A Prototype Physically-Based Model for the Prediction of the Spatial Distribution of Snowcover

K.M. SAMBLES, A. HARRISON AND M.G. ANDERSON

Department of Geography
University of Bristol
University Road
Bristol BS8 1SS, United Kingdom

T. PANGBURN

U.S. Army Cold Regions Research and Engineering Laboratory
72 Lyme Road
Hanover, New Hampshire 03755-1290, U.S.A.

ABSTRACT

A prototype digital model, SNOMO, has been developed to predict the pattern of snowcover and snowdepth distribution over a small catchment during the melt season. The catchment is subdivided into homogeneous areas on the basis of elevation, slope angle, aspect and vegetation cover using a GIS driven algorithm. The energy-budget of the snowpack is calculated for each area. A simplified version of the snowpack internal structure and characteristics is used to alleviate data availability problems. The energy-budget terms are used to calculate the amount of melt, which is then subtracted from the existing snowpack depth in terms of centimetres of snow. The model has been tested on the W3 watershed ($8.4 km^2$), part of the Sleepers River Research Watershed, Danville, Vermont. Point predictions are shown to accord well with observed values and spatial predictions of snow distributions for the complete catchment are presented.

INTRODUCTION

This paper presents a prototype distributed physically-based model, SNOMO (SNOw MOdel), that has been developed in response to the following criteria:

(1) A dichotomy exists at present between, as Ferguson & Morris (1987) state: "the sophistication of physics-based models available for predicting snowmelt at a point ... and the crudity but convenience of traditional models for snowmelt at the basin scale using valley-level air temperature as the main or sole predictor".

(2) There are currently no physically-based models that predict the pattern of snowcover and snowdepth distribution.

We realise that there are advantages (Roberge et.al., 1988) and disadvantages (Anderson, 1978) of using both index and physically-based models, but argue that to be of utility as a research tool a model would have to be a physically-based distributed model. A physically-based distributed model allows the simulation of varied environments and the modelling of the changes in the physical characteristics of the snowpack and the detailed snowcover and snowdepth distributions, these attributes are unobtainable with an index model.

The objectives of the proposed model are:

1 To simulate the pattern of snowcover and snowdepth distribution during the melt season.

2 To simulate the changes in the physical characteristics of the snowpack during the melt season.

3 To operate at an optimum complexity which ensures a balance between data availability, computational time and model methodology, but which utilizes fully physically-based equations wherever possible.

4 To simulate the volume of meltwater runoff.

The pattern of snowcover and snowdepth distribution is dependent upon the scale of the area which is being considered. This paper will consider the local scale, using Stepphun & Dyck's (1974) definition, that is 1000-5m^2. At this scale snowmelt patterns relate to local, within-field terrain variables (elevation, aspect and slope angle), vegetation distribution and vegetation variables (canopy density, tree species) and land use practices. These factors modify the snowpack energy-budget, resulting in differential snowpack conditions and depths. Additional factors such as snow drifting will also cause differential snowpack conditions and depths.

MODEL DESCRIPTION

2.2 Model structure

The basic structure of SNOMO is shown in figure 1. SNOMO operates on the basis of the subdivision of the catchment into computational areas (cells). The cells are homogeneous with respect to slope angle, aspect, elevation and vegetation cover. The snowdepth is calculated for each cell using the equations and logic structures described below. The results for each cell are then summarized for the whole catchment to obtain the pattern of snowcover and snowdepth distribution over the catchment.

SNOMO is based on the calculation of melt using the energy-budget equation:

$$\Delta Q_m = Q^* + Q_c + Q_e + Q_g + Q_p - \Delta Q_s \qquad (1)$$

where,

ΔQ_m latent heat storage change due to melting or freezing.

Q^* net radiation

Q_c sensible heat flux

Q_e latent heat flux

Q_g heat introduced to the pack from the ground

Q_p heat introduced to the pack by rain

ΔQ_s net heat storage term

(units: $MJm^{-2}day^{-1}$)

The components Q^*, Q_c and Q_e of equation (1) are calculated using a modified version of the Terrain Surface Temperature Model (TSTM), Balick <u>et.al.</u> (1981a & b). The TSTM is a finite difference physically-based energy-budget model originally used for the calculation of the surface temperature of a surface (soil, man-made or vegetated). The modifications made in SNOMO to the original TSTM are extensive and are primarily concerned with the reduction of the input requirements, the lengthening of the simulation time, the extraction of the output values for the components Q^*, Q_c and Q_e of equation (1) and the interfacing of the modified TSTM with the prototype model SNOMO. The modified TSTM calculates the snowpack surface temperature and this is also used in equation (1), as part of the calculation of ΔQ_s (equation 3). If required (for example, for validation purposes) the incoming and reflected long- and shortwave radiation and the snowpack temperatures at depth can be extracted from the modified TSTM, as these are calculated within the TSTM.

