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# Modelling Mountainous Water Systems Between Learning and Speculating Looking for Challenges

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For many years considerable efforts have been put into investigating and modelling hydrological processes of mountainous catchments. On the one hand, the complexity and intrinsically high variability of the involved processes as well as insufficient knowledge of the underlying physical mechanisms still induce large uncertainties in understanding observed phenomena and predicting the behaviour of the system. On the other hand, the demand for models that are able to simulate mountainous water resource systems is increasing because of the needs related to both water exploitation and water conservation, which clearly call for an integrated vision and modelling of these systems.

Accordingly, this paper moves from a brief survey of the most significant achievements in mountain hydrology to discuss what could be future challenging issues related to the broader spectrum of questions, which hydrologic modelling of mountainous river systems may face in the next decades. Firstly, reference is made to existing methodologies for modelling alpine water systems, focussing on some specific aspects that provide a basis for the discussion of the weaknesses and perspectives of present simulation tools. The future is thus discussed, delineating some of the research challenges that may foster a comprehensive and integrated vision of water related issues in mountainous regions.

## Introduction

Mountainous catchments are the origin of many of the largest rivers in the world and represent a major source of water availability for many countries. The increasing needs for optimal management of water resources whilst searching for a compromise between water exploitation and conservation require a comprehensive knowledge of the dynamics of mountainous river basins. They are typically characterised by a high intrinsic variability of spatial and temporal features and processes. Furthermore, compared with low or mid elevation sites, they particularly suffer from lack of meteorological and runoff data, due to accessibility conditions and difficulties of maintenance of the recording installations (see, *e.g.*, Williams *et al.* 1999). These two factors turn modelling hydrology of mountainous catchments into a challenging task, for which both the complexity of phenomena and the limitation of data should be taken into account.

A special case is represented by highly glacierised basins because of the even more difficult conditions for monitoring and the consequently limited knowledge about their hydrology. Glaciers can be considered, on the other hand, as one of the most effective indicators of climatic changes, being of either anthropogenic or natural origin (Munro 2000; Oerlemans *et al.* 1998; Seidel *et al.* 1998; Johannesson 1997; van de Wal and Oerlemans 1997; Braithwaite and Olesen 1993). Understanding how climate variations can affect the mid- and long-term behaviour of alpine glaciers is particularly important to detect anthropogenic climate change. Further, alpine glaciers affect significantly water management, being a local resource (local freshwater supply, hydropower generation), and considerably influence the runoff regime of the downstream rivers (see Munro 2000, for a detailed discussion). In this respect, understanding the peculiar hydrological behaviour of highly glacierised catchments and its variability and dependence on geographical, topographical and climatic conditions can provide the basis to increase knowledge on the dynamics of streamflow variability and, ultimately, on surface water resources from mountain rivers.

Because of the strong influence exerted by highly glacierised mountainous regions on mesoscale basins, close attention will be given in the following sections to such regions in mountainous catchments. The problems relevant to their analysis and modelling will mainly be discussed, bearing in mind the need for developing approaches that can reproduce the processes at the headwater scale, but that are also suitable for modelling the basin response at an immediately higher scale.

The complexity of glacierised catchments requires the analysis of a wide range of space and time scales, in order to assess how the small space scale variability can affect that of the large scale one, and how the short-term temporal variability can affect that of long-term. Looking for response mechanisms and for phenomenological dependences that are typical in most of the mountainous catchments, as well as searching for mathematical models that are able to reproduce those mechanisms in a simple but efficient way is still a major task of research. This question is particularly relevant in view of the increasing need for hydrological models that are able simultaneously to consider the variability of each single component of the water cycle and to reproduce the effects of such variability within the integrated response of the catchment (Munro 2000).

In this light, the models that have been developed are often too data demanding and too site-specific for operational water resources analysis. The main processes controlling alpine water systems, *i.e.* i) winter snow accumulation and redistribution due to wind and avalanches, ii) melting of snow and ice driven by the energy fluxes at the snow-air interface and iii) routing of the melted and precipitation water, have been extensively investigated, although most attention has been devoted to snowmelt models. Individual processes as well as their interactions have mainly been analysed using physically based models aimed at increasing process knowledge, whereas for water resources operation conceptual lumped models have been developed and explored. However, many constraints – from the complexity of the processes to the expensive and highly resource demanding field experiments – often limited the analysis to short-term campaigns and to specific objectives. Accordingly, a number of questions still represents a challenge to research, especially interfacing the traditional approach to mountain hydrology, essentially oriented towards understanding physical processes, with the need for a system-oriented approach suitable for water resources engineering.

Far from the purpose of providing an exhaustive analysis of the state-of-the-art in mountain catchment research, this paper intends suggesting what will likely be the problems to be tackled in the coming years. In this light, the following sections put forward a brief review of the significant advances in process understanding, and of the recent developments in modelling techniques to accurately simulate the response of mountainous catchments, and finally delineate some research challenges. The section on Snow Accumulation and Redistribution Models, below, points out the major limitations of these models; the section Snowmelt Models, p. 51, illustrates modelling techniques for snow- and ice- melting processes, emphasizing the merits and shortcomings; the section Runoff Routing Models, p. 53, discusses the mechanisms of snow and ice runoff generation and routing, addressing the adequacy of existing models with respect to operational needs. The section on the Role of Hydrological Data in Mountainous Catchment Modelling, p. 55, examines the crucial issue of data availability for both model calibration and validation, focussing on the validation needs of redistribution techniques. In the following section, p. 59, review of major research contributions finally provides the starting point to speculatively outline the challenging questions of mountain catchment research from the (biased) perspective of water resources engineering.

## Modelling Mountainous Water Systems

### Snow Accumulation and Redistribution Models

In mountainous catchments the temporal and spatial variability of snow storage plays an important role in the water cycle and the prediction of its fluctuations, since the spatial distribution of snow water equivalent (SWE) controls the mechanisms of runoff generation and provides the main water input, although transformed in space and time by the melting process. Correct understanding and modelling of the processes leading to snow cover formation is therefore crucial for a correct assessment of water resources availability (Marsh 1999), runoff forecasting, flood control and hydroelectric considerations and strategies (Engeset *et al.* 2000). From a water resources planning perspective, the need for robust quantitative models of snow accumulation spatial pattern is furthermore particularly important, in order to substitute observations when running simulation models for long-term (*e.g.* multiannual) prediction purposes.

