Nordic Hydrology, 25, 1994, 1-24

Entering the Era of Distributed Snow Models

Paper presented at EGS XVIII General Assembly
(Wiesbaden, Germany – May 1993)

R. Kirnbauer, G. Blöschl and D. Gutknecht
Inst. for Hydraulics, Hydrology and Water Resources Mgm.,
Technical University of Vienna, Austria

Traditionally, snowmelt modelling has been governed by the operational need for runoff forecasts. Parsimony in terms of model complexity and data requirements was a major concern. More recently, the increased importance of analyzing environmental problems and extreme conditions has motivated the development of distributed snow models.

Unfortunately, the use of this type of models is limited by a number of factors including a) the extreme heterogeneity of the hydrologic environment, b) the mismatch of scales between observed variables and model state variables, c) the large number of model parameters, and d) the observability/testability problem.

This paper discusses the implications of these constraints on the use of site and catchment scale concepts, regionalisation techniques, and calibration methods. In particular, the point is made that in many cases model parameters are poorly defined or not unique when being optimized on the basis of runoff data. Snow cover depletion patterns are shown to be vastly superior to runoff data for discriminating between alternative model assumptions. The patterns are capable of addressing individual model components representing snow deposition and albedo while the respective parameters are highly intercorrelated in terms of catchment runoff.

The paper concludes that site scale models of snow cover processes are fairly advanced but much is left to be done at the catchment scale. Specifically, more emphasis needs to be directed towards measuring and representing spatial variability in catchments as well as on spatially distributed model evaluation.

Introduction

Snowmelt modelling has traditionally been governed by the operational need for runoff forecasts. Parsimony in terms of model complexity and data requirements was a major concern. The main applications included predictions of catchment yield (on a seasonal basis) and simulations of catchment runoff (typically with a time step of one day) (USACE 1956; Anderson 1973, 1979; WMO 1986). Early interest in snow process research resided in laboratory experiments and well instrumented sites (*e.g.* Anderson 1968, 1976; Colbeck 1987).

More recently, an increased number of applications require spatially distributed estimates of snow cover and snowmelt. Such applications include erosion modelling, solute transport and land use change. Also, there is a trend towards more emphasis on understanding processes at the catchment scale which has been stimulated by interest in the assessment of anthropogenic effects, extreme situations and ungauged catchments (Dozier 1987, 1989).

These trends resulted in the development of fully distributed snow models (*e.g.* Leavesley and Stannard 1989, 1990; Blöschl *et al.* 1989, 1991; Lettenmaier and Wigmosta 1993). Computing power is no longer a constraint and sophisticated remote sensing and data collection techniques are available (Gurnell 1990; Dozier 1992), so these developments seem to be a logical step forward. This is exemplified by the large number of contributions to the present volume. However, care must be exercised in interpreting simulation results as the use of this type of models is limited by a number of constraints.

The purpose of this paper is a) to briefly review the current state-of-the-art in fully distributed snow modelling, b) to identify strengths and limitations of the approach, and c) to give directions for future research.

Excellent reviews on hydrological modelling in general and distributed snow modelling in particular are given in Obled and Harder (1979), Lang (1986), Leavesley (1989), Obled (1990) and Bergström (1991).

The Nature of Distributed Snow Models

Processes in the natural snow cover environment occur at a range of space-time scales (Blöschl and Sivapalan 1994). Distributed snow models (DSM) attempt to quantify these processes by subdividing the catchment into a number of units (*i.e.* subareas). These units may either be so-called hydrological response units (*e.g.* Leavesley and Stannard 1990) or, for convenience, square grid elements. In such an approach, processes with a characteristic length scale smaller than the grid/element size are assumed to be represented implicitly (= parameterized) while processes with length scales larger than the grid size are represented explicitly by element-to-element variations (see *e.g.* Smagorinsky 1974). This is shown in Fig. 1

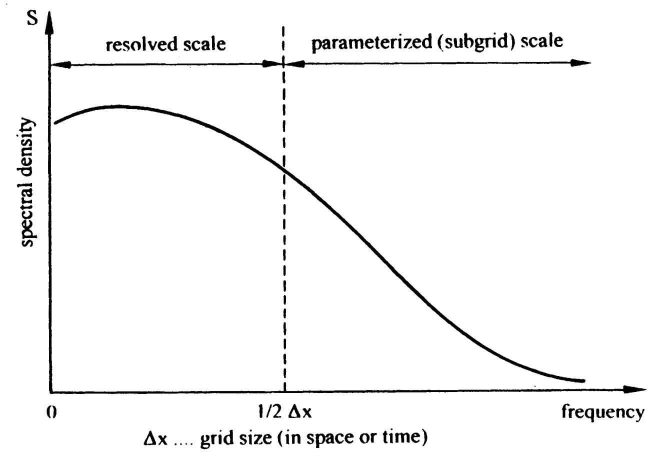

Fig. 1. Hypothetical power spectrum of snow cover related processes. Processes with a characteristic length scale smaller than the grid size are represented implicitly (= parameterized) while processes with length scales larger than the grid size are represented explicitly by element-to-element variations.

based on a schematic representation of the spectrum of some snow cover related process. For example, such a spectrum might be arrived at by, conceptually, sampling meltrates along a transect in a catchment and transforming these into the frequency domain. The spectrum in Fig. 1 indicates that large scale processes (low frequency) have more spectral power (= variance) than small scale processes which is typical of many hydrological phenomena. It is therefore reasonable to explicitly represent the large scale processes. The same applies to time scales and time spacings. The spectrum in Fig. 1 for snowmelt processes in the time domain, however, would show two marked peaks at frequencies corresponding to 1 day and 1 year.

Models that use elevation as the only criterion for spatial discretization are often referred to as semi-distributed models, while models with more detailed discretizations are termed fully distributed models. This review will focus on fully distributed models.

Virtually all DSM assume uniform parameters and processes within each unit. They also assume that site scale descriptions apply to the element scale and that the local (site) scale parameters are identical with the effective model parameters. 'Site scale' refers to the scale of a measurement site (or plot) which is of the order of 1 m. The 'element scale' refers to the dimension of a computational element and is in most cases much larger (*e.g.* 20-500 m). In DSM, processes in each element are often represented in considerable detail and include snow surface energy exchange and internal processes such as water and heat transport. To drive the models for each unit input parameters (*e.g.* precipitation, air temperature) need to be estimated for each element. This involves some sort of interpolation between observations.

The responses from individual elements should, ideally, be coupled (*e.g.* to account for lateral water flow in the snowpack, Colbeck 1978) but, more often than not, the individual elements are assumed to be independent. If required, snowmelt outflow from individual elements can be coupled with distributed or bulk runoff models.

Before using the model, proper calibration and/or evaluation is necessary. This is, in fact, not trivial and constitutes a major constraint in the use of DSM (*i.e.* the testability problem).

In summary, distributed snow modelling involves a) descriptions of snow processes at the site scale, and b) assumptions on discretisation, interpolation, and integration at the catchment scale. What follows is a brief review of concepts based on these two steps with an emphasis on distributed modelling.

Site Scale Approaches

Snow models at the site scale have enjoyed continuous attention and progress over the years. One of the main reasons for progress is that it is relatively easy to obtain detailed data for driving and verifying models. Among the processes at the site scale, snow surface energy exchange, internal processes and snow accumulation are of most importance to DSM.

A range of studies analyzed the relative importance of the individual components of snow surface energy exchange (*e.g.* Zuzel and Cox 1975; Male and Granger 1981; Kuusisto 1986; Blöschl *et al.* 1988; Dragoi *et al.* 1993). Typically, in mountainous regions, solar radiation is dominant while in lowlands turbulent transfer is the more important component for snowmelt. This is related to a) the later depletion in mountainous areas and consequently higher solar radiation, and b) lower air temperatures in higher altitudes and, consequently, less importance of turbulent transfer.

While modelling incoming solar radiation is reasonably well understood (*e.g.* Dozier 1980; Blöschl *et al.* 1987; Siemer 1988; Ranzi and Rosso 1991) modelling of the snow albedo is significantly less advanced (Colbeck 1988). Part of the problem is related to difficulties in its measurement. One of the early parameterisations of albedo is the so-called aging curve approach (USACE 1956) which is still frequently used (*e.g.* WMO 1986; Rohrer and Braun 1994). While there is a definitive tendency of albedo to decrease with time after snowfall it is important to notice that this relationship is not causal. More fundamental controls are snow grain size and impurities (Colbeck 1988). Marshall and Warren (1987), Choudhury and Chang (1981), Caroll and Fitch (1981), and Brun *et al.* (1989, 1992) proposed models that account for the effects of grain size as well as atmospheric controls.

Trofimova (1970) and Siemer (1988) parameterized albedo as a function of the net energy input to snow and Rohrer (1992) based his parameterisation on air temperature. Models of longwave radiation over snow have been summarized by Male and Granger (1981), Kimball *et al.* (1982) and Olyphant (1986), and turbulent transfer has been reviewed by Brutsaert (1982), Kuhn (1984), and Morris (1989).