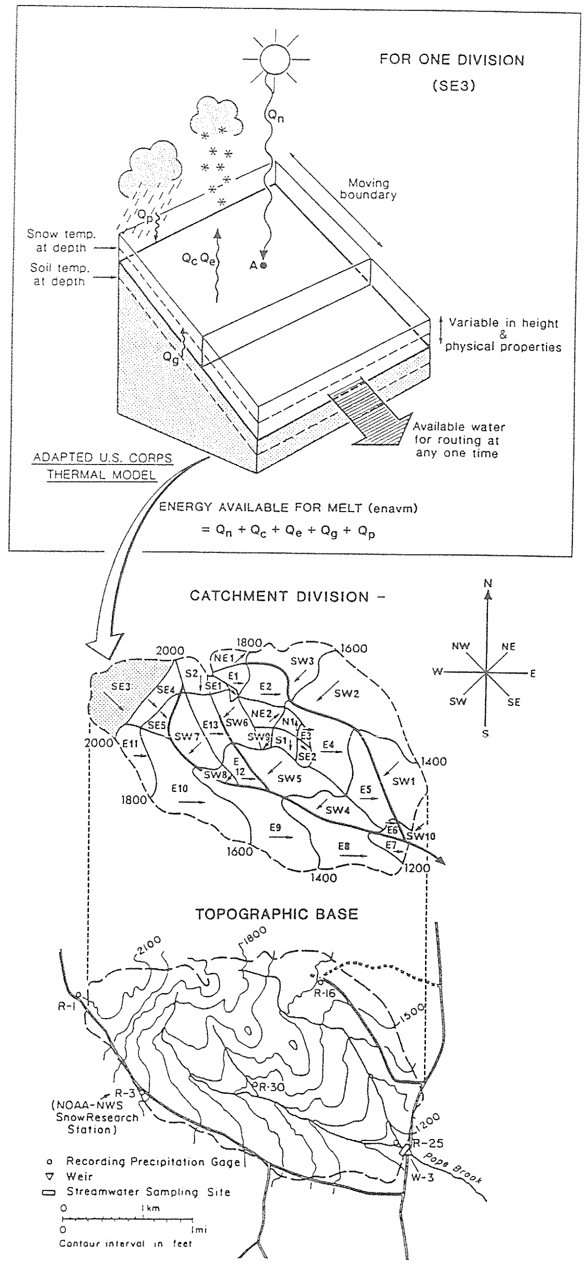

Figure 1. Basic structure of SNOMO.

The remaining components of equation (1) are calculated using physically-based equations taken from the literature. Q_p is calculated using equation (2), taken from Male & Granger (1978):

$$Q_p = \rho_w Cp_w (T_p - T_{sn}) P/1000 \qquad (2)$$

where,

ρ_w density of water, kgm^{-3}

Cp_w specific heat of water, $kJkg^{-1}\circ C^{-1}$

T_p temperature of rain, °C

T_{sn} temperature of snow, °C

P precipitation rate, $mmday^{-1}$.

ΔQ_s is calculated using equation (3), taken from Anderson (1976):

$$\Delta Q_s = (d\rho_{sn})^t \, [(Cp_i T_{sn})^{t+\Delta t} - (Cp_i T_{sn})^t] \qquad (3)$$

where,

d depth of snowpack, m

ρ_{sn} density of snow, kgm^{-3}

Cp_i specific heat of ice, $MJkg^{-1}\circ K^{-1}$

T_{sn} snow temperature, °K - calculated by TSTM

t time unit, one day

Q_g is set to zero. It is realised that in reality Q_g is usually greater than zero. However, various studies (Male & Gray, 1981 and Kuusisto, 1986) indicate that in most snow environments Q_g is a small or insignificant component of the snowpack energy-budget. Therefore to simplify the modelling conditions for the prototype model Q_g is set to zero.