The two main processes governing the formation of snow covers are accumulation and ablation. While vegetation plays a significant role in controlling snow distribution in forest areas, accumulation in open catchments is considerably affected by snow redistribution through avalanches and wind, mainly governed by orographic and topographic factors. The latter also significantly affect the melting process, since they strongly control the distribution of radiation and the energy exchange at the snow surface, and may have some influence on the local redistribution of precipitation.

Over the last 20 years advances have been made in understanding and modelling the processes which control snow accumulation and distribution, and determine the snowcover spatial pattern. However, the complexity of the mechanisms mainly favoured the development of statistical and conceptual approaches, especially in the alpine environment (Marsh 1999). Modelling the dynamics of the accumulation phase has often been disregarded to the advantage of the characterisation of the snow spatial variability computed from snow depth measurements at the beginning of the melting season. Two approaches have been used for this purpose, namely based on interpolation of measurements or making use of redistribution models.

Interpolation techniques mainly based on geostatistics have been adopted to describe the spatial pattern of the snow cover from snow depth observations (Balk and Elder 2000; Carrol and Cressie 1997; Carrol and Cressie 1996; Hosang and Dettwiler 1991). A major limitation to these techniques is, however, represented by the need to establish and maintain demanding field campaigns to obtain the necessary rich data pool. A further limit is that interpolated maps from snow measurements are hardly compatible with use in continuous simulation, and mainly provide either the initial conditions for seasonal melting models, or a periodical update of snow cover maps (US National Weather Service, see Carroll and Cressie 1997).

An alternative method is the use of redistribution models, which produce a snow accumulation pattern variable in space on the basis of available precipitation and climate records (Hartman *et al.* 1999; Blöschl *et al.* 1991). Precipitation measured at a point is generally considered to be snowfall on the basis of a fixed temperature threshold (see, *e.g.*, Dunn and Colohan 1999), and is then redistributed over the catchment by accounting for factors such as wind, gravity, topography and vegetation. To this purpose empirical and conceptual methods are adopted, assuming that the distribution of snow in space depends on few significant parameters, generally of topographic nature and easy to derive, and able to explain some of the observed variability of the process (Blöschl *et al.* 1991). Problems related to the identification of the correct temperature threshold (Strasser 1998) and to measurement errors may, however, affect the quantitative accuracy of these methods.

A conceptual approach has recently been adopted by Hartmann *et al.* (1999), assuming that snow redistribution is governed by the »topographic similarity index« (TSI), this assumption being conceptually similar to the topographic index approach (the well known TOPMODEL by Beven and Kirkby 1979) used to simulate runoff generation mechanisms. Snow transport is thus assumed to follow the flow paths of water. Similarly, Blöschl *et al.* (1991) adopted an interpolation scheme based on elevation, slope and local relief, the latter being expressed by the terrain curvature. Both these approaches seem to be convenient, since the controlling variables can be easily derived from digital elevation models.

Modelling snow redistribution by means of physically based models has also been attempted, mainly addressing the phenomenon of blowing snow, which produces a significant redistribution due to snow saltation and suspension. Although numerous investigations of this problem were carried out have been performed prior to the late '70s (Marsh 1999), the first quantitative models reproducing the phenomena of blowing snow and forest canopy interception were developed, tested and validated in the 1990s (*e.g.* Essery *et al.* 1999a; Pomeroy *et al.* 1997; Pomeroy *et al.* 1998; Liston and Sturm 1998) for applications to large territories of North-American. Such models can not be applied to mountainous areas, where the process of snow cover evolution is far more complex (Liston and Sturm 1998). In Europe, the first physically based models describing the transport and deposition of snow have been developed with the establishment of operational avalanche risk prediction services. These models are capable of producing maps of snow water equivalent that reasonably predict its natural distribution (Guyomarc'h and Merindol 1998). The development of these models requires, however, intensive field measurements and laboratory studies. Moreover, since such studies have not been developed and validated for catchment scales, their output can hardly be used as an input for snowmelt models.

It is therefore clear that both conceptual and physically based models suffer significant restrictions, which limit their extensive application and integration into simulation models in view of assessing mid- and long-term water resources variability due to climatic fluctuations. Further research is accordingly needed to overcome such limitations and »bring knowledge about the accumulation regime up to par with that of the ablation regime...« (Munro 2000).

### Snowmelt Models

As already mentioned, knowledge of the temporal evolution of snow storage is essential for a broad variety of aspects of water resources. The simulation of its evolution, especially during the melting phase, has been modelled by two different approaches, namely conceptually formulated and energy balance models.

Conceptual snowmelt models are essentially based on indices that characterise the amount of heat available for snowmelt. Those indices are combined with easily available hydrometeorological variables, such as the average daily temperature, in order to get an estimate of the expected melt runoff. The so-called »degree-day« method belongs to this category. The calibration of the index has generally been carried out by means of fitting the predicted to the observed melt runoff (see, *e.g.*, Martinec 1984). Due to its simple structure, the degree-day based methods became relatively popular for inclusion in water balance and precipitation-runoff models like the HBV model (see, *e.g.*, Bergström 1992) or the SRM (Martinec *et al.* 1983).

Apart from availability of temperature data, the adequacy of techniques to interpolate it and the need to provide the proportion of snow coverage as initial conditions (see Section 2.1), a few major limitations, however, characterise this approach. For instance, direct dependence on daily temperature data does not allow a good representation of melting processes at temporal scales shorter than one day (Lang and Braun 1990). Other investigations have shown that under certain meteorological conditions temperature is not a good indicator for the amount of energy available for melting (Andersson 1992). Therefore, the temperature-index method has been investigated by several authors looking for improvements, mostly by introducing different degree-day factors for snow coverage in forest areas, open land and on the glacier (Lang *et al.* 1977; Rango and Martinec 1995; Singh *et al.* 2000). It is of interest to note the inclusion in a degree day scheme of a radiation component, that has been shown to improve the overall performance (see, *e.g.*, Kustas *et al.* 1994; Cazorzi and Dalla Fontana 1996; Brubaker *et al.* 1996; Hock 1999; Schuler *et al.* 2001, this issue). These improvements do not, however, consider the explicit variability of the degree day factor with space and time, as dependent on topographic and radiation factors. This would require considerable effort in terms of measurements necessary to infer such dependence, but could provide an improvement for sub-daily scales without requiring switching to energy balance models.