Precipitation reaching the snow surface can be significantly higher than that recorded by a raingauge at the same site. This is due to the catch deficit of the gauge which can be up to 50% for snowfall during strong winds. A number of methods have been suggested to correct for this effect on a monthly or seasonal basis (*e.g.* Sevruk 1986, 1989), but no techniques are available for timesteps of, say, an hour. One alternative is to regularly measure new snow on the ground rather than precipitation in a raingauge. The importance of air temperature on the state of precipitation has been investigated by a multitude of studies over the years (*e.g.* USACE 1956; Rohrer 1992, 1993).

Water movement within the snowpack in early studies was modelled by the water retention concept (Amorocho and Espildora 1966; Braun 1985; Blöschl *et al.* 1990) which suggests runoff from the snowpack after a threshold value of water is satisfied. Alternative representations include linear wave routing (Obled and Rosse 1977) and non-linear functional relationships (Anderson 1973, 1976). Colbeck (1972) and Colbeck and Davidson (1973) proposed a kinematic wave theory which since then has been widely used (*e.g.* Jordan 1983; Akan 1984; Morris 1987; Siemer 1988; Blöschl and Kirnbauer 1991). More recently, the effects of fingering (Wankiewicz 1979), preferential flow paths (Marsh and Woo 1985) and layering (Colbeck 1991; Richter-Menge *et al.* 1991) have been accounted for. Similarly to the transport of water, the transport of heat has been modelled by a range of models from simple cold content concepts to solutions to Fourier's law of heat conduction (*e.g.* Anderson 1976). A substantial body of literature (particularly from the avalanche forecasting community) deals with the effects of metamorphism and grain size and developed a spectrum of sophisticated models at the site scale (*e.g.* Morris 1983; 1991; Kelly *et al.* 1986; Bauwens 1988; Brun *et al.* 1992; Bader and Weilenmann 1992; Morris *et al.* 1993). Fig. 2 gives an example of how well a sophisticated snow model (Brun *et al.* 1992) can simulate snowmelt at a site.

Snow models at the site scale are either single layer (bulk) models, double layer, or multilayer models. Double layer models (such as in Marks 1988; Neale *et al.* 1992) involve an 'active' surface layer for modelling the feedback between internal and surficial processes. The question of the appropriate or optimum level of detail of site scale models has traditionally attracted significant attention. For example, Blöschl and Kirnbauer (1991) compared a multilayer and a bulk model in an alpine (1,930 m a.s.l.) setting. They concluded that the multilayer model was superior in simulating the time variations of liquid water content but that both models yielded good estimates of the timing of the onset of melt after a cold period. It is believed, however, that the question of site scale model complexity will decrease in import-

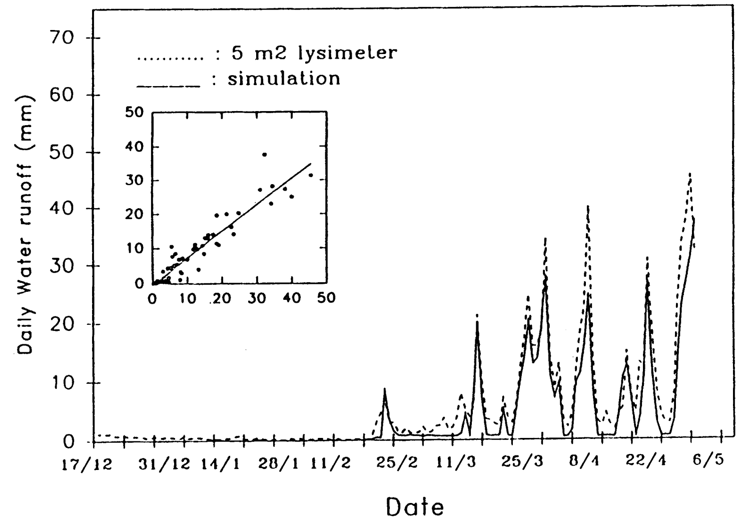

Fig. 2. Observed and simulated snow cover outflow for a site at Col de Porte (French Alps) 1,320 m a.s.l. (from Brun *et al.* 1992).

ance as computer time constraints are becoming less restrictive. Provided the dominant processes are included in a site scale model, the appropriate estimation of boundary conditions within a catchment (*e.g.* distributing air temperature to each element) will be of overwhelming importance.

Catchment Scale Approaches

The most important variables that need to be distributed (*i.e.* interpolated) from observation points to each computational element are air temperature and precipitation.

Approaches to interpolating air temperature invariably involve some estimate of the lapse rate (*i.e.* decrease of air temperature with altitude, *e.g.* WMO 1986). Anderson (1973) and Moore and Owens (1984), however, pointed out that the lapse rate in the atmosphere (*i.e.* along a vertical profile) is not necessarily the same as the gradient along a hillside (*i.e.* at screen level). It is the latter quantity that is of interest to distributed snow modelling. Lapse rates are either estimated from data (*e.g.* WMO 1986), physical considerations (adiabatic lapse rates) or a combination of both (*e.g.* Blöschl *et al.* 1990). Examples of diurnal and seasonal variations of the lapse rate are given in Moore and Owens (1984), Braun (1985) and Blöschl (1991). More sophisticated approaches involve distance to the observation point (Jensen 1989; Braun 1985). Still more sophisticated methods use data from upper air soundings and mesoscale meteorological forecast models. Such an interpolation scheme has been developed by Durand *et al.* (1993). The scheme provides hourly estimates of air temperature and other quantities for various elevations and aspects in the French Alps. Braun *et al.* (1994) use this scheme to drive a DSM.

The effect on snowpack simulations of interpolating air temperature has been analyzed by Blöschl (1991) for a region in the Austrian Alps. The study concluded that random errors in air temperature introduced by regionalisation largely cancel when simulating water equivalent. However, bias which may result from local effects such as sensor exposure is of marked influence on the simulations. High quality data still seem to be a prerequisite for successful spatial interpolation.

Precipitation is extremely variable at a range of scales (*e.g.* Kumar and Foufoula-Georgiou 1993; Rohrer *et al.* 1994) which complicates interpolation between raingauges substantially. A number of interpolation techniques have been suggested, ranging from purely statistical (*e.g.* Jensen 1989) to dynamic approaches (*e.g.* Barros and Lettenmaier 1991; Leavesley *et al.* 1991). Precipitation has a tendency to increase with elevation on an event (*e.g.* Fitzharris 1975) and seasonal scale (Lang 1985) but this is not necessarily the case for hourly or shorter scales (Obled 1990). Also, it is a challenge to find representative sites when setting up raingauges.

The threshold temperature for discriminating rain from snow may depend on the topographic configuration of a particular site. Specifically, Rohrer (1993), in a study in Switzerland, found average threshold temperatures of 0.25°C and 2.1°C on mountain tops and in valley floors, respectively, when using daily mean air temperatures.

Distributing wind speed to each computational element is associated with even more uncertainty. Some authors advocate the use of dynamic mesoscale models but – sophisticated as the state-of-the-art in modelling air flow over complex terrain may be – most scenarios involve steady state and/or a single hill in flat terrain (*e.g.* Finnigan 1988; Finnigan and Raupach 1993). Substantial progress seems to be needed before such models can be used to drive DSM for real world applications. Once estimates of air temperatures and wind speeds for an element are known, there is still the problem of calculating the turbulent fluxes (Morris 1989). Virtually all approaches to energy and vapour exchange assume flat terrain of infinite size (*e.g.* Bailey *et al.* 1990). Notions such as 'stability' or 'roughness length' are no longer meaningful in complex terrain as the basic assumptions are violated. It may well be that basic empirical relationships that account for local characteristics, even though in a crude way, outperform those based on boundary layer theory (*e.g.* Olyphant and Isard 1988).

Little is known, quantitatively, about the spatial distribution of albedo in catchments (see *e.g.* Mannstein 1985). Among the few studies is O'Neill and Gray (1973) who measured point and areal albedo in a Canadian prairie environment. They concluded that the point measurements were good indices to the areal values.

They also suggested that the aging curve approach (USACE 1956) was not an appropriate model for the shallow snowpacks found in the Canadian prairies.

One common approach is to simulate albedo, in each element as a function of other variables rather than to interpolate/extrapolate it directly. Blöschl *et al.* (1991), based on a study in Austria, suggested that such an approach may overestimate albedo on south facing slopes and underestimate it on north facing slopes. It is clear that a substantial research effort is needed to better understand the spatial distribution of albedo. It is also recognized that this will be no easy task, given the difficulties of measuring albedo accurately even at the site scale.

Similarly, the spatial distribution of longwave radiation is hard to observe and the effect of surrounding terrain may be large (Obled and Harder 1979). Olyphant (1986) suggested that the rockwalls surrounding an alpine cirque may substantially enhance energy input through longwave emission. The added energy may be equivalent to 500 mm melt over an entire snowmelt season.

