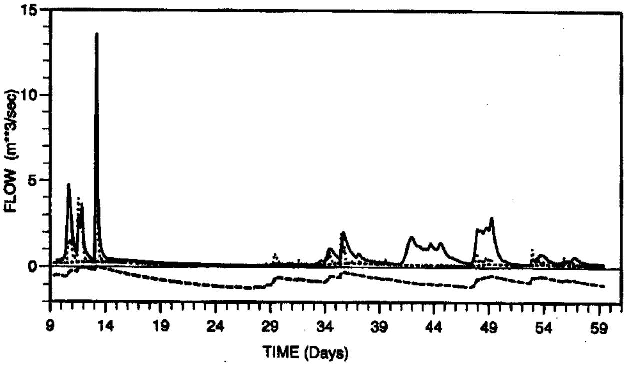
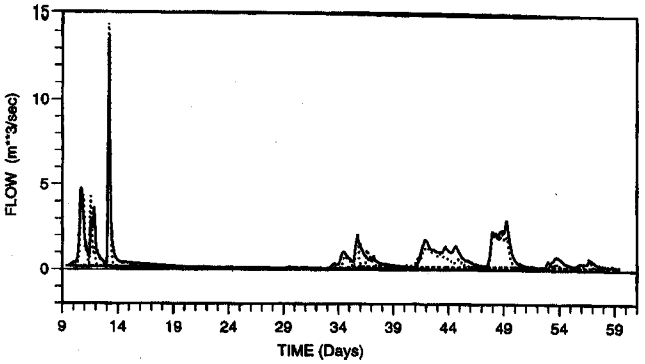


Fig. 4. *Maps of the Monachyle Burn and Trout Beck catchments showing the river network, elevation, and locations of the automatic weather station and snow survey sites (grid coordinates in km). Inset maps show the locations of the catchments within the UK.*

(a) No snowmelt component, PDM catchment runoff model



(b) PACK module with PDM catchment runoff model



(c) PACK module with Simple Distributed Model

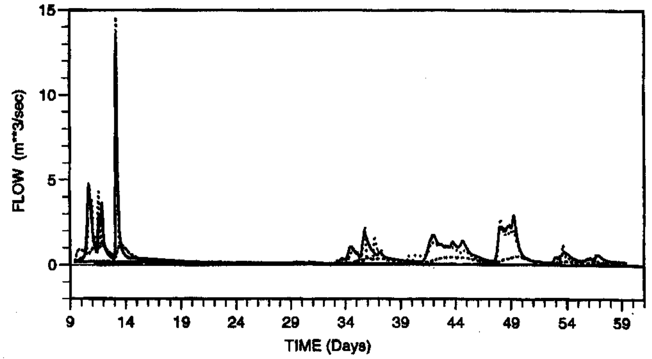


Fig. 5. *Effect of no snowmelt component and lumped (PDM) and distributed catchment runoff models; Lower Monachyle Burn near Balquhidder, 9 January to 28 February 1984. (Solid line: observed flow; dotted line: simulated total flow; dashed line: simulated 'baseflow'. Below origin (on a proportional scale) for (a) only: dashed line: simulated storage deficit).*

temperature excess melt equation, incorporating wind and rain heating effects, failed to improve on the performance obtained from the basic equation; results from this extended equation are therefore not presented. Evaluation of the energy balance melt formulation against the simple temperature excess equation is considered only for the Trout Beck catchment where better, and more detailed, measurements are available. The components of the energy balance contributing to potential melt are also analysed so as to gain a better understanding of the predominant melt mechanisms and determine which approximations are most likely to work. Results obtained from models incorporating elevation zones are presented only for the Lower Monachyle catchment since their use for the Trout Beck catchment made little appreciable difference. The importance of incorporating a snowmelt model in combination with a rainfall-runoff model is demonstrated for both catchments by obtaining flow simulations from a model without a snowmelt component.