The meltrate (in centimetres of snow or millimetres of water equivalent) is therefore expressed as:

$$\Delta r = \frac{\Delta Q_m}{L_f \rho_{sn}} .100 \qquad (4)$$

where,

Δr melt rate, cm snow day^{-1}

L_f latent heat of fusion, $MJkg^{-1}$

SNOMO models the physical characteristics of the snowpack such as the albedo, thermal diffusivity and density by the operation of a simplistic snowpack layering routine. The snowpack is modelled as either 'old' snow, 'new' snow or as a layered combination of both. The maximum number of snow layers is two ('old' underlying 'new' snow). The 'old' and 'new' snow each have a characteristic density, albedo, emissivity, thermal conductivity and thermal diffusivity which is unvaried throughout the simulation. The values for these characteristics are obtained from the literature (Oke, 1987, Grey & Male, 1981 and Balick et.al., 1981a). A logic structure converts 'new' snow to 'old' snow and vice versa, depending upon the occurrence and timing of snowfall or melt and the relevant physical characteristics are utilized to calculate melt. Mean snowpack density is also calculated if the pack is two-layered. Compaction and reduction in pack height occurs with conversion of 'new' to 'old' snow. The modification of the snowpack energy-budget components by forest vegetation is modelled by VEGIE, a submodel of the TSTM (Balick et.al., 1981b). Again, VEGIE has been modified to accommodate addition to SNOMO.

The equations and logic structure discussed above are the basic components of SNOMO. The input data required for SNOMO is shown in table 1. If a forest snowpack is being modelled then the vegetation input parameters shown in table 1 are also required. These can be obtained from the relevant literature (Geiger, 1965 and Deardorff, 1978), if the vegetation cover type is known. SNOMO has been designed to require a minimum of daily field measured data. The minimum daily measurements that are required are cloud cover, relative humidity, air temperature, precipitation and wind speed. A stochastic sensitivity analysis performed on the variables relative humidity, wind speed, air temperature and precipitation concluded that the model SNOMO was insensitive to these variables. SNOMO is designed, at present, to model the pattern of snowcover and snowdepth distribution over small catchments (<20km^2). SNOMO is designed to operate using daily meteorological input data that is taken from a site that is either within the catchment boundary or in close proximity to the boundary. The input variable air temperature is modified for elevation from its measurement site using a local lapse rate.

Table 1. Operational data requirements

Instrument shelter height
Latitude

For each cell:
Air pressure
Air temperature (maximum and minimum) *
Cloud cover amount *
Cloud cover type
Elevation
Initial snowdepth
Julian day
Precipitation amount
Relative humidity *
Slope angle
Slope aspect
Snow density
Snow surface absorptivity
Snow surface emissivity
Snow heat conductivity
Snow thermal diffusivity
Wind speed *

For a vegetated cell, in addition:
Foliage cover fraction
Foliage emissivity
Foliage height
Foliage shortwave absorptivity
State of vegetation

* daily input data.

The subdivision of the watershed into computational units (cells) is facilitated by the use of a GIS. The subdivision of the catchment into homogeneous units (cells) was undertaken as follows:

(1) The topographic and vegetation cover maps and the catchment mask were digitized.

(2) A Digital Elevation Map (DEM) was created from the digitized topographic map, using the algorithm by Roberts (1980).

(3) Maps of slope angle and aspect were obtained from the DEM using algorithms from Garg & Harrison (1990).

(4) The slope, aspect and elevation were taken from the digitized topographic map and clustered to determine a set of spatially unique terrain classes. The clustering algorithm used was that available on the I^2S image processing system. The means and standard deviations of the values in each terrain class are available.

(5) The boundaries of the terrain classes were smoothed and isolated pixels, edge affects and misclassified areas were removed. The catchment mask was also superimposed. This resulted in set of terrain cells each with a dominant terrain class (slope angle, aspect and elevation).

(6) The vegetation map was superimposed upon the terrain cells and the vegetation within each cell assigned the dominant vegetation type.

The subdivision algorithm resulted in the subdivision of the catchment into cells. The location, area, mean slope angle, mean aspect and mean elevation of each cell is known. The primary advantages of the subdivision algorithm are that it is objective, repeatable and provides some indication of the variability within each cell.