When DSM are started during the snow cover period, the spatial distribution of snow water equivalent is required for initializing the model. Snow water equivalent is known to be highly variable at a range of space scales. Values at a single index plot are not always representative of a catchment (*e.g.* Granberg 1972; Woo and Steer 1986; Golding and Swanson 1986; Gubler and Rychetnik 1991; Blöschl 1993).

Interpolation procedures often are based on snow course data (*e.g.* Reuna 1992) and many involve relations to terrain characteristics (*e.g.* Golding 1974; Woo *et al.* 1983a,b; Blöschl *et al.* 1991). For example, the interpolation procedure as used in Blöschl *et al.* (1991) was based on elevation, slope and curvature. The parameters relating water equivalent to elevation were based on a best fit to snow course data while the other parameters were derived from qualitative considerations. Elder *et al.* (1989) addressed the interpolation problem by classifying a great number of depth measurements into terrain and radiation classes. On a larger scale, Lang and Rohrer (1987) showed synoptic meteorological information and radiosonde data to be promising predictors for snowfall depths in various regions in Switzerland.

An obvious consideration for interpolating water equivalent is to use remotely sensed data. For example, Ferris and Congalton (1989) and Ranzi *et al.* (1993) use near infrared NOAA-AVHRR satellite imagery in the Colorado River Basin (644,000 km^2) and for a number of medium sized catchments in Northern Italy, respectively, and Wankiewicz (1991) used microwave data from NIMBUS 7 SMMR satellite for estimating the snow water equivalent in Canadian basins. Bergström and Brandt (1985) and Brandt and Bergström (1994) estimated water equivalent based on measurements of natural gamma radiation along certain flight lines. A more detailed review is given in Gurnell (1990) and Braun (1991), and the potential of various satellite platforms and sensors is assessed in Rott (1986, 1987, 1993) and Rott and Markl (1989).

Using the concepts reviewed above, a range of (fully) DSM have been proposed: Charbonneau *et al.* (1981) presented a model which accounted for variations of solar radiation and snow surface temperatures at slopes of different aspects. Leavesley and Stannard (1989, 1990) simulated snowmelt processes in a mountainous basin in the Sierra Nevada, California, subdividing the basin into hydrological response units. These were defined as areas of uniform soil, vegetation and topographic characteristics. Blöschl *et al.* (1989, 1991), Ranzi and Rosso (1993) and Lettenmaier and Wigmosta (1993) used raster based approaches in an Austrian catchment (25 m grid spacing), a North Italian catchment (200 m grid spacing) and a basin in North America (90 m grid spacing), respectively. All three studies represented the individual components of the energy balance (such as topographically controlled solar radiation input) while Lettenmaier and Wigmosta (1993) also included a detailed representation of the effects of vegetation cover. Neale *et al.* (1992) and Tarboton *et al.* (1993) developed a raster snowmelt model (30 m grid spacing) for assessing soil erosion in a small catchment in Idaho. Bathurst and Cooley (1993a, b) applied the snowmelt component of SHE (Systeme Hydrologique Europeen) Morris and Godfrey (1979) to three nested catchments in Idaho. Braun *et al.* (1994) use a combination of a sophisticated interpolation scheme for meteorological controls (Durand *et al.* 1993) and a detailed site scale stratigraphic model (Brun *et al.* 1992) in a 224 km^2 basin in the French Alps. Braun *et al.* (1994) subdivided the basin into elements of uniform slope aspects and elevations following the interpolation scheme of Durand *et al.* (1993) and routed meltwater to the basin outlet by the conceptual HBV-model (Bergström 1976).

DSM – Strengths and Limitations

Many arguments have been put forward in favour of distributed snow models (*e.g.* Day *et al.* 1990). While DSM never lived up to their expectations in terms of their performance of simulating runoff (*e.g.* Charbonneau *et al.* 1981; Braun 1985) this should not come as a surprise: this has long been known for the case of distributed rainfall-runoff models (*e.g.* Freeze and Harlan 1969; WMO 1975; Naef 1981; Loague and Freeze 1985). Bergström (1991) presented an excellent discussion on modelling philosophy in hydrology in general and model complexity in particular. Clearly, the optimal model complexity depends on the nature of a specific problem. There is a wide range of problems where bulk models cannot do the job and DSM are called for. These include those where spatially distributed estimates of snow cover and snowmelt are required and/or a high degree of process understanding is needed (Leavesely 1989; Bergström 1991).

Unfortunately, DSM invariably suffer from a number of limitations (see *e.g.* Beven 1989, 1991; Grayson *et al.* 1992, 1993 for the rainfall – runoff case). It is important to clearly recognize these for rapid progress in distributed snow modelling. These limitations include:

- the extreme heterogeneity of the hydrologic environment,
- the mismatch of scales between observed variables and model state variables,
- the large number of model parameters, and
- the observability/testability problem.

It is clear that the high degree of heterogeneity in natural catchments greatly complicates distributed modelling. As pointed out earlier, this heterogeneity may be quantified either as element-to-element variation or as subgrid variability (see Fig. 1). While DSM always addresses the former, the latter has often been neglected. For example, how does the average albedo over an element change when the snowcover in this element partly disappears? Such questions lead to the notion of 'effective parameters'. These are defined as parameters of an (equivalent) homogeneous system which gives the same response as the heterogeneous system (see *e.g.* Gelhar 1986; Dagan 1986, for the groundwater case). Effective parameters (and an equivalent homogeneous system) do not always exist, particularly when the processes are non-linear (as is the case here). A generalisation for non-linear systems is to use distribution functions rather than single values (*e.g.* Marsh and Woo 1985; Buttle and McDonnell 1987) but it is clear that this complicates identifiability significantly. An example of an effective parameter in the time domain is the factor of refreezing: some site scale models do not explicitly model the night time refreezing of the snow surface (*e.g.* due to a computational time step of one day). One way to handle this subgrid (*i.e.* diurnal) variability is to assume 0°C surface temperature and to reduce energy losses from the pack by a factor of refreezing.

Even in detailed physically-based site scale models there are relations which one might call 'hidden empiricism'. Saturated hydraulic conductivity as a function of grain size and relative density is one example (Bender 1957; Shimizu 1970; Morris 1991). The relationships shown in Fig. 3 greatly differ and it is interesting to note that recent work by Sommerfeld and Rocchio (1993) suggests no significant influence of grain size on conductivity. Such discrepancies are greatly exacerbated when moving from the site scale to the element scale.

At present the methodology for estimating effective parameters is incomplete and it is necessary to calibrate the important model parameters using measured data. This introduces additional problems. Specifically, Bathurst and Cooley (1993a) stated "A complicating feature of multiple parameter models is the possibility that apparently equally satisfactory simulations can be achieved with different combinations of physically realistic parameter values, the change in one parameter being compensated for by a change in another". Such compensations of correlated model parameters may be within the DSM itself or between snow model and runoff model. While runoff is still widely used as the sole criterion for evaluating snowmelt runoff models, a number of researchers have suggested using snow cover parameters such as snow water equivalent for cross-checking (*e.g.* Anderson

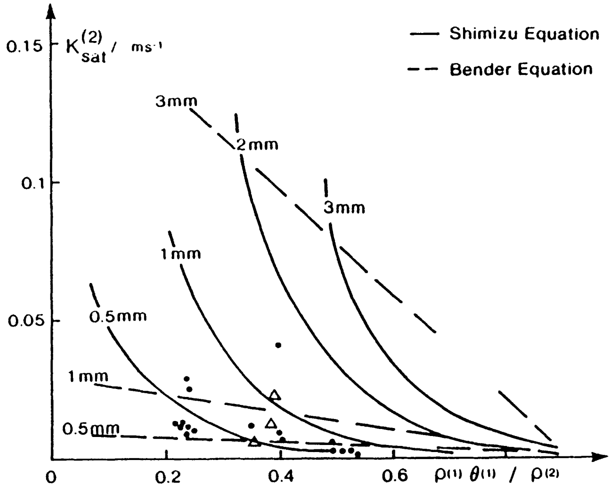

Fig. 3. Saturated hydraulic conductivity as a function of grain size and relative density (from Morris, 1991).

1979; Moore and Owens 1984; Braun 1985, 1988; Obled 1990). This is certainly valuable. However, the problem with snow water equivalents is that they are invariably point values (*e.g.* snow course data) which may not be representative of effective element values. Sometimes the elevation of the snowline (Bathurst and Cooley 1993a) is used for comparison. Meier and Schädler (1979) were the first to emphasize the potential of snow cover patterns. Snow cover depletion patterns a) have the advantage of representativeness and b) allow the spatially distributed assessment of the model. It is believed that both aspects are critically important for the accurate evaluation of distributed models.

Leavesley and Stannard (1989, 1990) used spaceborne snow cover patterns for evaluating a DSM in a 840 km^2 catchment in California, and Blöschl *et al.* (1989, 1991) performed a similar analysis for the 10 km^2 Längental catchment in the Austrian Alps using snow cover patterns derived from aerial photographs (Blöschl and Kirnbauer 1992) Figs. 4 and 5 show an aerial photograph of the Längental basin along with the simulated results. These results were obtained by running a DSM over two months. It is clear that a point value, placed at random in the catchment, may be greatly in error when comparing simulation and observation. Such a point value may be a very poor indicator of model performance while the patterns appear to be much more suited. Also, the patterns allow the detection of local effects. For example, at the base of the steep cliff in the centre of the photo the model underestimates the snow cover. This derives from redistribution processes such as avalanching and wind drift as observed in reality but not accounted for in the model.