Model results which exclude updating using snow observations are not presented. This is because updating is used in part to compensate for a lack of explicit measurements of snowfall. Raingauge data are declared missing when the pack is increasing and air temperature is below the snow/rain threshold value. At such times snow core, or pillow, measurements are used to re-initialise the pack water equivalent and density. Updating is not invoked during the melt phase, as judged by a non-increasing pack, so as to judge the simulation performance of the model. Thus, the partial updating used here is invoked (i) to re-initialise the snowpack to compensate for the lack of snowfall data, and (ii) to focus on a simulation-mode assessment of the different process model formulations. In practice, in a real-time flood forecasting context, the pack would be updated using the most recent observations of lying snow and measured flow at the catchment outlet would be used to correct further the model forecasts. Such forecasts are likely to be appreciably more accurate than those presented here, particularly for shorter lead times. The presence of a snow pillow in the vicinity of the Trout Beck catchment has allowed updating using daily snow core measurements to be compared with updating using hourly snow pillow observations; no pillow exists in the proximity of the Monachyle catchment. A feature of the Monachyle snow core dataset is that on some days only snow depth is recorded, and not water equivalent. Results have been obtained using water equivalent alone and in combination with snow depth measurements.

The availability of data for only one snow season per catchment has meant that the model variants have been calibrated and evaluated on the same dataset. Also the partial cover component of the PACK module has not been invoked due to lack of data activating this feature of the model.

RESULTS OF EVALUATION

Model results for the Lower Monachyle have been obtained for the exceptionally snowy period from 9 January to 28 February 1984 when daily snow cores were made at Tulloch Farm. Snow was present on the catchment from 12 January to mid February. Temperatures over this period ranged from –14 to 8 °C, with above zero temperatures corresponding with periods of rain, snowmelt and higher flows. An hourly time-step is used corresponding to the flow, rainfall and temperature data available over this period. Performance is assessed (i) with

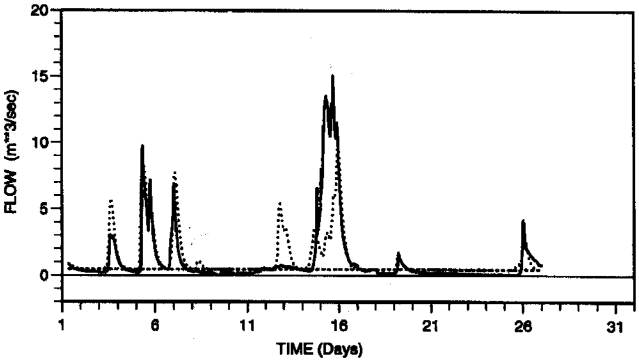
Table 2. Assessment of model performance: Monachyle Burn, 9 January to 28 February 1984

Model features	Objective function	Flow R^2		Snow WE R^2	
		Distributed Model	PDM Model	Distributed Model	PDM Model
Ignores snow	Flow	—	0.457	—	—
(a) Updating using Snow WE and depth					
Single elevation zone	Snow WE	—	—	—	0.997
	Flow	—	0.799	—	0.974
Five elevation zones	Snow WE	—	—	0.999	0.998
	Flow	0.843	0.811	—	0.933
(b) Updating using Snow WE only					
Single elevation zone	Snow WE	—	—	—	0.904
	Flow	—	0.816	0.862	–2.98
Five elevation zones	Snow WE	—	—	0.909	0.909
	Flow	0.898	0.873	–3.69	–1.86