Energy-balance models are based on physical approaches for the simulation of the heat fluxes affecting the snow cover. The first comprehensive physically based snow model was developed by Anderson (1976). From the late '80s onwards several snow models have appeared in the literature (see, *e.g.*, Todini 1986; Bathurst and Cooley 1993) following the concept first implemented in the Système Hydrologique Européen (SHE, Abbott *et al.* 1986). A large number of energy balance models of widely varying complexity have furthermore been developed and designed for hydrological applications (Blöschl *et al.* 1987; Kuchment and Gelfan 1995; Cline *et al.* 1998b), glaciological simulations (Arnold *et al.* 1996; Escher-Vetter 2000), as well as multi-layer models for avalanche risk prediction (Brun *et al.* 1992; Lehning *et al.* 1998). Most recent models all significantly profited from the expanding knowledge on the turbulent transfer in the atmospheric boundary layer above snow (Martin and Lejeune 1998).

While the suitability of these models for specific applications has been and still is under investigation (WMO 1986; Essery *et al.* 1999b; Strasser *et al.* 2001, this issue; SNOWMIP 2001), it must be recognised that energy balance models indeed require detailed meteorological input data, rendering them only suitable for catchments covered by a comprehensive monitoring network or in the presence of adequate models describing the space-time variability of input data, such as wind speed and radiation, which can hardly be interpolated from sparse point measurements in orographically complex regions. This suggests, as pointed out by Braun (1985), that modelling melting processes by means of detailed physically based energy balance models does not imply achieving better results than by using simpler conceptual models, especially for large regions. Accordingly, a reduction of input requirements may be pursued (see, *e.g.*, Obled 1990), also aiming at reducing the risk of having overparameterised models, the calibration of which may result in being affected by equifinality problems (Beven 2001). On the other hand, specific field campaigns coupled with highly detailed physically based modelling exercises may be necessary to properly identify and characterise dependences between factors used by conceptual models and topographic or radiation controls, as further discussed in this paper.

### Runoff Routing Models

The third component of streamflow models of snow fed rivers is the routing of melted runoff. While this is in general influenced by the complexity and the accuracy of the model used to simulate snow accumulation and melting processes, as discussed in the above sections, a special case is represented by the routing of runoff generated by melting processes on glaciers. This is indeed one of the most challenging research issues of alpine hydrology and is hereafter briefly discussed.

In a glacierised basin, in fact, melt water is stored in the snow layer and internal cavities and is routed partially on the surface through the snowpack and partially through the glacier body by means of a drainage system. Such system evolves during the melting season and is different from glacier to glacier, depending on bed topography and geology, and involves a number of different space and time scales. Such a complexity of mechanisms forced experimental investigations to concentrate on single aspects, such as the flux of water through snow, or the routing of melt water from one well identified moulin to the snout, searching for equations that can describe the physics of the system. Research efforts accordingly produced detailed physically based models that reproduce single phenomena, such as the physics of water percolation through snow (see, *e.g.*, Jordan 1991; Brun *et al.* 1992), rather than attempting to model the combined effects from the many runoff components illustrated by Röthlisberger and Lang (1987).

In recent years, the interest in understanding the mechanisms of the routing of melt runoff through the intra and subglacial system initiated several investigations. The most significant contribution to understanding of glacier runoff routing is probably provided by tracer investigations (see, *e.g.*, Nienow *et al.* 1998; Hubbard *et al.* 1995; Tranter *et al.* 1996). Such investigations can be used to identify a likely but not comprehensive topology of the internal drainage network (Gordon *et al.* 1998; Kulessa and Hubbard 1997; Nienow *et al.* 1996a and b) and to derive the main characteristics of their hydraulic geometry, such as flow velocity, flow condition (open channel *vs.* pressure flow), shape of the channel/pipe cross section, and travel time from a moulin to the outlet or dimensions of the hydraulic sections. Unfortunately, the knowledge gained is mainly site-specific, thereby offering limited information content. Moreover, experimental evidence indicates that the internal drainage network evolves throughout the melting season, also suggesting that flow conditions, channel size and topology may drastically change (Nienow *et al.* 1996a and b; Brown *et al.* 1996; Schuler 2001, this issue). Subsequently, and considering the extremely large effort required to carry out extensive field campaigns, it is easy to argue that this methodology can not provide a suitable tool for models aiming at integrated simulation of water resources.

However, some significant insights from tracer experiments have been obtained, which can provide a basis for developing simpler conceptually based models. Nienow *et al.* (1998) showed, for instance, that the evolution of the subglacial system from a distributed, low efficiency system to a channelised hydraulically efficient configuration is strictly correlated to the position of the snowline and its retreating. On the basis of extensive investigation work, comprising chemical, hydrological and glaciological analyses and enabling the description of the configuration network for a specific site (Richards *et al.* 1996; Arnold *et al.* 1996; Sharp *et al.* 1993; Nienow *et al.* 1998; Kulessa and Hubbard; 1997), Arnold *et al.* (1998) simulated the subglacial drainage system as a sewer network, where the flow is modelled by means of the De Saint-Venant equations, also accounting for the evolution of the pipe/channel parameterisation.

A somewhat simplified approach, still based on knowledge of a precise topology of the subglacial drainage network, was proposed by Clarke (1996), who intepreted the theory of water flow in internal glacial channels first introduced by Röthlisberger (Röthlisberger 1972; Röthlisberger and Lang 1987; Fountain and Walder 1998) by means of electric analogies. This describes the network by means of head generators, flow resistors, pulsers, storages and switches that feature the discharge and the pressure head in the internal glacial channels. The promising results suggest that a conceptualisation of the complex process of flows in the internal glacial drainage system is possible. But the need for highly detailed input data, thereby including detailed knowledge of the network topology and the pressure heads in boreholes located along such a network, still represents a major limitation to its extensive application.

Because of the constraints summarised above, alternative approaches have been used in the literature, aiming at modelling the glacier runoff routing on the basis of simple conceptual methods. The use of a linear reservoir conceptual scheme has been thus adopted by several authors to route glacier runoff in a lumped form at the basin scale and at a daily temporal resolution or higher (see, *e.g.*, Obled 1990; Hock

1999; Escher-Vetter 2000). A few reservoirs are generally used to describe the contribution of melting runoff from snow, ice and firn, assuming time (and space) invariance of the recession coefficients. A drawback of this approach clearly consists in failing to describe any physical aspect of the processes, thereby also including temporal changes, which should account for the observed phenomena of network evolution. An improvement with respect to model flexibility was introduced by Moore (1993), who allowed the reservoir parameter to vary on a daily basis according to an Antecedent Flow Index (AFI), which is computed as a function of the inflow to the glacial reservoir for the same day. This however does not solve properly the need for a modelling scheme that can adequately discriminate routing patterns which may be considerably different, depending on the season, the glacier morphology and temporal scale of the analysis. In particular, subdaily fluctuations, which may be of some relevance for the operation of interconnected systems of reservoirs and for flood modelling, cannot be satisfactorily captured.