Snow cover patterns can effectively discriminate between combinations of

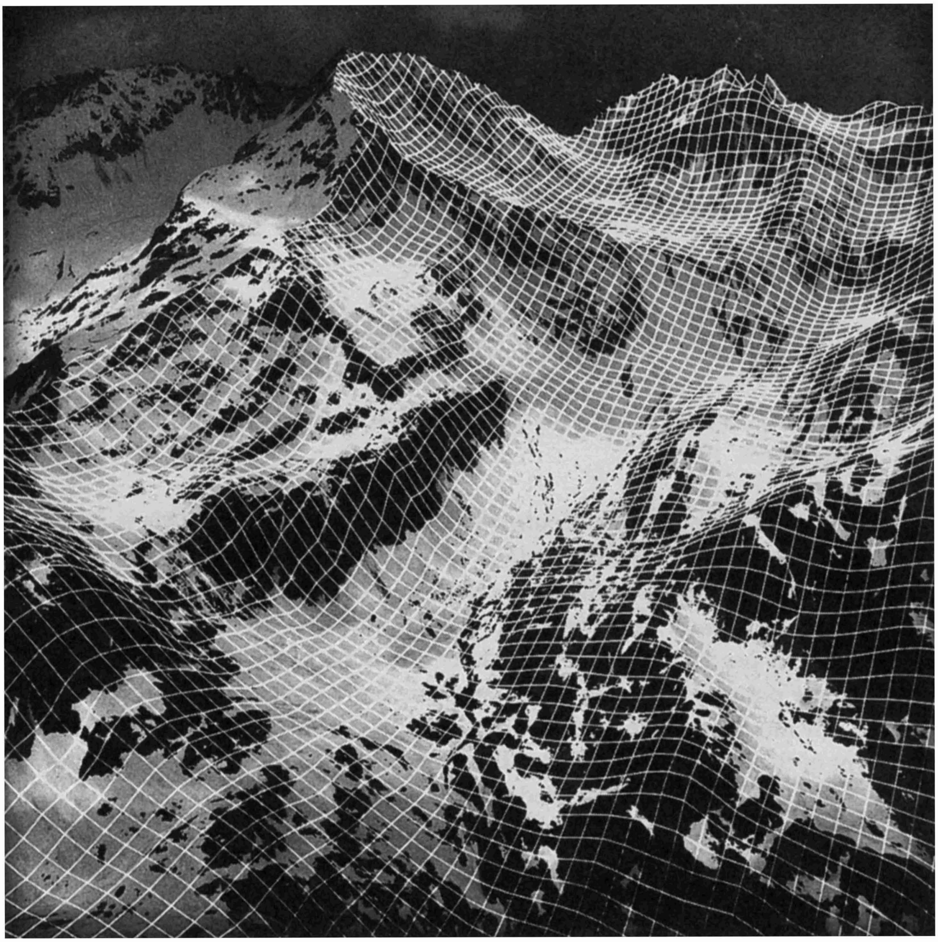

Fig. 4. Air photo of the upper part of the Längental catchment on June 26, 1989, showing grid elements 25×25m. By permission of BMLV, 13088/502-1.6/89) (from Blöschl *et al.* 1991).

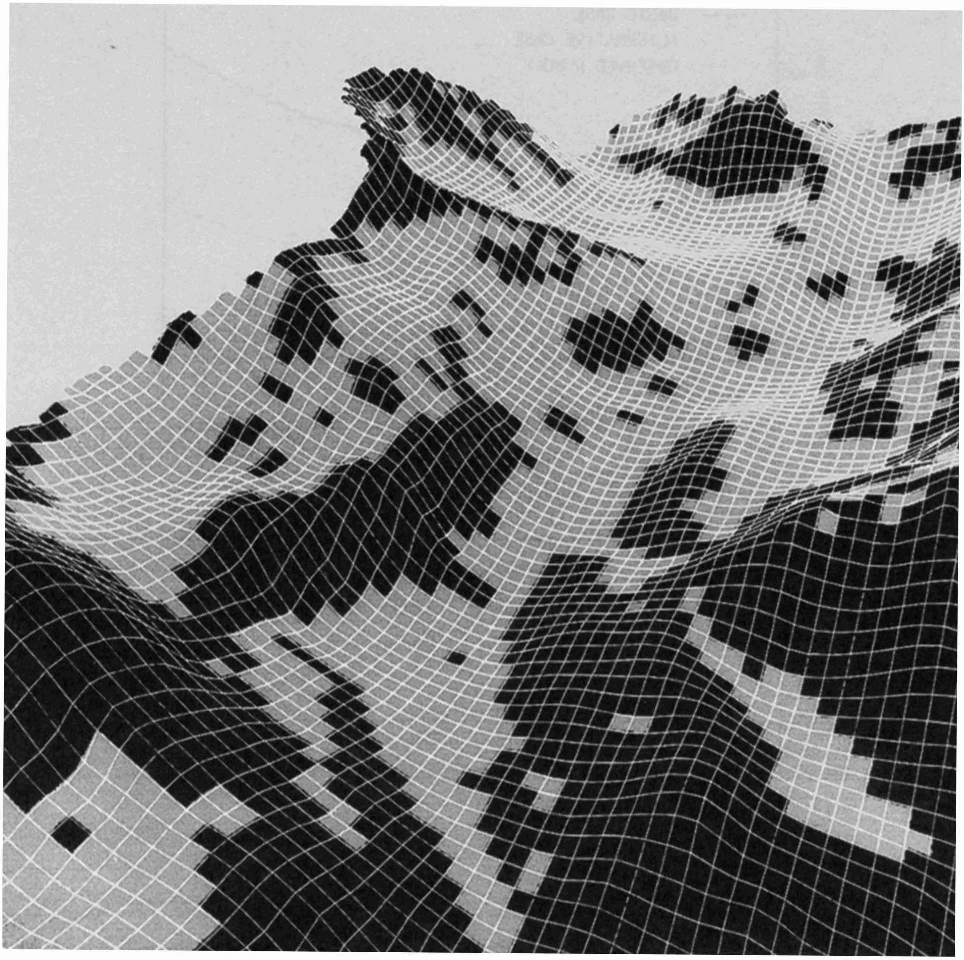

Fig. 5. Simulated snow cover on June 26, 1989. Dark areas denote bare ground and light areas denote snow cover (from Blöschl *et al.* 1991).

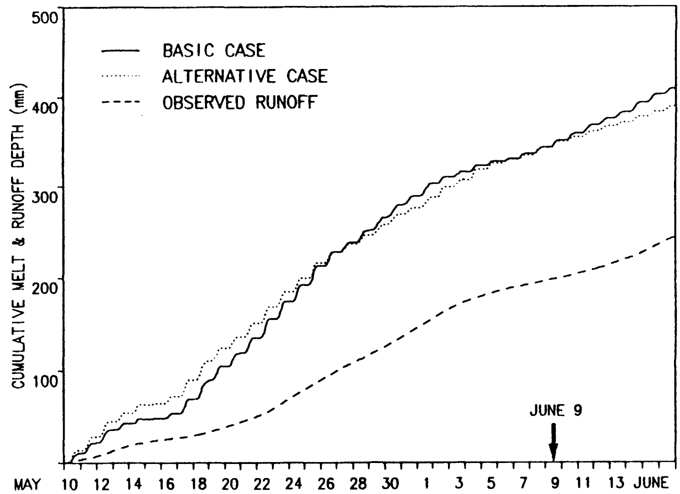

Fig. 6. Simulated cumulative mean basin melt and observed runoff depths. The solid line refers to the basic (realistic) case (albedo = 0.6, snow line at 1,600 m, gradient of water equivalent = 1 mm/m) and the dotted line refers to the alternative (unrealistic) case (albedo = 0.4, snow line at 2,000 m, gradient of water equivalent = 2 mm/m) (from Blöschl *et al.* 1993).