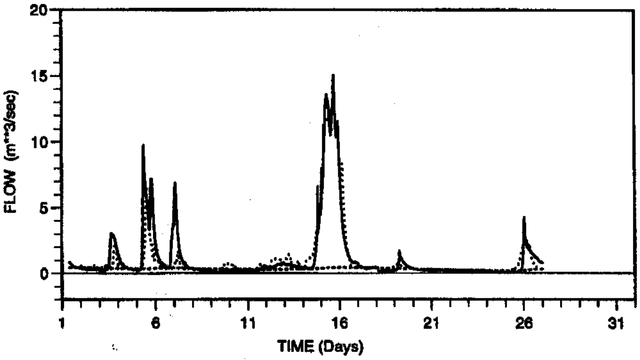
regard to snow water equivalent, measured at the snow survey site and predicted from the PACK snowmelt module, and (ii) with regard to observed flow and the coupled PACK and catchment model simulation of flow. In the former case, only periods of melt with no snowfall (which is not measured explicitly) are used when forming the R^2 performance statistic (this gives the proportion of variance in the observations accounted for by the model simulation). Since there are only a few such periods, the values of R^2 obtained are close to unity and tend to give too good an impression of model fit. Table 2 and Fig. 5 present a selection of results obtained, highlighting the poor simulation of flow when snow is ignored (R^2 = 0.457), the improvement introduced by incorporating a PACK snowmelt module with five elevation zones (R^2 = 0.873, an increase from 0.816 for one zone) and the use of a distributed rather than lumped (PDM) catchment runoff model (R^2 = 0.898, an increase from 0.873 for the PDM model). Note that the more frequent updating of the pack made possible by the inclusion of snow depth observations (at times when no water equivalent values are available) makes the snowpack model more robust, as judged by the Snow WE R^2, when using flow to optimise the model; negative Snow WE R^2 values result when updating is done less frequently, corresponding to the times when the snow cores are weighed to obtain water equivalents. However, surprisingly, this more frequent updating worsens the more important Flow R^2 values, for example from 0.898 to 0.843 in the case of the Distributed Model. This may reflect the poor siting of the snow survey site with respect to the catchment, being 5 km from the catchment and 167 m lower in altitude than the catchment outlet.

Results for the Trout Beck catchment using the PDM catchment model have been obtained for the snowy period from 4 to 30 December 1993. Snow was present on the catchment from 8 December onwards. Temperatures over this period ranged from –9 to 8 °C, with above zero temperatures generally corresponding to periods of higher flow. A selection of the results is presented in Table 3 and Fig. 6. A 15 minute time-step is used corresponding to the flow and rainfall measurement data interval; hourly weather station data are employed. Ignoring the presence of snow produces a poor model forecast (R^2 = 0.484). Model calibration results were obtained using either daily snow core data or hourly snow pillow measurements, in addition to river flow. The snow pillow data in this case seems to offer no advantage over the daily snow core measurements when predicting river flow (R^2 of 0.839 compared to 0.854). Note that the water equivalent results are not comparable, with only six snow core observations as opposed to 570 snow pillow values. All results relate to the use of a single elevation zone since no improvement was obtained using more. The more complex energy budget melt formulation provides worse results than the simple temperature excess melt equation used as standard. However, the energy budget model used with the Moor House AWS data has proved useful in understanding the mechanism of melt during the main melt phase on 17 and 18 December 1993. This is discussed in the next section where a physical interpretation for the success of the simple melt equation based on temperature excess is given. Note that the use of the energy budget formulation involves only one parameter to be optimised, the aerodynamic roughness, whilst the temperature excess equation involves both the melt factor and threshold melt temperature. It is unlikely that the poorer results obtained using the energy budget formulation reflect calibration problems.