The need for robust, easy-to-operate and representative routing models for operational and planning purposes is nevertheless high, in order to fulfil the need for the production of water resources scenarios that accounts for long-term natural variability, anthropogenic changes and potential increasing pressure for optimal management with respect to policy changes. Hydropower, for instance, already faces increasing pressure to comply with stricter ecological constraints that require hydrological simulation at the temporal scale of ecosystem dynamics. Similarly, the apparently increasing and consistent retreat of glaciers and the expected effects of a potential climate change also call for simulation tools that are able to investigate the sensitivity of the system to such changes. The liberalisation of the energy market may finally induce considerable changes in hydropower policy production that would also require the investigation of scenarios, which integrate the impact of climatic fluctuations with the constraints posed by an environmentally safe and economically sound planning and management. The timing of such future needs will dictate to some extent the development of new modelling techniques, which should definitely combine the knowledge gained by means of experimental investigations and by sensitivity analysis through physically based models with the operational efficiency and robustness of conceptual schemes.

## The Role of Hydrological Data in Mountainous Catchment Modelling

The question of data representativeness and availability already indirectly arose in the previous sections. Scarcity of data is generally a problem in hydrological modelling, but is a particularly significant issue in mountain hydrology due to the very high space-time variability of processes. Two major aspects should be, however, especially addressed, with regard to limitations of the modelling techniques previously discussed. On the one hand, the lack of adequate *input* data can render ineffective the effort of using sophisticated physically based models that can only be fed by input data obtained by means of simplistic assumptions on spatial and temporal variability, or extrapolated by questionable modelling techniques. On the other hand scarcity of data in both quantity and type can remarkably affect the *validation* procedure of the model. This indeed limits both the possibility of performing cross and/or internal validation on additional variables that are not used for calibration, and an extensive validation necessary to evaluate indeed robustness. In this respect the following sections aim at outlining a few incongruent aspects related to data representativeness in mountainous catchment investigations and modelling.

## Point *vs* Catchment Scale and Data Representativeness

During the last ten to twenty years increasing efforts have been concentrated on the development of distributed models, also for simulating the behaviour of alpine catchments (Obled 1990; Kirnbauer *et al.* 1994). Most models, but especially melting models, use a physically based representation of processes. This is generally achieved by a raster representation of the catchment, thereby implying that input and parameter values have to be provided or estimated for each cell of the discretisation grid (see, *e.g.*, Kirnbauer *et al.* 1994). The latter requirement clearly clashes with the inadequate availability of actual measurements, which are generally confined to point measurements carried out by a single climatological station, located where energy is available and accessibility is possible rather than where it would provide more representative measurements. Moreover, these stations operate for a limited temporal window, generally corresponding to the duration of a summer field campaign. In addition, data provided by standard national networks can only rarely be used, since stations are normally remote from high elevation catchments to minimise technical problems due to malfunctions.

The paradoxical consequence is that highly detailed, physically based models run with input data and parameters estimated by means of interpolation and redistribution techniques, which are recognised to be rough or simplistic. Even the air temperature, which generally shows gentle gradients both in time and space that can therefore be reasonably predicted, may show an actual variability which considerably differs from the computed variability due to local topographical and climatic conditions (Holko and Lepisto 1997). As a consequence of these uncertainties, the literature provides reference to air temperature lapse rates estimated from data (WMO 1986; Blöschl *et al.* 1991; Arnold *et al.* 1996), from physical considerations (adiabatic lapse rate, Todini 1986) or from a combination of both (Blöschl *et al.* 1990). Realistic estimates of the spatial distribution of hydrological variables can be obtained for areas that are provided with an adequate density of measurements by means of interpolation techniques mainly based on geostatistical techniques, as shown by numerous authors (Susong *et al.* 1999; Marks *et al.* 1999; Carroll and Cressie 1996, 1997; Hosang and Dettwiler 1991).

In both the above cases, however, the prerequisite for obtaining representative data from conceptual/empirical models or from geostatistical interpolation techniques is the availability of high quality data, as already recognised by Blöschl (1991). This is especially true in the case of energy balance models that require a high number of input data, the estimation of which has been recognised to be possible by introducing innovative estimation techniques (Kirnbauer *et al.* 1994). A decisive improvement in this respect could be achieved by inference of dependences between hydrological variables and catchment morphology on the basis of targeted field investigations, which integrate conventional ground monitoring with remote sensing images and digital elevation maps. A pioneering work in this direction can be considered the approach used by Carroll and Cressie (1997), who introduced the influence of topographic parameters, such as elevation, slope, aspect and tree cover, into the mere statistical spatial correlation function. Systematically addressing the dependence of key variables such as temperature and albedo from catchment characteristics that can be derived from digital morphological data seems to be, at the present stage, the most challenging route towards improving the efficiency and the robustness of conceptually based modelling techniques.

An interesting and complementary approach to describe the space and time variability of variables relevant for snowmelt processes is related to scaling properties exihibited by such variables (Cline *et al.* 1998a; Blöschl 1999) and which could be used for upscaling and downscaling purposes from and to different spatial resolutions. Recent literature devoted some attention to investigating the influence of grid resolution on the description of the relevant processes for both non-glacierised basins (Braun *et al.* 1997, Thieken *et al.* 1999; Wolock and McCabe 2000), and glacierised or mountainous basins (Cline *et al.* 1998a; Luce *et al.* 1999). When the variable (or the parameter) is characterised by a spatial scaling behaviour, the loss of information is dictated by grid size used to discretise the topography of the catchment, being possible to downscale the values of the variables (or, alternatively, of the parameter) from a coarser set of measurements. When the variability of parameters and variables across scales is not ruled by scaling laws, the loss of information is still related to the topographic grid size, but is additionally affected by the effective information content of the variable (or parameter) at that scale. In this respect, a critical quantity deserving more attention because of its key role in the melting process and its extremely high space variability is the albedo. A tentative reference is made to a new approach to model space-time variability in the next section.