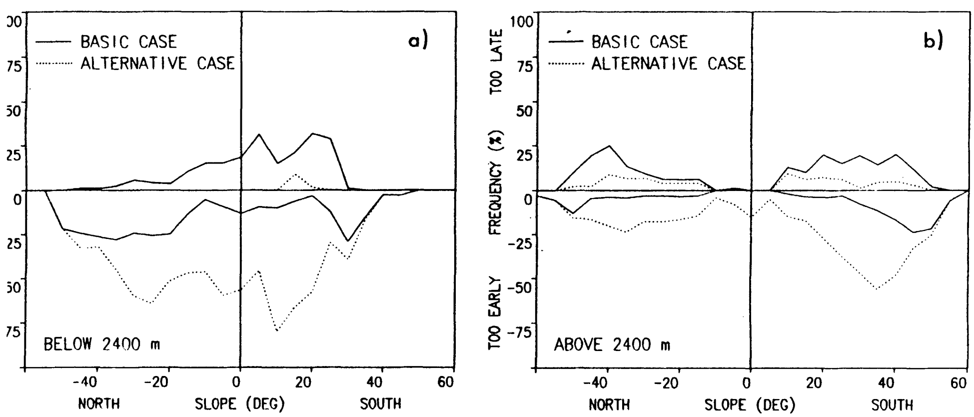

Fig. 7. Per cent error in snow cover on north and south facing slopes, June 9, 1989, a) below 2,400 m a.s.l. and b) above 2,400 m a.s.l. (too late: snow cover simulated, bare observed; too early: bare simulated, snow cover observed). The solid line refers to the basic (realistisc) case and the dotted line refers to the alternative (unrealistic) case (see Fig. 6) (from Blöschl *et al.* 1993).

model parameters that integrated measures such as runoff cannot distinguish. Fig. 6 presents a sensitivity analysis for the same catchment. Simulated cumulative mean basin melt rates are plotted for two cases. These relate to different assumptions on snow albedo and initial snow water equivalent. As can be seen from Fig. 6, the melt rates for the two cases are very similar. Indeed, the differences are so small that, by comparison with observed runoff depths, the more appropriate of the two cases could by no means be identified. Fig. 7 shows an evaluation of sensitivity in terms of snow cover patterns on an element-by-element basis for June 9. The elements are subdivided into classes according to slope and aspect, separately for the upper and the lower part of the basin. The percentage denoted by 'too late' refers to elements with snow cover simulated and bare ground observed, *i.e.* an overestimation of snow cover. In terms of snow cover, the two cases differ substantially. In the lower part of the basin (Fig. 7a) the basic case (solid line) gives generally low magnitudes of the error (less than 30 %) indicating good agreement of simulated and observed snow cover patterns. The alternative case (dotted line), however, substantially underestimates snow cover (up to 80 %) on both north and south facing slopes. Clearly, this discrepancy derives from an unrealistically high selection of the snow line in the alternative case. In the upper part of the basin (Fig. 7b) the basic case, again, indicates good agreement while the alternative case underestimates snow cover, particularly on south facing slopes. These differences may easily be traced back to the influence of albedo, which is more important on south facing slopes. Fig. 7 clearly shows that a comparison of patterns is very efficient for discriminating between alternative model assumptions. It is also capable of addressing individual model components such as initial snow deposition and albedo.

Conclusions

'We are entering an era of distributed snow models'. The authors are convinced that this is a most welcome trend with the potential of addressing a wide variety of real world problems. However, throughout this paper the authors have emphasized the limitations of the approach rather than its strengths. It is felt that a clear recognition of the constraints is vital to rapid progress in the area.

Much progress has been achieved at the site scale (Colbeck 1987; Morris 1991) and there seems to be a multitude of open problems. However, it is felt that research into spatial processes within catchments is significantly less advanced. New and innovative techniques need to be explored to obtain reliable spatial distributions of quantities such as snow albedo and snow water equivalent. Also, from a modelling point of view, representations of catchment scale processes vastly lag behind those at the site scale. Some of the crucial aspects identified in this paper include:

a) the extreme heterogeneity of the hydrologic environment,
b) the mismatch of scales between observed variables and model state variables,
c) the large number of model parameters, and
d) the observability/testability problem.

To address the range of problems related to these aspects will be a challenge for future research.

Acknowledgements

The authors wish to thank the Fonds zur Förderung der wissenschaftlichen Forschung, Vienna, project Nos. P6387P, P7002PHY and J0699-PHY for financial support.

References

Akan, A.O. (1984) Simulation of runoff from snow-covered hillslopes, *Water Resour. Res., Vol. 20, No. 6*, pp. 707-713.

Amorocho, J., and Espildora, B. (1966) Mathematical simulation of the snow melting process. Water Science and Engineering Papers No. 3001, Dept. Wat. Sci. Eng., Univ. California, Davies, 156 pp.

Anderson, E.A. (1968) Development and testing of snowpack energy balance equations, *Water Resour. Res., Vol. 4, No. 1,* pp. 19-37.

Anderson, E.A. (1973) National Weather Service river forecast system – snow accumulation and ablation model. NOAA Tech. Rep. NWS HYDRO-17, US Dept. of Commerce, Silver Spring, Maryland.

Anderson, E.A. (1976) A point energy and mass balance model of a snow cover. NOAA Tech. Rep. NWS HYDRO-19, US Dept. of Commerce, Silver Spring, Maryland.

Anderson, E.A. (1979) Stream flow simulation models for use on snow covered watersheds. In: Modelling of Snow Cover Runoff (*ed.* by S.C. Colbeck and M. Ray, Proc. Meeting, Hanover, New Hampshire, Sept. 1978), US Army Cold Regions Research and Engineerring Laboratory, pp. 336-350.

Bader, H.-P., and Weilenmann, P. (1992) Modeling temperature distribution, energy and mass flow in a (phase-changing) snowpack. I. Model and case studies, *Cold Regions Sci. and Technol., Vol. 20*, pp. 157-181.

Bailey, W.G., Saunders, I.R., and Bowers, J.D. (1990) Atmosphere and surface control on evaporation from alpine tundra in the Canadian Cordillera. In: Hydrology in Mountainous Regions. I-Hydrological Measurements; the Water Cycle (*ed.* by H. Lang and A. Musy, Proc. Lausanne Symp., Aug. 1990), IAHS Publ. 193, pp. 45-52.

Barros, A.P., and Lettenmaier, D.P. (1991) Dynamic modeling of the spatial distribution of precipitation in remote mountainous areas. Trans. AGU. Suppl. Oct. 29, 1991

Bathurst, J.C., and Cooley, K.R. (1993a) Use of the SHE hydrological modelling system to investigate basin response to snowmelt at Reynolds Creek, Idaho, *J. Hydrol.,* in print.

Bathurst, J.C., and Cooley, K.R. (1993b) Application of the SHE distributed snowmelt model at three spacial scales. (Abstract of a Lecture of the EGS Gen. Ass., Wiesbaden May 1993), Annales Geophysicae, Supplement II to Vol. 11, Part II, p. C245.

Bauwens, W. (1988) Snowmelt models with different degrees of complexity applied to shallow and short-living snowpacks in lowland basins. Proc. 45th Eastern Snow Conf., Lake Placid, June 1988.

Bender, J.A. (1957) Air permeability of snow. Res. Rep. 37, Snow, Ice and Permafrost Research Establishment. (US Army Corps of Engineers) Wilmette, Illinois.

Bergström, S. (1976) Development and application of a conceptual runoff model for Scandinavian catchments. Dept. of Water Resour. Engineering, Lund Inst. of Technol./Univ. of Lund, Bull. Ser. A. No. 52. 134 pp.

Bergström, S. (1991) Principles and confidence in hydrological modelling, *Nordic Hydrol., Vol. 22*, pp. 123-136.

Bergström, S., and Brandt, M. (1985) Measurements of areal water equivalent of snow by natural gamma radiation – experiences from Northern Sweden, *Hydrological Sci. J., Vol. 30, No. 4*, pp. 465-477.

Beven, K. (1989) Changing ideas in hydrology – the case of physically based models, *J. Hydrol. Vol. 105*, pp. 157-172.

Beven, K. (1991) Scale considerations. In: Bowles, D.S. and O'Connell, P.E. (*Eds*), *Recent Advances in the Modelling of Hydrologic Systems*, Kluwer, Dordrecht, pp. 357-371.

Blöschl, G. (1991) The influence of uncertainty in air temperature and albedo on snowmelt, *Nord. Hydrol., Vol. 22, No. 2*, pp. 95-108.

Blöschl, G. (1993) Saisonale Schneeschmelzvorhersagen – Die Problematik der quantitativen Erfassung der Rücklage. In: Schneehydrologie – Modellierung der Schneedecke in Einzugsgebieten (Hrsg.: G. Blöschl, D. Gutknecht und R. Kirnbauer, Hochschulkurs Wien, Dezember 1990) Forschungsinitiative der Verbundgesellschaft, Bd. 13, pp. 67-86.

Blöschl, G., and Sivapalan, M. (1994) Scale issues in hydrological modelling – a review. *Hydrol. Processes*, in press.

Blöschl, G., Kirnbauer, R., und Gutknecht, D. (1987) Zur Berechnung des Wärmeeintrages an einem Punkt der Schneedecke, *Deutsche Gewässerkundliche Mitteilungen, 31 (5)*, pp. 149-155.

Blöschl, G., Gutknecht, D., und Kirnbauer, R. (1988) Berechnung des Wärmeeintrages in eine Schneedecke – Analyse des Einflusses unterschiedlicher meteorologischer Bedingungen, *Deutsche Gewässerkundliche Mitteilungen, 32 (1/2)*, pp. 34-39.