(a) No snowmelt component



(b) Snow survey data



(c) Snow pillow data

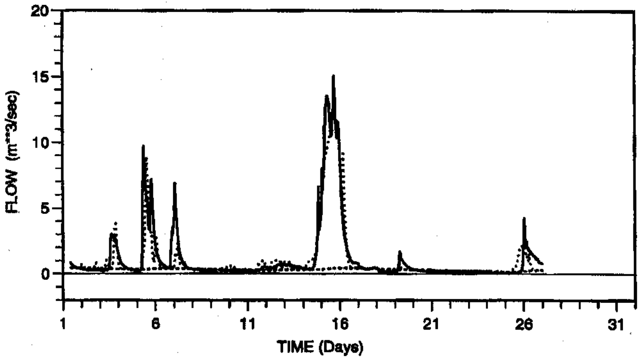


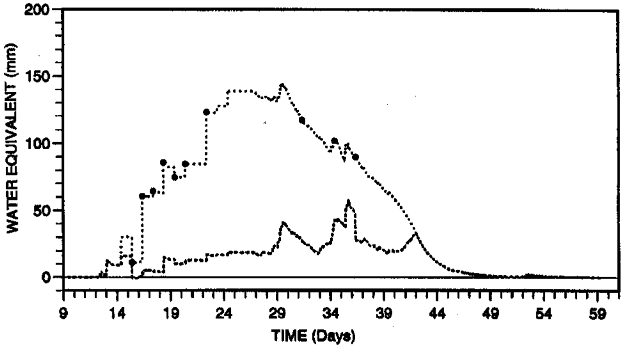
Fig. 6. *Effect of no snowmelt component and snowmelt models calibrated using snow survey or snow pillow data; Trout Beck, 4 to 30 December 1993, PDM catchment model. (Solid line: observed flow; dotted line: simulated total flow; dashed line: simulated 'baseflow'.)*

Finally, Fig. 7 presents plots of the PACK snowmelt model predictions compared with the snow survey observations obtained for the two catchments, and snow pillow observations in the case of Trout Beck. Note the tendency for snow to melt preferentially from the pillow (Fig. 7(c)) than from the surrounding land (as indicated by the snow survey measurements and model results in Fig. 7(b)); day 15 is especially relevant.

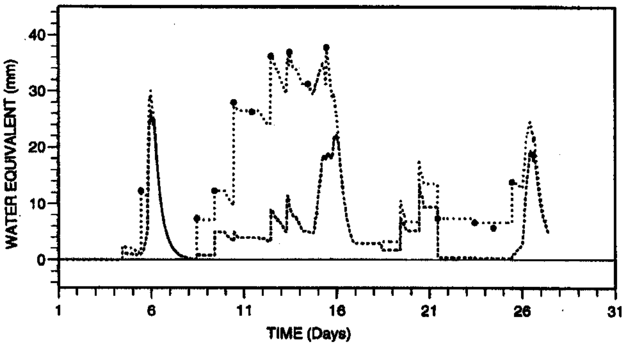
A physical interpretation

Of particular scientific interest is an analysis of the energy components of melt during the melt phase on 17 and 18 December 1993 at Moor House in the Trout Beck catchment. The components of potential melt are estimated using meteorological observations from the automatic weather station at Moor House as input to the energy balance model; fixed values of albedo (0.5) and groundmelt (2 W m^{-2}) are assumed. Figure 8 shows the energy flux in W m^{-2} of the main components contributing to potential melt and the cumulative energy expressed as mm melt potential; note that 1 W m^{-2} equates over a day to 0.258 mm melt potential. The temperature rose from freezing early on the 17th to 8 °C at midnight on the 18th. Over this period, potential melt occurred in almost equal measure by sensible heat exchange and by latent heat of condensation, as warm air near saturation in cloud condensed on the