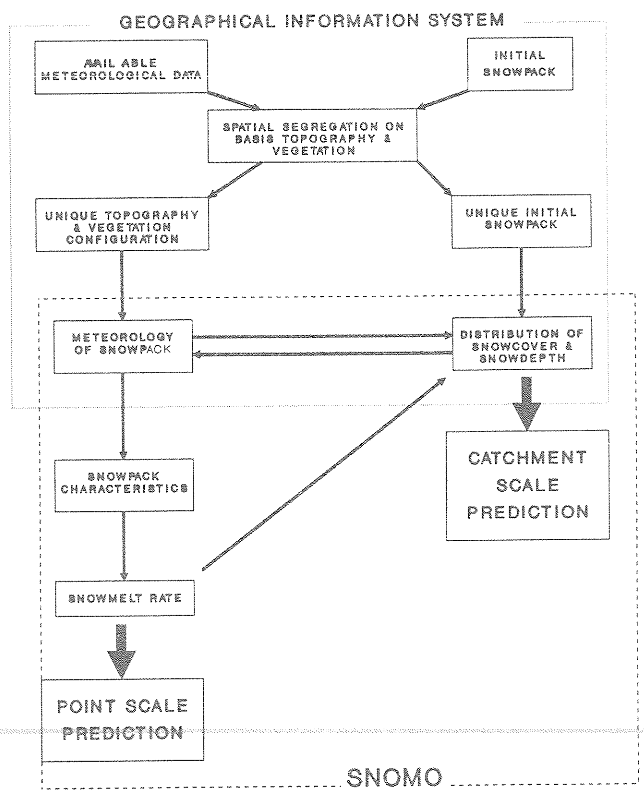

Figure 2. Relationship between SNOMO and the GIS.

The relationship between SNOMO and the GIS is shown in figure 2. The equations discussed above are solved for each cell and spatial output is obtained using the ARC-INFO data manipulation package. The primary output from the prototype model SNOMO is snowdepth and snowmelt volume (snowmelt volume = Δr x cell area). Additional outputs are snow temperatures and the snowpack energy-budget components of incoming and reflected short- and longwave radiation, Q_c, Q_e, Q_p and Q_g. These outputs are calculated for every cell. The results for every cell are plotted on the catchment division map for the simulated catchment to obtain the spatial distribution of these outputs. The spatial distribution of the snowdepth output indicates the snowcover distribution.

MODEL APPLICATION

Watershed selection

The W3 catchment, Sleepers River Research Watershed, Danville, Vermont, is considered to be representative of the landuse, cover, soil and topographic conditions that are found in the northern areas of the New England states and southern Quebec. A more detailed description of W3 is given in Anderson, et.al. (1977) and Pionke, et.al.(1978). The basin has an area of 8.4km^2 and varies in elevation from 346 to 695 metres above mean sea level. Vegetation cover is predominantly forest, coniferous, deciduous and mixed with some areas of open pasture. There is no arable land at W3. The main deciduous species are Birch (yellow - *Betula allegheniensis*, white - *B. papyrifera* and grey - *B. populifolia*), Beech (*Fagus americana*) and Maple (sugar - *Acer saccharum* and red - *A. rubrum*). The major coniferous species are Red Spruce (*Picea rubra*) and Balsam Fir (*Abies balsamea*). There has been and continues to be forestry activity in certain areas of W3, mainly in the coniferous areas which has resulted in large tracts of clear-cut.

Model predictions

The model was run for the 1988 melt season at W3. Figure 3 shows the predicted snowdepths against the observed snowdepths at the Townline meteorological station. Figure 3 shows that an acceptable level of correspondence is achieved for those days on which observations are available from the meteorological station. Figure 3 also shows