## The Issue of Model Validation

Many years have passed since Klemes' provocative statement (1986) about models getting the right results for the wrong reason. More recently, Andersson (1992) expressed a similar concept, emphasizing the concept that models should work »right for the right reason«. Other interesting contributions (see among others, Seibert *et al.* 2000; Beven 2001) pointed out the need for internal and cross validation of distributed models. These arguments are especially true for mountainous catchments because of both the complexity of the processes and the difficulties related to data acquisition, the latter problem having been addressed by Kirnbauer *et al.* (1994) as the »testability« problem. Appropriate validation of models will, however, become essential once complex and integrated hydrological models are operationally used to predict not only the traditional processes, like streamflow, but also other processes, which are too expensive (or too difficult) to be extensively and systematically monitored. Due to many inherent difficulties, internal validation has been conversely generally neglected, particularly in the case of mountainous catchments, where it appears difficult to identify appropriate variables to be used for this purpose.

Consequently, most of the coupled melt and routing models have been tested against runoff measurements, even in cases where the variability of the processes at an hourly resolution was the target of modelling (see, *e.g.*, Bell and Moore 1999; Hock and Noetzli 1997; Holko and Lepisto 1997; Hock 1999). In such cases, the reasons for good (or conversely poor) results cannot be clearly established, since discharge is an integrated result of variability of single processes, and its fitting can be generally achieved by adjusting almost any of the melt and routing component parameters, in some cases even without being able to justify the reason for the selected tuning policy. Although this is not the main problem for models explicitly conceived to model a single and stable system, it appears to be a major limitation for models required to be transferable, that is able to capture the variability of mountainous catchments at different locations, accounting for significant topographical and climatic differences.

Only recently a few literature contributions provided a quantitative insight about the importance and utility of addressing the question of internal model validation. In this respect, Dunn and Colohan (1999) report of the evaluation of the performance of a distributed hydrological model accounting for more components than only the total runoff. In particular, they show that accounting for validation of baseflow components, snow depth and snow line predictions allowed to understand and quantify the importance of the wind redistribution function used by the model. The inclusion of the wind redistribution component did indeed not increase the total flow efficiency of the model, but had considerable effects on components that are often neglected or do not represent an output of major interest.

Other attempts to account for internal validation of complex models have mainly focused on matching the predicted with the observed snow- and icemelt, and the predicted with the observed snowline position (Bathurst and Cooley 1996; Dunn and Colohan 1999). Advances in measuring devices are of course a prerequisite to make observation possible at the temporal and spatial scales complying with the distributed character of the most recent models. Remote sensing imagery and automated cameras, as discussed in the following section seem to offer an efficient tool to acquire non-conventional data for model validation.

Snowmelt has been traditionally observed by means of ablation stakes that are located along the centre line of glaciers, and cannot therefore provide any information about snowmelt on lateral locations where slope, aspect and other topographic features may exert a higher and more variable control on melting processes. Moreover, observations are carried out manually, which prevents investigation of the variability at high temporal resolution. For this reason, most of the models, even those highly sophisticated, are generally validated against daily or cumulative readings of melt (Braithwaite and Olesen 1993, van de Wal and Russel 1994, Arnold *et al.* 1996, Hock 1999, Williams and Tarboton 1999), thereby questioning, to some extent, the use of complex modelling techniques capable of yielding hourly values as an output. Very few melt models have been conversely tested against hourly measurements of melt runoff (Willis *et al.* 2001). Among these it is worth mentioning the study of Munro (1990), who tested an energy balance model against hourly data for 16 days at a snow site and 21 days at an ice site, and that of Brugman (1991), who validated an energy balance model against 2 days of hourly melt data on snow. These two experiments were, however, limited to the melting model.

A more comprehensive effort characterises the experiment run by Willis *et al.* (2001), who tested against field measurements the energy-balance based melting component of a distributed physically snowmelt-runoff model (Arnold *et al.* 1996, Brock *et al.* 2000), aiming at investigating the role played by the melting component with respect to the overall performance of the model tested against runoff at the glacier outlet (Arnold *et al.* 1998). Hourly values of snowmelt were recorded by an ultrasonic distance sensor installed above the glacier surface for about one month, checked for errors and, subsequently, used for the internal validation of the complex model. The analysis of Willis *et al.* (2001) made possible, due to its uniqueness for the highly sophisticated level of field measurements, to recognise that the modelled and measured ablation rates compare favourably overall, thereby including temporal fluctuations. Some minor discrepancies, however, seem to be systematically due to the melting and freezing diurnal cycle of the surface water layer, which the model does not take into account.

## What is the Future of Modelling Mountainous Water Systems?

The considerations outlined in the previous sections suggest that some major gaps in the understanding of the processes controlling the water budget of mountainous catchments still remain, although knowledge has greatly improved over the last 20 years. Such gaps, regardless of their nature, limit to some extent the predictive capability of existing modelling approaches. The question whether improvements can be expected and what are the directions, which research should take, is the object of speculations reported in the present section.

The first issue is probably relevant to recognise that detailed physically based models will never be able to provide an appropriate simulation of the complex dynamic of ice- and snowmelt runoff if the data necessary to calibrate and validate the model itself are missing at both the adequate scales and for many different experiments. A second consideration is concerned with the significant discrepancy between the scale of interest of water resources analysis and the scale of development of the most recent physically based models. A third reflection concerns the need to understand the long-term reaction of mountainous water systems, especially highly glacierised basins, to climatic forcings. It can first be observed that, complying with the three above issues influences to some extent a priori the structure of the »ideal« model, which is further discussed in the following. This cannot be a fully detailed physically based model, essentially because of data and computational requirements and space-time scale of operation. Conversely, it should

- be distributed in space to account for the variability which is detectable through topographical heterogeneities;
- be physically oriented, but conceptual in structure, to discriminate among the different relevant processes, without formulating a model that is too demanding in data and computing resources;
- allow for extensive simulations that can be used as a surrogate of observations which anyhow are unavailable, in order to analyse the sensitivity of the system to climatic forcings, thereby including natural and anthropogenic non-stationarities.

To support this vision discussion of fostering a modelling philosophy, which aims at being more compatible with the emerging needs for integrated water resources modelling, follows hereafter.

## Advanced Modelling *vs* Targeted Modelling

Since a decade distributed models have been investigated and tested and have been increasingly developed. An excellent discussion on the topic is provided by Kirnbauer *et al.* (1994). However, they have been mostly conceived as physically based. A major limitation of data available for extensive calibration and validation under different catchment characteristics and climate either confines their use to selected locations, or often forces assumptions being made on required input, which are almost impossible to test against observation. There is no question that these advanced models can offer a better degree of representation of physical processes at small space-time scales, but it can be observed that they hardly serve the purpose of targeted modelling, necessary for water resources analyses.