Blöschl, G., Gutknecht, D., and Kirnbauer, R. (1993) On the evaluation of distributed hydrologic models. In: R. Rosso (*ed.*), Advances in distributed hydrology. Proceedings of a workshop held in Bergamo, Italy, June 1992. Water Resour. Publications. In press.

Blöschl, G., Kirnbauer, R., and Gutknecht, D. (1989) Assessment of snowmelt simulations in Alpine terrain on the basis of depletion patterns, *Trans. AGU 70 (43)*, p. 1113.

Blöschl, G., Kirnbauer, R., and Gutknecht, D. (1990) Modelling snowmelt in a mountainous river basin on an event basis, *J. Hydrol., Vol. 113*, pp. 207-229.

Blöschl, G., and Kirnbauer, R. (1991) Point snowmelt models with different degrees of complexity – internal processes, *J. Hydrol., Vol. 129,* pp. 127-147.

Blöschl, G., Kirnbauer, R., and Gutknecht, D. (1991) Distributed snowmelt simulations in an Alpine catchment. 1. Model evaluation on the basis of snow cover patterns, *Water Resour. Res., Vol. 27, No. 12*, pp. 3171-3179.

Blöschl, G., and Kirnbauer, R. (1992) An analysis of snow cover patterns in a small alpine catchment, *Hydrological Proccesses, Vol. 6*, pp. 99-109.

Brandt, M., and Bergström, S. (1994) Integration of field data into operational snowmelt-runoff models, *Nordic Hydrology, Vol. 25,* pp. 101-112.

Braun, L.N. (1985) Simulation of snowmelt-runoff in lowland and lower alpine regions of Switzerland, *Zürcher Geopgraphische Schriften, Heft 21,* Geographisches Institut ETH Zürich, 166 pp.

Braun, L.N. (1988) Parameterization of snow- and glaciermelt. Berichte und Skripten 34, Geographisches Institut der Eidgenössischen Technischen Hochschule Zürich.

Braun, L.N. (1991) Modelling of the snow-water equivalent in the mountain environment. In: Snow, Hydrology and Forests in High Alpine Areas (*ed.* by H. Bergmann, H. Lang, W. Frey, D. Issler and B. Salm, Proc. Vienna Symp. Aug. 1991), IAHS Publ. No. 205, pp. 3-17.

Braun, L.N., Brun, E., Durand, Y., Martin, E., and Tourasse, P. (1994) Simulation of discharge using different methods of meteorological data distribution, basin discretization and snow modelling, *Nordic Hydrology, Vol. 25,* pp. 129-144.

Brun, E., Martin, E., Simon, V., Gendre, C., and Coleou, C. (1989) An energy and mass model of snow cover suitable for operational avalanche forecasting, *J. Glaciol., Vol. 35, No. 121*, pp. 333-342.

Brun, E., David, P., Sudul, M., and Brunot, G. (1992) A numerical model to simulate snowcover stratigraphy for operational avalanche forecasting, *J. Glaciol., Vol. 28, No. 128*, pp. 13-22.

Brutsaert, W.H. (1982) *Evaporation into the Atmosphere*, Reidel, Dordrecht, 299 pp.

Buttle, J.M., and McDonell, J.J. (1987) Modelling the areal depletion of snow cover in a forested catchment, *J. Hydrol., Vol. 90, No. 1/2*, pp. 43-60.

Caroll, J.J., and Fitch, B.W. (1981) Effect of solar elevation and cloudiness on snow albedo at the South Pole, *J. Geophys. Res., Vol. 86, No. C6*, pp. 5271-5276.

Charbonneau, R., Lardeau, J.P., and Obled, Ch. (1981) Problems of modelling a high mountainous drainage basin with predominant snow yields, *Hydrol. Sci. Bull., Vol. 26, No. 4*, pp. 345-361.

Choudhury, B.J., and Chang, A.T.C. (1981) The albedo of snow for partially cloudy skies, *Boundary Layer Meteorology, Vol. 20*, pp. 371-389.

Colbeck, S.C. (1972) A theory of water percolation in snow, *J. Glaciol., Vol. 11*, pp. 369-385.

Colbeck, S.C., and Davidson, G. (1973) Water percolation through homogeneous snow. In: The role of Snow and Ice in Hydrology (Proc. of the Banff Symp., Sept. 1972), IAHS Publ. No. 107, Vol. 1, pp. 242-257.

Colbeck, S.C. (1978) The physical aspects of water flow through snow. In: *Advances in Hydroscience* (Ven Te Chow, *ed.*) Academic Press, New York, *Vol. 11*, pp. 165-206.

Colbeck, S.C. (1987) History of snow-cover research, *J. Glaciol., Special Issue*, pp. 60-65.

Colbeck, S.C. (1988) Snowmelt increase through albedo reduction, Workshop on Snow Hydrology, November 1988, Manali (India).

Colbeck, S.C. (1991) The layered character of snow covers, *Rev. Geophys., Vol. 29, No. 1*, pp. 81-96.

Dagan, G. (1986) Statistical theory of groundwater flow and transport: Pore to laboratory, laboratory to formation and formation to regional scale, *Water Resour. Res., Vol. 22, No.*

9, pp. 120S-134S.

Day, G., Dozier, J., and Lettenmaier, D. (1990) Methods evolve for snowmelt runoff analysis, Trans. AGU February 20, 1990.

Dozier, J. (1980) A clear-sky spectral solar radiation model for snow-covered mountainous terrain, *Water Resour. Res., Vol. 16, No. 4* pp. 709-718.

Dozier, J. (1987) Recent research in snow hydrology, *Rev. Geophys., Vol. 25, No. 2* pp. 153-161.

Dozier, J. (1989) Remote sensing of the spatial variation of snow properties in alpine watersheds, *Trans. AGU 70 (43)*, p. 1107.

Dozier, J. (1992) Opportunities to improve hydrologic data, *Rev. Geophys., Vol. 30, No. 4*, pp. 315-331.

Dragoi, E., Adler, M.J., and Ioan, E. (1993) Relation from experimental data upon runoff from snowlayer under the rainfalls action. (Abstract of a Lecture at the EGS Gen. Ass., Wiesbaden May 1993), Annales Geophysicae, Supplement II to Vol. 11, Part II, p. C246.

Durand, Y., Brun, E., Merindol, L., Guyomarc'h, G., Lesaffre, B., and Martin, E. (1993) A meteorological estimation of relevant parameters of snow models, *Annals of Glaciol., Vol. 17*, in print.

Elder, K., Dozier, J., and Michaelsen, J. (1989) Spatial and temporal variation of new snow accumulation in a small alpine watershed, Emerald Lake basin, Sierra Nevada, California, U.S.A., *Annals of Glaciol., Vol. 13*, pp. 56-63.

Ferris, J.S., and Congalton, R.G. (1989) Satellite and geographic information system estimates of Colorado River basin snowpack, *Photogrammetric Engineering and Remote Sensing, Vol. 55, No. 11*, pp. 1629-1635.

Finnigan, J.J. (1988) Air flow over complex terrain. In: Steffen, W.L. and Denmead, O.T. *(eds.) Flow and Transport in the Natural Environment: Advances and Applications*, Springer. Berlin, pp. 183-229.

Finnigan, J.J., and Raupach, M.R. (1993) Scale issues in boundary layer meteorology. In: Kalma, J., Sivapalan, M., and Wood, E.F. (eds.) Scale Issues in Hydrological/Environmental Modelling, CRES. Australian National University, Canberra, Australia.

Fitzharris, B.B. (1975) Snow accumulation and deposition on a westcoast midlatitude mountain. Ph.D. thesis, University of British Columbia, Vancouver.

Freeze, R.A., and Harlan, R.L. (1969) Blueprint for a physically-based, digitally simulated hydrologic response model, *J. Hydrol., Vol. 9, No. 3*, pp. 237-258.

Gelhar, L.W. (1986) Stochastic subsurface hydrology from theory to applications, *Water Resour. Res., Vol. 22, No. 9*, pp. 135S-145S.

Golding, D.L. (1974) The correlation of snowpack with topography and snowmelt runoff on Marmot Creek basin, Alberta, *Atmosphere, Vol. 12, No. 1*, pp. 31-38.

Golding, D.L., and Swanson R.H. (1986) Snow distribution patterns in clearings and adjacent forest, *Water Resour. Res., Vol. 22, No. 13*, pp. 1931-1940.

Granberg, H.B. (1972) Snow depth variations in a forest-tundra environment, Schefferville, P.Q. Unpubl. M:.Sc. thesis, McGill University, Montreal.

Grayson, R.B., Moore, I.D., and McMahon, T.A. (1992) Physically-based hydrologic modelling: 2. Is the concept realistic? *Water Resour. Res., Vol. 26, No. 10*, pp. 2659-2666.

Grayson, R.B., Blöschl, G., Barling, R.D., and Moore, I.D. (1993) Process, scale and constraints to hydrological modelling in GIS. In: Applications of Geographic Information Systems in Hydrology and Water Resources Management (*ed.* by K. Kovar and H.P.