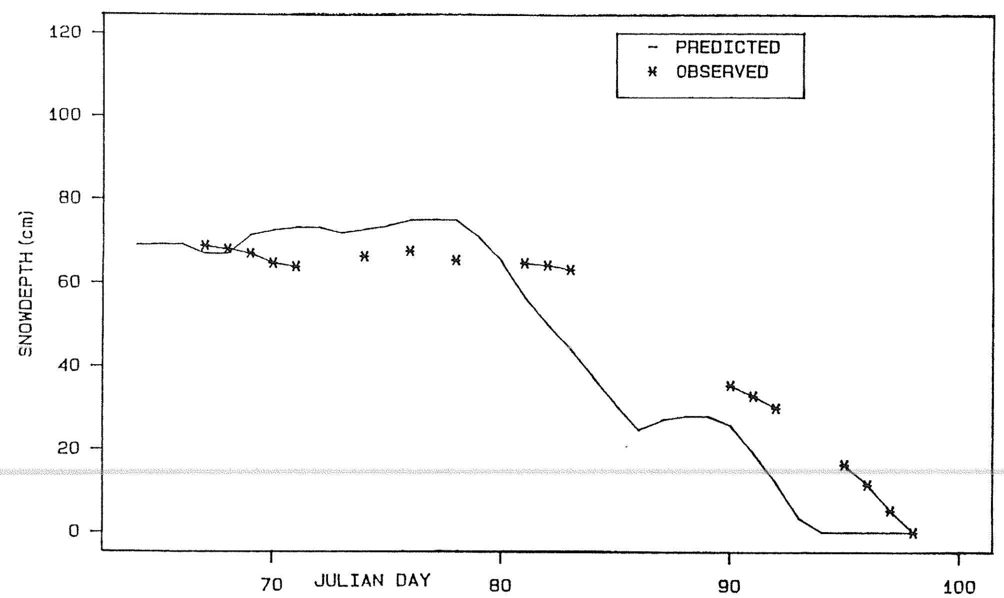

Figure 3. Predicted against observed snowdepths for the Townline meteorological station, W3 catchment, 1988.

that the model has a tendency to overpredict the snowmelt, that is to predict that the snow melts faster than in reality. This results in a four day discrepancy between observed and predicted total snow disappearance. This level of predictive accuracy is within acceptable limits due to the problems in obtaining a representative snowdepth. Snowcover is highly variable and a predictive discrepancy of about 10cm and 4 days is acceptable at present. The model is a prototype and further investigations as to its sensitivity to variables such as cloud cover and initial snowdepth will be conducted.

Table 2. Comparison between the calculated and observed snowdepths (centimetres) for points over the W3 catchment.

CELL 29 (Deciduous, 1832m elevation, 8.45°slope, 99°aspect)

Julian day	Calculated	Observed (1)	Observed (2)
83	72	65	73
90	61	46	49
97	23	15	13

CELL 30 (Deciduous, 1969m elevation, 9°slope, 143°aspect)

Julian day	Calculated	Observed (1)	Observed (2)
83	68	65	73
90	55	46	49
97	12	15	13

CELL 9 (Mixed, 1226m elevation, 4°slope, 77°aspect)

Julian day	Calculated	Observed
83	60	55
90	53	30
97	21	0

CELL 24 (Open, 1563m elevation, 6°slope, 79°aspect)

Julian day	Calculated	Observed (1)	Observed (2)	Observed (3)
83	46	47	49	58
90	28	24	21	26
97	0	0	0	0

Table 2 shows the calculated and observed results for selected cells within the W3 catchment and demonstrates the range of conditions that exist at W3. Again the simulations are acceptable. Table 2 illustrates the problem of validating a model such as SNOMO. The difficulties of obtaining a representative snowdepth, to use as a validation tool are apparent. The observed values in table 2 are snowcourse values, that is they are the mean value of 5 snowdepths measured at adjacent snowcourse sites. Some cells (cells 29, 30 and 24) possessed more than one snowcourse site within the cell. The variation of the measured snowdepth between these sites is as much as 9cm. The utility therefore of validating a model such as SNOMO, which predicts snowdepth, and expecting exact correspondence between the simulated and the measured snowdepths is questionable. Correspondence within a certain range of values and exhibition of a correct melt trend would be of more use and is the result that SNOMO achieves

Figure 4 shows the results of the spatial plotting of the cell results showing the first day of zero snowcover (melt day). Validation of this prediction and the spatial predictions is not really possible at present because of insufficient snowcover data