A way to compromise between the need for accuracy in process description and the suitability for targeted modelling is represented by distributed models that are based on conceptual modelling schemes applied to a raster-based discretisation of the catchment. Since the parameterisation of such models is possible for data that can be generally easily gathered or estimated (such as the temperature), these models can be better transferred from one catchment to another, which is essential for water resources modelling. As discussed previously, conceptual models of mountainous water systems essentially consist of two modelling components, namely the snow- and icemelt runoff generation and the runoff routing component, for which improvements are possible.

An interesting framework for further development among conceptual models for snow-and icemelt runoff generation can be the degree-day approach, which has been widely adopted to simulate snow- and icemelt generally for temporal scales longer than one day. Despite some limits due to its simple structure, it has been observed that some low-demanding correction in terms of radiative fluxes improved its predictive performance (see, *e.g.*, Cazorzi and Dalla Fontana 1996; Brubaker *et al.* 1996; Hock 1999, Schuler *et al.* 2001, this issue). A margin of improvement is, however, possible, by substituting each of the fixed values of the degree-day factor – one for snow, one for firn, and one for ice – by space-time variable formulations. These should accordingly account for

- intrinsic space variability, as induced by topographic characteristics, such as aspect and slope, and
- spatiotemporal variability of structural changes of snow and ice cover due to aging processes, as determined by the number of effective hours of exposition to sun, which depends on both climatic variability, described by air temperature and/or cloud cover time variability, and topographical characteristics such as elevation and aspect.

This can be done either by mathematical formulation of the dependence of the degree-day factors from the above indicated variables, or by modifying the degree-day equation by additional and/or multiplicative factors, as already suggested by other authors for a lumped formulation. In this respect, the first option looks to be more demanding, since it would require more extensive and complex field investigations, similar to that needed by physically based models. The second, perhaps less effective in terms of gain of performance, can, however, help in accounting for critical processes, such as space-time variation of albedo and wind affected snow accumulation.

The latter aspect can probably profit from advancements achieved in wind engineering, aiming at modelling wind fields in urban landscapes (see, *e.g.*, Kiefer and Plate 1998; Kastner-Klein and Plate 1999), the rugged aspect of which could resemble some of the complexity of turbulent fluxes occurring in alpine valleys. Nesting small scale wind models, capable of modelling the effect of the orographic macro-roughness within main wind fields available from either statistical or climatic models, may help in understanding the dominant pattern of the interaction between wind and orography. This can lead to the formulation of a redistribution function of snow accumulation, which depends on the local topography and may be parameterised on the basis of the prevailing wind fields as observed by seasonal weather pattern or predicted by operational weather models.

If modelling snow redistribution by wind remains an ambitious goal, introducing an albedo dependent parameterisation of the degree-day equation seems a more reasonable objective. In this respect, a model of space-time variability of albedo must be obtained by combining its direct measurement on the ground at different locations in the catchment and the value that can be estimated by corresponding satellite images. The latter provide a basis for space interpolation, whereas ground measurements provide the reference scale for quantitative image analysis. By systematically repeating the measurements over more than one melting period, and contemporarily measuring the climate variables, the temporal albedo variability as a function of climatic variability can be also be conjectured.

How to improve the modelling of meltwater routing to the glacier outlet, especially in view of distributed application, is far more complicated. This complexity stems from the yet insufficient knowledge available to characterise the subglacial drainage network and, above all, from the high variability and apparent unpredictability of its changes across the melting season. Nevertheless, some attempt to model the intra- and subglacial runoff can be envisaged, for instance, by borrowing modelling schemes used to describe other processes in hydrology. Two techniques could in this respect be considered to explore a distributed approach alternative to the lumped reservoir widely used in the literature, namely the Muskingum-Cunge routing scheme, which has been shown to be very efficient for flood routing, and artificial neural networks (ANNs, see, *e.g.*, Rojas 1996), which are increasingly adopted to model hydrological processes that look highly variable, such as precipitation and streamflow.

Because it is essentially based on the linear reservoir conceptual scheme, the use of the Muskingum-Cunge method (Cunge 1969) could reproduce the storage effect that has already been used by several authors to route in a lumped form the glacier runoff (see, *e.g.*, Hock 1999). Under the assumption that the topology of a subglacial network can be inferred from the topography of the glacier, and that the inglacial flow is a free surface flow, the propagation along such a network can be modelled by means of a distributed Muskingum-Cunge scheme. This propagates the flow to and from each grid element of the discretised network by integrating the continuity equation between the upstream inflow side of the grid element and the downstream outflow, assuming that the resulting storage variation is expressed by a linear law. Both the parameter of the linear reservoir and the coefficient, which expresses the influence of the inflow runoff to the element compared to the outflow, can vary along the network, and, in principle, with time, if the hydraulic geometry of the channels is expected to vary. A further refinement can be represented by the possibility of defining more levels of the subglacial network, assuming that the meltwater runoff is partitioned through several subglacial networks before being routed to the glacier outlet. Although the scheme in principle looks very flexible, two major drawbacks can make it fail, namely the required a priori knowledge of the subglacial network(s), and the inherent difficulty of producing realistic estimates of the parameters, without running the risk of turning into an over parameterisation problem, or, equivalently into a parameter equifinality circumstance. Inferring the subglacial network as a projection of the surface drainage network as derived from the digital elevation model may be a starting point, at least in those cases where glacier topography appears to be significantly regular.

In order to circumvent these problems, but still keeping in mind the need for a flexible model component that is homogeneous with a conceptual approach to simulating snowmelt runoff, modelling the routing of meltwater runoff by means of ANNs can be envisaged. In this case the ability of ANNs to learn the transformation rule between two processes by means of a training set should allow to build a so-called »black-box« model of the routing process. For a given set of meltwater inputs distributed over the catchment, and the concurrent set of runoff measured at the glacier outlet, a neural network can be, in principle, trained to simulate the response of the subglacial network without any information about its topology. The resulting model can be then used for further simulation under the assumption that the system response remains stationary. Because of the seasonal variation of the subglacial drainage system, one can derive different ANN structures by partitioning the input into different subsets, and by repeating the ANN training and deriving different ANN structures, a main limit to this being only the minimum amount of data required as a training set. Should these routes be able to provide successful results under different climatic conditions and throughout the season, a runoff routing model could be available, the main requirement of which is »only« the availability of adequate input data in the form of meltwater. Regardless of the need for evaluation of the performance of ANNs for different topographical conditions, this transfers back the problem to the quality of the snow- and icemelt model, and to its requirement for data necessary to perform internal validation.