Nachtnebel, Proc. Vienna Symp., April 1993), IAHS Publ. No. 211, pp. 83-92.

Gubler, H., and Rychetnik, J. (1991) Effects of forests near the timberline on avalanche formation. In: Snow, Hydrology and Forests in High Alpine Areas (*ed.* by H. Bergmann, H. Lang, W. Frey, D. Issler and B. Salm, Proc. Vienna Symp. Aug. 1991), IAHS Publ. No. 205, pp. 19-38.

Gurnell, A.M. (1990) Improved methods of assessment of snow and glaciers as water balance and river flow components. In: Hydrology in Mountainous Regions. I-Hydrological Measurements; the Water Cycle (*ed.* by H. Lang and A. Musy, Proc. Lausanne Symp., Aug. 1990), IAHS Publ. No. 193, pp. 157-172.

Jensen, H. (1989) Räumliche Interpolation der Stundenwerte von Niederschlag, Temperatur und Schneehöhe, *Zürcher Geographische Schriften, Heft* 35. Geographisches Institut, ETH, Zürich, 70 pp.

Jordan, P. (1983) Meltwater movement in a deep snowpack, 2, Simulation model, *Water Resour. Res., Vol. 19, No. 4*, pp. 979-985.

Kelly, R.J., Morland, L.W., and Morris, E.M. (1986) A three phase mixture model for melting snow. In: Modelling Snowmelt-Induced Processes (*ed.* by E.M. Morris, Proc. Budapest Symp., July 1986), IAHS Publ. No. 155, pp. 17-26.

Kimball, B.A., Idso, S.B., and Aase, J.K. (1982) A model of thermal radiation from partly cloudy and overcast skies, *Water Resour. Res., Vol. 18, No. 4*, pp. 931-936.

Kuhn, M. (1984) Physikalische Grundlagen des Energie- und Massenhaushalts der Schneedecke. In: Snow Hydrologic Research in Central Europe (*ed.* by H.M. Brechtel), Mitteilungen des Deutschen Verbandes für Wasserwirtschaft und Kulturbau 7, pp. 5-56.

Kumar, P., and Foufoula-Georgiou, E. (1993) A multicomponent decomposition of spatial rainfall fields, 2, Self-similarity in fluctuations, *Water Resour. Res., Vol. 29, No. 8*, pp. 2533-2544.

Kuusisto, E. (1986) The energy balance of a melting snow cover in different environments. In: Modelling Snowmelt-Induced Processes (*ed.* by E.M. Morris, Proc. Budapest Symp., July 1986), IAHS Publ. No. 155, pp. 37-45.

Lang, H. (1985) Höhenabhängigkeit der Niederschläge. In: Der Niederschlag in der Schweiz, Beiträge zur Geologie der Schweiz, Nr. 31. Verl. Kümmerly + Frey, Bern, pp. 149-157.

Lang, H. (1986) Forecasting meltwater runoff from snow covered areas and from glacier basins. In: *River Flow Modelling and Forecasting* (*ed.* by D.A. Kraijenhoff and J.R. Moll). Reidel Publishing Company, Dordrecht, pp. 99-127.

Lang, H., and Rohrer, M. (1987) Temporal and spatial variations of the snow cover in the Swiss Alps. In: Large Scale Effects of Seasonal Snow Cover (*ed.* by B.E. Goodison, R.G. Barry and J. Dozier, Proc. Vancouver Symp., Aug. 1987), IAHS Publ. No. 166, pp. 79-82.

Leavesley, G.H. (1989) Problems of snowmelt runoff modelling for a variety of physiographic and climatic conditions, *Hydrol. Sci. J., Vol. 34, No. 6*, pp. 617-634.

Leavesley, G.H.,, and Stannard, L.G. (1989) A distributed-parameter, energy-budget, snowmelt-runoff model for basin-scale application, *Trans. AGU. 70 (43)*, pp. 1109.

Leavesley, G.H., and Stannard, L.G. (1990) Application of remotely sensed data in a distributed-parameter watershed model. In: Proc. Workshop on Applications of Remote Sensing in Hydrology, Saskatoon, Feb. 1990 (*ed.* by G.W. Kite and A. Wankiewicz), pp. 47-64.

Leavesley, G.H., Branson, M.D., Hay, L.E., and Parker, R.S. (1991) Coupled orographic-precipitation and distributed-parameter hydrologic models for investigating the effects of climate change in mountainous regions, *Trans. AGU. Suppl. Oct. 29, 1991.*

Lettenmaier, D.P., and Wigmosta, M.S. (1993) Influence of vegetation, topography, and climate on hydrologic processes in a mountainous watershed. In: R. Rosso (*ed.*), Workshop on Advances in Distributed Hydrology, Bergamo, Italy, June 1992, Water Resour. Publications, in press.

Loague, K.M., and Freeze, R.A. (1985) A comparison of rainfall-runoff modelling techniques on small upland catchments, *Water Resour. Res., Vol. 21, No. 2*, pp. 229-248.

Male, D.H., and Granger, R.J. (1981) Snow surface energy exchange, *Water Resour. Res., Vol. 17, No. 3*, pp. 609-627.

Mannstein, H. (1985) The interpretation of albedo measurements on a snowcovered slope, *Arch. f. Meteorol., Geophys. u. Bioklimatol., Ser. B 36,* pp. 73-81.

Marks, D. (1988) Climate, Energy Exchange, and Snowmelt in Emerald Lake Watershed, Sierra Nevada. PhD. Dissertation, Remote Sensing Hydrology, Univ. of California, Santa Barbara, 158 pp.

Marsh, P., and Woo, M.-k. (1985) Meltwater movement in natural heterogeneous snow covers, *Water Resour. Res., Vol. 21, No. 11*, pp. 1710-1716.

Marshall, S.E., and Warren, S.G. (1987) Parameterization of snow albedo for climate models. In: Large Scale Effects of Seasonal Snow Cover (*ed.* by B.E. Goodison, R.G. Barry and J. Dozier, Proc. Vancouver Symp., Aug. 1987), IAHS Publ. No. 166, pp. 43-50.

Meier, R., and Schädler, B. (1979) Die Ausaperung der Schneedecke in Abhängigkeit von Strahlung und Relief, *Arch. f. Meteorol., Geophys. u. Bioklimatol., Ser. B. Vol. 27*, pp. 151-158.

Moore, R.D., and Owens, I.F. (1984a) Modelling alpine snow accumulation and ablation using daily climate observations, *J. Hydrol. (NZ), Vol. 23, No. 2*, pp. 73-83.

Moore, R.D., and Owens, I.F. (1984b) A conceptual runoff model for a mountainous rain-on-snow environment, Craigieburn Range, New Zealand, *J. Hydrol. (NZ), Vol. 23, No. 2*, pp. 84-99.

Morris, E.M. (1983) Modelling the flow of mass and energy within a snowpack for hydrological forecasting, *Ann. Glaciol., Vol. 4*, pp. 198-203.

Morris, E.M. (1987) Modelling of water flow through snowpacks. In: *Seasonal Snowcovers: Physics, Chemistry, Hydrology* (*ed.* by H.G. Jones and W.J. Orville-Thomas), D. Reidel Publ. Comp., pp. 179-208.

Morris, E.M. (1989) Turbulent transfer over snow and ice, *J. Hydrol., Vol. 105,* pp. 205-223.

Morris, E.M. (1991) Physics-based models of snow. In: *Recent Advances in the Modelling of Hydrologic Systems* (*ed.* by D.S. Bowles and P.E. O'Connell), Kluwer Academic Publishers, pp. 85-112.

Morris, E.M., and Godfrey, J. (1979) The European hydrologic system snow routine. In: Modelling of Snow Cover Runoff (*ed.* by S.C. Colbeck and M. Ray, Proc. Meeting, Hanover, New Hampshire, Sept. 1978), US Army Cold Regions Research and Engineering Laboratory, pp. 269-278.

Morris, E.M., Bader, H.-P., and Weilenmann, P. (1993) Modelling temperature variations in ploar snow using the DAISY distributed snow model. (Abstract of a Lecture at the

EGS Gen. Ass., Wiesbaden May 1993), Annales Geophysicae, Supplement II to Vol. 11, Part II, p. C247.

Naef, F. (1981) Can we model the rainfall-runoff process today? *Hydrol. Sci. Bull. Vol. 26, No. 3*, pp. 281-289.

Neale, C.M.U., Tarboton, D.G., and McDonnell, J.J. (1992) A spatially distributed water balance based on physical, isotropic and airborne remotely sensed data. Annual Tech. Rep., submitted to the U.S. Geological Survey. Utah State Univ., Utah Water Res. Lab., Logan.

O'Neill, A.D.J., and Gray, D.M. (1973) Spatial and temporal variations of the albedo of Prairie snow pack. In: The Role of Snow and Ice in Hydrology (Proc. of the Banff Symp., Sept. 1972), IAHS Publ. No. 107, Vol. 1, pp. 176-186.