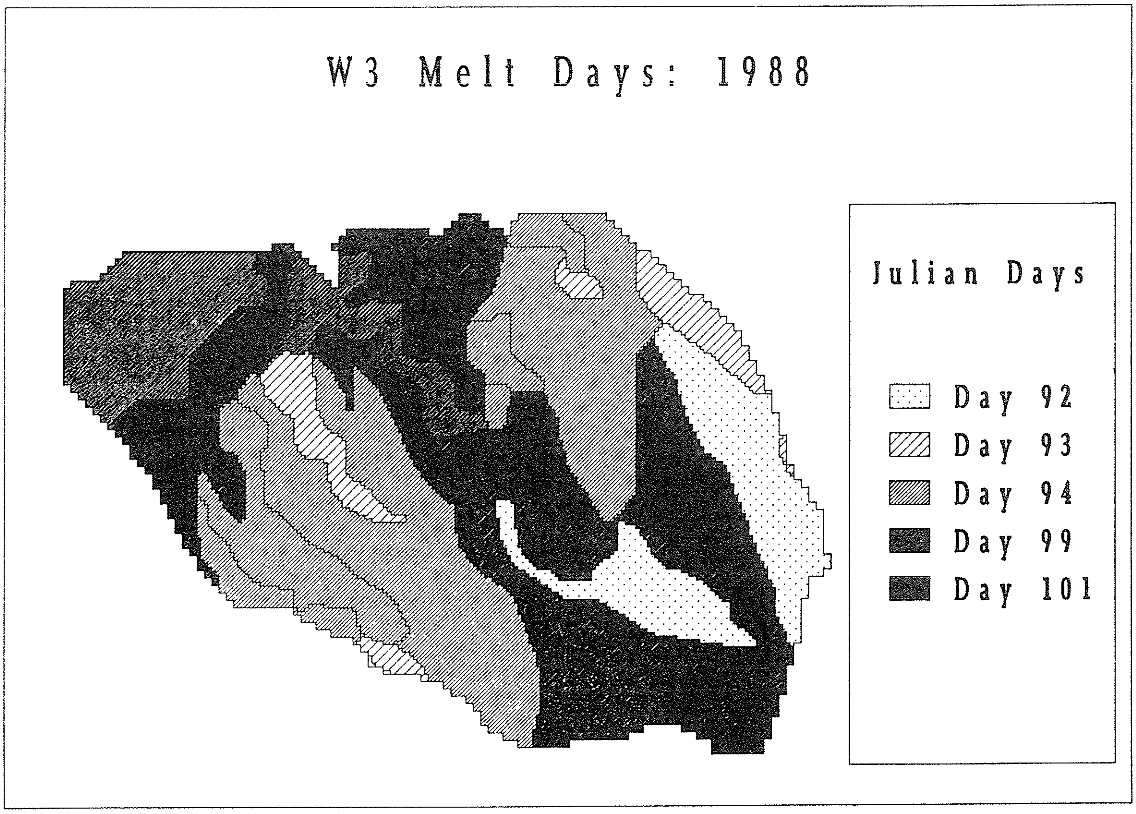

Figure 4. Melt day prediction for the W3 catchment, 1988.

over the entire catchment, only spatially restricted point observations (such as at Townline) are available.

The scope of the prediction that the SNOMO scheme offers clearly facilitates the establishment of field research designs in respect of snowdepth field measurement programmes. This is a major element of validation concern because of the resources and time demands in establishing field depths over large spatial areas on a daily basis. The argument would therefore be that initial prototype predictions could be undertaken using SNOMO to devise a field validation design against which subsequent runs of SNOMO would then be validated.

DISCUSSION

A GIS driven physically-based catchment scale distributed model has been developed and presented (equations 1-4). Initial results of this energy-budget scheme appear encouraging in terms of both point predictions and spatial resolution when applied to the catchment scale. Problems of validation of this snowcover prediction model appear to represent the next area of research. We have suggested that prototype runs on selected input data scenarios may be an appropriate approach to the problem of selecting field locations for snowdepth measurements during melt at the catchment scale. The primary utility of the prototype model SNOMO is in the calculation of spatial snowdepth and snowcover distribution. The variable initial snowpack extent is an important variable in many snowmelt forecasting models, for example, Rango & Martinec (1982) and Ferguson (1984). The calculations used in SNOMO are physically-based unlike, for example, the Leaf & Brink model (1973a & b) which calculates spatial melt using a mixture of temperature and semi-physically-based methods. The use of physically-based equations enables the additional output (if required), on a spatial basis, of the energy-budget values of incoming and reflected short- and longwave radiation, Q_c, Q_e, Q_p and Q_g. The spatial and physical basis of the prototype model SNOMO enables the potential inclusion of SNOMO into a suite of models to predict the eco/hydro-system, for example in a forest ecosystem model. The subdivision of the catchment is conducted using an original computerized division method. This is advantageous when compared to current manual division methods, for example Leaf & Brink (1973a & b) and Stepphun & Dyck (1974). The SNOMO subdivision is objective, repeatable and gives an indication of the variability present in the resultant subdivision.

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