## Non Conventional Input Data and Internal Model Validation

The problem of availability of data necessary to input snowmelt-runoff models and to their internal validation depends essentially on the nature of the model, as already mentioned. If detailed physically based models necessarily require to set up highly demanding ground based field investigations, some alternative routes are available for the conceptual model, previously illustrated.

Conceptual snow- and icemelt models do not indeed require detailed information on energy fluxes as an input. Rather, they need a distributed estimate of factors conditioning the melting process such as temperature and albedo. Although the issue of space interpolation of temperature is to a large extent still an unresolved problem, the reader is referred in this case to specialised literature (see Section 3.1) for the issue of space interpolation of temperature. It is conversely interesting to note how the assessment of spatio-temporal variability of albedo can be obtained by combining a set of ground measurements with remote sensing imagery and topography. An example of such combined use is given by Knap *et al.* (1999), but more elaborate experiments are required to more extensively validate the algorithms used to derive albedo from satellite images, before using the estimated space-time variability to infer dependence on topographic characteristics.

Satellite data are moreover extremely useful in providing a good platform for val-

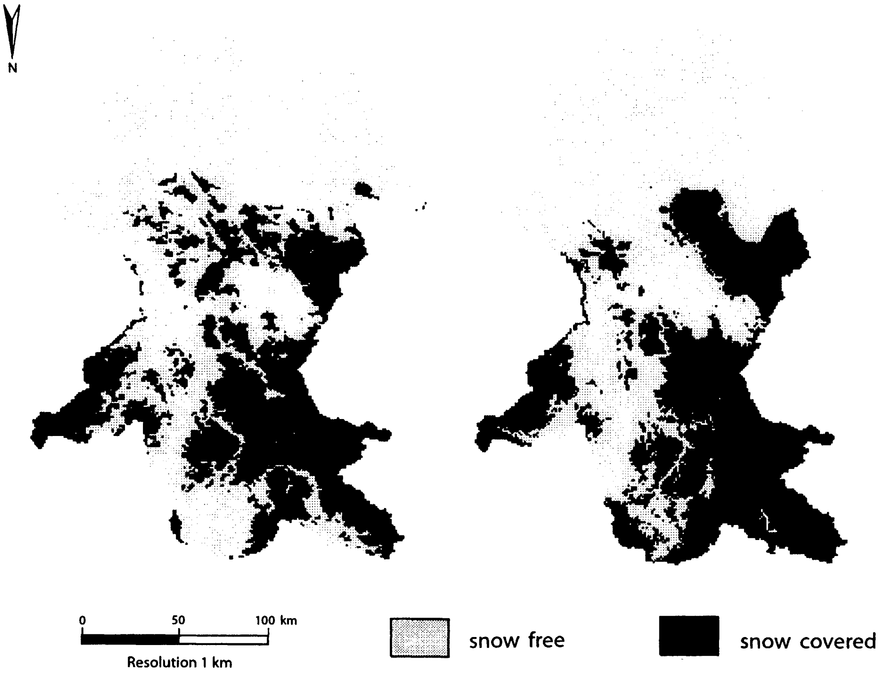


Fig. 1. Comparison between snow cover in the Weser catchment on February 14th, 1994 as detected by NOAA-AVHRR (left) and modelled with ESCIMO (right). The percentage of snow covered raster elements in the NOAA-AVHRR image is 32%, whereas it is 36% in that computed by the model. The image-to-image comparison shows that the snow cover situtation (snow covered or snow free, respectively) is correctly modelled for 84.2% of the raster elements (from Strasser 1998).

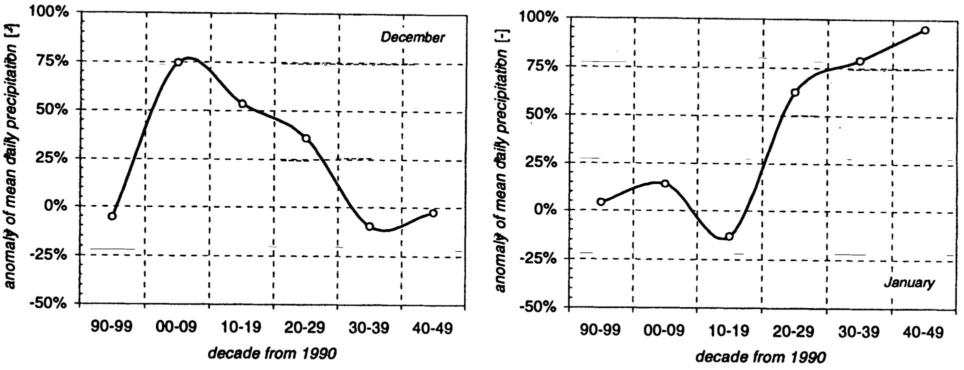
idation of snow- and icemelt models that can predict snow water equivalent and snow-line position. A number of contributions can be found in the literature, indicating that simulated and observed snow covers yield similar patterns, as illustrated by Fig.1. Accordingly, snowmelt models aimed at simulating melt water volumes can be internally validated against a time series of snow line positions estimated from satellite images. However, if snow is detected by satellite images, it is then necessary that data acquisition directed at validating snowmelt models on the basis of remote sensing imagery is coupled with additional monitoring of the snowline, for instance, by means of automated cameras, which periodically take pictures of the target area. Remote survey still must be integrated by the traditional and necessary survey activity on the ground, for which new criteria of network design must be elaborated and new instruments must be adopted to achieve a space-time distribution that is compatible with remote sensing images. Improving the accuracy of the latter is a crucial issue in view of extending their use for analysing the snowline evolution in any generic mountainous catchment.

Since other promising remote techniques, such as laser altimetry, are still in their infancy, the internal validation of snow accumulation and redistribution models, presently based on ground measurements only, remains more critical. Otherwise, assuming to have available an efficient distributed snowmelt model and accurate distributed measurements of the snow line, the snow accumulation component can be validated by matching the continuity of the system mass.