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



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



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

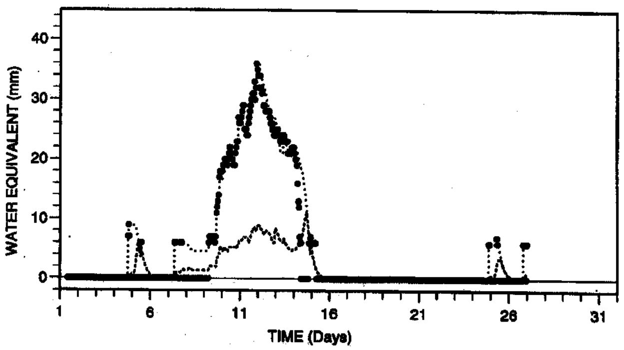
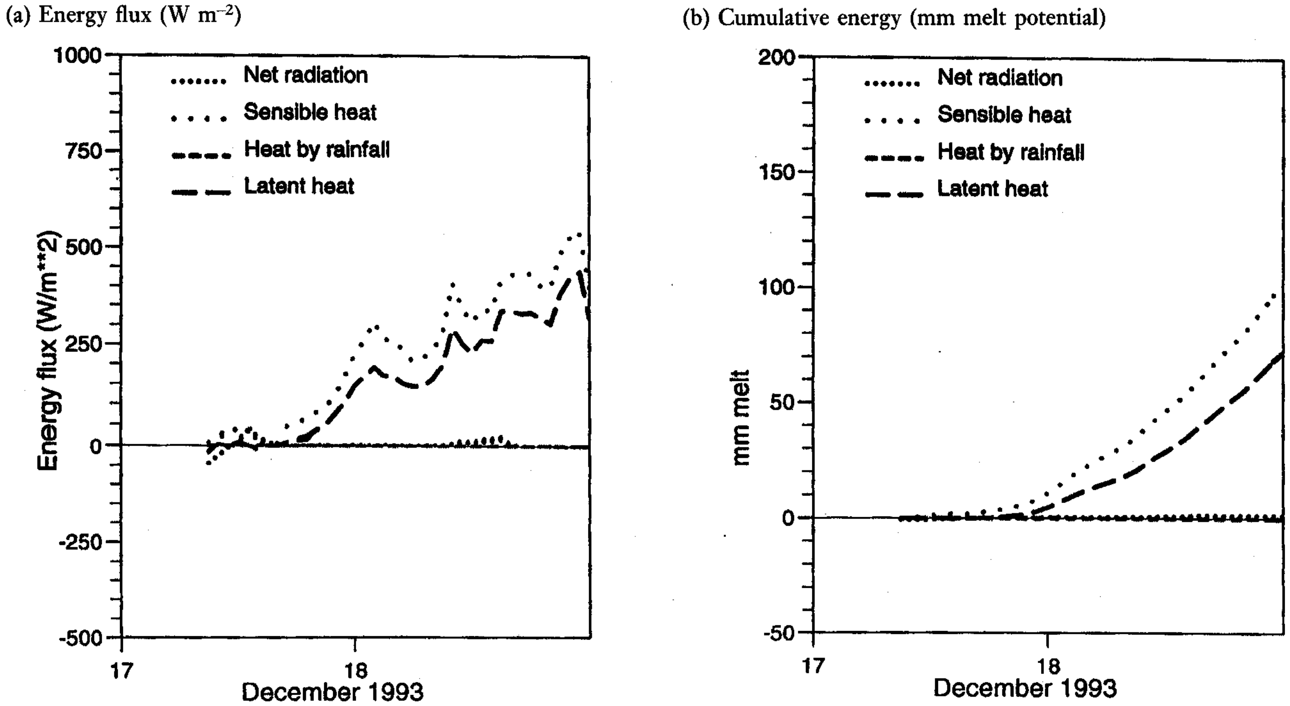


Fig. 7. *Measured (large dots) and predicted (dotted line) snow water equivalent, and wet snow component (dashed line) using snow survey and snow pillow observations.*

Table 3. Assessment of model performance: Trout Beck, 4 to 30 December 1993

Model features	Objective function	Flow R^2		Snow WE R^2	
		Distributed Model	PDM Model	Distributed Model	PDM Model
Ignores snow	Flow	—	0.484	—	—
(a) Updating using Snow WE and depth					
Temperature excess	Snow WE	—	—	0.999	0.999
	Flow	0.840	0.854	0.997	0.995
Energy budget	Snow WE	—	—	—	—
	Flow	—	0.731	—	0.999
(b) Snow pillow data					
Temperature excess	Snow WE	—	—	0.940	0.924
	Flow	0.476	0.839	0.918	0.869
Energy budget	Snow WE	—	—	—	0.630
	Flow	—	0.427	—	0.444

snowpack. Net radiation in this upland cloudy environment was negligible in contrast to conditions of melt in Alpine areas and on occasions (particularly in Spring) in the Scottish Highlands. The dominance of turbulent heat exchange in the melting process explains the success of the simple temperature index method for melt conditions experienced in upland Britain. Over these two days, the potential melt water equivalents attributed to sensible heat and latent heat transfer are 100 and 70 mm respectively, giving a total of 170 mm. This potential melt rate is consistent with Archer's observations (Archer, 1981) of rates as high as 60 mm day^{-1} in this area, with peak rates of 5 mm h^{-1}, and provides a physical explanation for such high rates under cloudy skies in upland Britain. These results also reinforce the findings of Mawdsley *et al.* (1991) who were unable to quantify the potential melt due to conden-