Obled, Ch. (1990) Hydrological modelling in regions of rugged relief. In: Hydrology in Mountainous Regions. I-Hydrological Measurements; the Water Cycle (*ed.* by H. Lang and A. Musy, Proc. Lausanne Symp., Aug. 1990), IAHS Publ. 193, pp. 599-613.

Obled, Ch., and Harder, H. (1979) A review of snow melt in the mountain environment. In: Modelling of Snow Cover Runoff (*ed.* by S.C. Colbeck and M. Ray, Proc. Meeting, Hanover, New Hampshire, Sept. 1978), US Army Cold Regions Research and Engineering Laboratory, pp. 179-204.

Obled, Ch., and Rosse, B. (1977) Mathematical models for a melting snowpack at an index plot, *J. Hydrol., Vol. 32*, pp. 139-163.

Olyphant, G.A. (1986) Longwave radiation in mountainous areas and its influence on the energy balance of alpine snowfields, *Water Resour. Res., Vol. 21, No. 1*, pp. 62-66.

Olyphant, G.A., and Isard, S.A. (1988) Role of advection in the energy balance of late-lying snowfields: Niwot Ridge, Front Range, Colorado, *Water Resour. Res., Vol. 24*, pp. 1962-1968.

Ranzi, R., and Rosso, R. (1991) A physically based approach to modelling distributed snowmelt in a small alpine catchment. In: Snow, Hydrology and Forests in High Alpine Areas (*ed.* by H. Bergmann, H. Lang, W. Frey, D. Issler and B. Salm, Proc. Vienna Symp. Aug. 1991), IAHS Publ. No. 205, pp. 141-150.

Ranzi, R., and Rosso, R. (1993) Scale effects in distributed modelling of energy exchange between snow field and atmosphere. In: R. Rosso (*ed.*), Workshop on Advances in Distributed Hydrology, Bergamo, Italy, June 1992, Water Resour. Publications, in press.

Ranzi, R., Rosso, R., Pollicini, P. and Bacchi, B. (1993) Coupling NOAA-AVHRR imagery with a GIS to estimate the distributed water equivalent in large alpine basins. (Abstract of a Lecture at the EGS Gen. Ass., Wiesbaden May 1993), Annales Geophysicae, Supplement II to Vol. 11, Part II, p. C247.

Reuna, M. (1992) An operational grid method for estimation of the areal water equivalent of snow, EGS XVII Assembly, Edinburgh.

Richter-Menge, J.A., Colbeck, S.C., and Jezek, K.C. (1991) Recent progress in snow and ice research, Rev. Geophys. Suppl., pp. 218-226.

Rohrer, M.B. (1992) Die Schneedecke im Schweizer Alpenraum und ihre Modellierung, *Züricher Geographische Schriften, Heft 49.* Geographisches Institut, ETH, Zürich, 178 pp.

Rohrer, M.B. (1993) Importance of time step in modelling the aggregational state of precipitation. (Abstract of a Lecture at the EGS Gen. Ass., Wiesbaden May 1993), Annales Geophysicae, Supplement II to Vol. 11, Part II, p. C247.

Rohrer, M.B., and Lang, H. (1990) Point modelling of snow cover water equivalent based on observed variables of the standard meteorological networks. In: Hydrology in Mountainous Regions. I-Hydrological Measurements; the Water Cycle (*ed.* by H. Lang and A. Musy, Proc. Lausanne Symp., Aug. 1990), IAHS Publ. No. 193, pp. 197-204.

Rohrer, M.B., Braun, L.N., and Lang, H. (1994) Long-term records of the snow cover water equivalent in the Swiss Alps: 1. Analysis, *Nordic Hydrology, Vol. 25,* pp. 53-64.

Rohrer, M.B., and Braun, L.N. (1994) Long-term records of the snow cover water equivalent in the Swiss Alps: 2. Simulation, *Nordic Hydrology, Vol. 25,* pp. 65-78.

Rott, H. (1986) Prospects of microwave remote sensing for snow hydrology. In: Hydrologic Applications of Space Technology (*ed.* by A.I. Johnson, Proc. Cocoa Beach Workshop, Florida, August 1985), IAHS Publ. No. 160, pp. 215-223.

Rott, H. (1987) Remote sensing of snow. In: Large Scale Effects of Seasonal Snow Cover (*ed.* by B.E. Goodison, R.G. Barry and J. Dozier, Proc. Vancouver Symp., Aug. 1987), IAHS Publ. No. 166, pp. 279-290.

Rott, H. (1993) Fernerkundungsverfahren für die Schneehydrologie. In: Schneehydrologie – Modellierung der Schneedecke in Einzugsgebieten (*Hrsg.:* G. Blöschl, D. Gutknecht und R. Kirnbauer, Hochschulkurs Wien, Dezember 1990), Forschungsinitiative der Verbundgesellschaft, Bd. 13, pp. 29-48.

Rott, H., and Markl. G. (1989) Improved snow and glacier monitoring by the Landsat Thematic Mapper. Proc. Workshop on Landsat Thematic Mapper Applications, Frascati, Italy, Dec. 1987, ESA SP-1102, pp. 3-12.

Sevruk, B. (1986) Conversion of snowfall depths to water equivalents in the Swiss Alps. In: Workshop on Correction of Precipitation Measurements. Zürcher Geographische Schriften 23. Geographisches Institut der Eidgenössischen Technischen Hochschule Zürich. pp. 81-88.

Sevruk, B. (1989) (Ed.) IAHS/WMO/ETH International Workshop on Precipitation Measurement, St. Moritz, Switzerland 1989.

Shimizu, H. (1970) Air permeability of deposited snow, Low Temp. Sci., Ser. A22, pp. 1-32.

Siemer, A.H. (1988) Ein eindimensionales Energie – Massenbilanzmodell einer Schneedecke unter Berücksichtigung der Flüssigwassertransmission. Berichte des Institutes für Meteorologie und Klimatologie der Universität Hannover, Heft 34, 167 pp.

Smagorinsky, J. (1974) Global atmospheric modelling and the numerical simulation of climate. In: Hess, W.N. (*ed.*) *Weather and Climate Modification*, Wiley, New York.

Sommerfeld, R.A., and Rocchio, J.E. (1993) Permeability measurements on new and equitemperature snow, *Water Resour. Res., Vol. 29, No. 8*, pp. 2485-2490.

Tarboton, D.G., Chowdhury, T.G., Jackson, T.H., and Bowles, D.S. (1993) A spatially distributed energy balance snowmelt model. (Abstract of a Lecture at the EGS Gen. Ass., Wiesbaden May 1993), Annales Geophysicae, Supplement II to Vol. 11, Part II, p. C248.

Trofimova, E.B. (1970) A method for calculating the reflective properties of snow surfaces (in Russian). Sredneasiatskij Nauchno Issledovatelskij Gidrometeorologicheskij Institut, Leningrad, 52 (67), pp. 21-25.

USACE, U.S. Army Corps of Engineers (1956) Snow hydrology. Summary report of the snow investigations. Portland, Oregon.

Wankiewicz, A. (1979) A review of water movement in snow. In: Modelling of Snow Cover Runoff (*ed.* by S.C. Colbeck and M. Ray, Proc. Meeting, Hanover, New Hampshire, Sept. 1978), US Army Cold Regions Research and Engineering Laboratory, pp. 222-252a.

Wankiewicz, A. (1991) Mountain snowpack observations by microwave satellite. In.: Snow, Hydrology and Forests in High Alpine Areas (*ed.* by H. Bergmann, H. Lang, W. Frey, D. Issler and B. Salm, Proc. Vienna Symp., Aug. 1991), IAHS Publ. No. 205, pp. 151-168.

WMO (1975) Intercomparison of conceptual models used in operational hydrological forecasting. Operational Hydrology Report No. 7., Secretariat of the World Meteorological Organisation, Geneva, Switzerland.

WMO (1986) Intercomparison of models of snowmelt runoff. Operational Hydrology Report No. 23. WMO-No. 646, Secretariat of the World Meteorological Organisation, Geneva, Switzerland.

Woo, M.-k., Heron, R., Marsh, P., and Steer, P. (1983a) Comparison of weather station snowfall with winter snow accumulation in High Arctic Basins, *Atmosphere – Ocean, Vol. 21, No. 3*, pp. 312-325.

Woo, M.-k., Marsh, P., and Steer, P. (1983b) Basin water balance in a continuous permafrost environment. In: Permafrost, Fourth International Conference. National Academy Press, Washington, D.C., pp. 1407-1411.

Woo, M.-k., and Steer, P. (1986) Monte Carlo simulation of snow depth in a forest, *Water Resour. Res., Vol. 22, No. 6*, pp. 864-868.

Zuzel, J.F., and Cox, L.M. (1975) Relative importance of meteorological variables in snowmelt, *Water Resour. Res., Vol. 11, No. 1*, pp. 174-176.

First received: September, 1993
Final version received: 22 November, 1993
Accepted: 24 November, 1993

Address:
Institute for Hydraulics, Hydrology and Water Resources Management,
Technical University of Vienna,
Karlsplatz 13/223,
A-1040 Vienna,
Austria.