(a) Energy flux (W m^{-2})

(b) Cumulative energy (mm melt potential)

Fig. 8. *Components of the energy balance for Moor House, from the start of above freezing temperatures to the disappearance of snow, 09.00 17 to 00.00 19 December 1993.*

sation but recognised its significance along with sensible heat. Note that the potential melt volumes would not have been realised in practice given that the snow water equivalent at both the snow pillow and survey site peaked at a value of only circa 38 mm. The cumulative effect of radiation melt might be expected to prove more important for longer-lived, deeper packs during the Spring season and be more typical of catchments at higher elevations in the Highlands of Scotland. However, as previously discussed, radiation-dominated melt is less likely to be associated with flooding conditions; also, its effect on the snowpack water equivalent can be corrected via state updating prior to the main melt phase.

Conclusions

This investigation has demonstrated that a snowmelt component within a catchment runoff model can prove essential for successful flood forecasting in upland Britain. Whilst the two catchments considered here do not experience significant damage from flooding, they may be thought of as indicative of others that do. Upland catchments of this kind also feed to lowland rivers where the cumulative effect of snowmelt in the uplands (and possibly lowlands) can be a significant component of the flood response. The results suggest that in higher relief catchments, even of modest size, model performance can be improved through the use of elevation zones to introduce the effect of temperature lapse rates on melt. Whilst this may not always be the case, as seen with Trout Beck, use of elevation zones appears to offer a conservative option. Given that elevation zones can be delineated automatically with the aid of a digital terrain model, along with the fractional area of the catchment they occupy, their use in a model is also very easy to invoke. Neither lumped nor distributed catchment runoff models prove consistently superior. Again digital terrain models are helpful in automating the configuration and parameterisation of the distributed model: they are used to define the isochrones used for flow routing and the absorption capacities controlling runoff production (Bell and Moore, 1998a).

Updating a snowmelt model using snow core, or pillow, measurements can serve to re-initialise the model snowpack after times of snowfall, when the absence of direct measurements prevents the water balance of the model pack being properly maintained. Hourly snow pillow estimates of snow water equivalent provide an attractive alternative to daily snow core measurements, particularly for remote sites that might be inaccessible at times of significant lying snow. However, the experience here indicates that care is needed in using these data and preferential melting over the pillow, relative to the surrounding land, can be a problem.

An analysis of the energy budget during the final phases of melt suggests that latent heat, generated by condensation on the pack, can be as large as sensible heat when the uplands are under cloud in warm moist air, typical of frontal conditions. Radiation plays only a minor role at such times. This explains the success of the simple temperature excess method for melt conditions experienced in upland Britain during the main melt phase giving rise to flooding. The simplicity of this melt function, its limited data requirements and physical justification, as an approximation under typical "main melt phase" conditions experienced in upland Britain, argues for its adoption. The results for Trout Beck support this view, although they are limited to just one snow season and catchment. Maintaining reliable measurements during adverse conditions, particularly of humidity, in support of an energy balance approach must be seen as a problem; extrapolating such measurements to obtain melt rates relevant at the catchment scale brings further difficulties and further justifies a simpler approach. The stability of the melt factor in the temperature excess method has still to be investigated, with the help of more field data, and may provide the reason for pursuing a more complex melt formulation.

Model development and evaluation is currently constrained by a lack of data for significant snowmelt events, especially in Scotland, and further field monitoring is needed to gain greater confidence in the operational use of snowmelt models for flood forecasting and warning. Characterising the distribution of snow cover and weather variables over a catchment poses a major research challenge for the improved specification of a distributed snowmelt model suitable for flood forecasting. Model parameterisation supported by a digital terrain model, together with new advances in satellite imagery, is thought to be a fruitful area for future research.

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