### Long Term Sensitivity to Climatic Forcing

As repeatedly mentioned, a major lack of the present state-of-the-art of models used to reproduce the behaviour of mountainous catchment water systems is the inability to simulate their long-term response. This is especially serious in view of the rising pressure to assess the impact of a potential climate change on snow-fed river systems and on highly glacierised catchments. Considerable efforts have been invested to investigate the latter problem (see among others, Braun *et al.* 2000; Westaway 2000; Haeberli *et al.* 1999; Singh and Kumar 1997; Watson *et al.* 1996; Burlando and Grossi 1996; Leavesley 1994). In many cases, however, hypothetical climate scenarios, accounting for a fixed increase of the temperature and/or of the precipitation, have been used to investigate the average effect on monthly and annual streamflows, without considering the effect of increased variability. Although glacierised areas of alpine regions are a suitable indicator of climatic fluctuations because of their pronounced memory and temporally delayed and filtered response to climate variability (Haeberli 1995), little is known about their response to high frequency fluctuations and interannual variability, which are expected to occur because of global change (see Fig. 2). The mass-balance approach traditionally used to assess the retreat or the accretion of glaciers, indeed does not provide any clue about the response of a glacier to a persistent »dry« period – *i.e.* low precipitation and prevailing clear sky conditions – or to a persistent »wet« period – *i.e.* frequent precipitation and prevailing cloudiness. Regardless of the fact that climatic fluctuations are of an anthropogenic nature or due to natural variability, they may significantly influence not only the dynamic of snowmelt runoff (Collins 1982; Escher-Vetter and Reinwarth 1994), but also the mass-balance of the glacier. Investigating glacier response to short-term climatic fluctuations and their variability, as well as to extreme events, such as the persistence of wet and dry periods, can help to understand how the high frequency response can be responsible for apparent trends of glacier dynamics. In this respect, specific techniques are available, which are suitable for long-term simulations, and can therefore be easily coupled with conceptual snowmelt-runoff models. Stochastic models of temperature and precipitation can be used to this purpose, since they have been proven to provide satisfactory representation of the natural processes (see, *e.g.*, Burlando and Rosso 1993; Cowpertwait *et al.*. 1996a) and easily allow to generate transient climate change scenarios downscaled from GCMs simulations to the catchment scale (see, *e.g.*, Burlando and Rosso 1991, 2001; Cowpertwait *et al.*. 1996b, Kilsby *et al.* 1998).

Mean daily precipitation in winter months



Probability of dry period in summer months

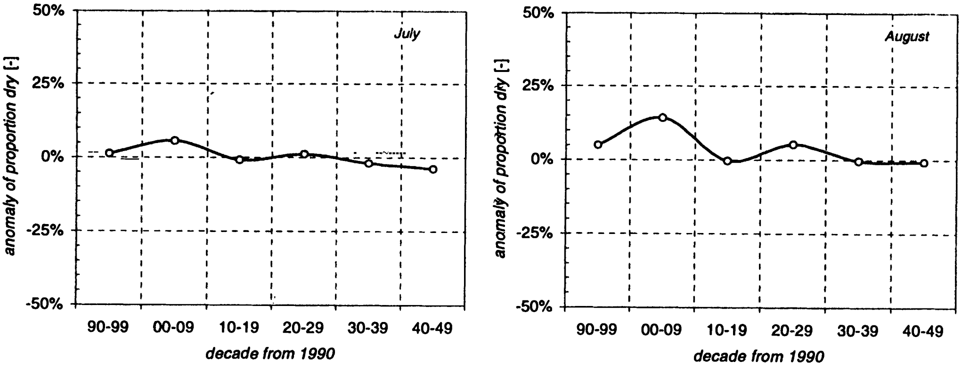


Fig. 2. Example of anomalies of mean daily precipitation and proportion dry for the station of Malga Mare (1,970 m.a.s.l., Alto Noce river basin, Northern Italy) as estimated from climate change scenarios downscaled according to Burlando and Rosso (1991).

Accordingly, a few key questions arise, which are expected to be answered by modelling response to long-term simulation of climatic fluctuations, namely:

- the existence of some threshold mechanisms related to persistent weather conditions (dry and wet), which can apparently trigger irreversible retreating trends of glacier mass-balance;
- the assessment of how an increased variability of short-term precipitation process, expected in the form of longer summer dry intervals and higher precipitation volumes concentrated in a short time, as well as higher winter precipitation volumes, can affect the seasonal snowmelt runoff dynamics and the long-term evolution of the glacier response, for instance by increasing the retreat rate;
- investigating whether higher summer temperatures and radiation fluxes in a changed climate can be compensated by higher winter precipitation volumes, thus slowing down the retreat process.

Answering these questions would probably provide both a better understanding of glacier evolution and a more realistic assessment of glacier response in future climate scenarios, thereby allowing an improved estimation of water resources availability from mountainous catchments and an enhanced assessment of the consistency of the rather catastrophic prediction about the future of alpine glaciers.

## Concluding Remarks

Recent developments in computer technologies and electronics have increased the possibility to simulate the functioning of many natural systems. The description of the hydrological behaviour of mountainous catchments has also profited, both in terms of more sophisticated field experiments and development of very complex physically based models. The achievements are, however, still insufficient to satisfy, on the one hand, the need for improved understanding of the extremely high complexity of processes occurring in high mountain basins, and, on the other hand, the search for robust modelling tools that allow their flexible simulation within a context of water resources analysis. In this respect some issues, which could characterise future research, can be outlined.

The first question is relevant to the level of complexity that models should afford. If it is clear that only physically based approaches can offer the necessary insight into processes to recognise the governing laws, it is still often the case that simplified targeted models have some advantages. This is mainly true in two circumstances: when adequate data for calibration and validation of highly detailed models are partially unavailable, and when model transferability and scenario generation force to select conceptually based models, which are parsimonious in parameter and computational requirements. This suggests that future research should aim at combining the best of the two approaches, searching for a sort of unified technique allowing to adjust the complexity of the system representation as a function of the modelling target, rather than evoking a dualism between two modelling philosophies. Identifying the representative elementary time and space scales and developing distributed models are key points to this issue.

The above consideration leads immediately to the issue of data requirements. Great effort should be made in investigating techniques that can substitute direct measurements via resource demanding and comprehensive instrumental networks with data representation derived from easily available data. In this respect, the functional space time dependence of temperature and albedo fields from topographic controls should firstly be further explored, since these two variables represent the main input of conceptually based models. A combination of remote sensing estimations from advanced sensors with an intensive and targeted field campaign should therefore be organised, aimed at providing experimental evidence of site independent functional relationships, for instance, between albedo and aspect. Concentrating such an effort on those few key variables, the estimation of which can benefit from the digital distributed description of catchment characteristics and from remote sensing surveys, will simultaneously provide an improvement of conceptual schemes, and additional data for calibration and validation of physically based models.

In view of the strong effects of potential climatic changes on glaciers, increased attention should also be paid to the investigation of the sensitivity of mountainous systems to extreme, but short-term climatic deviations, and to long-term changes. Hypothetical scenarios should accordingly be substituted with fully dynamic simulations of climatic fluctuations in order to detect how an increased variability of the precipitation process (longer dry summers and winters with more abundant snowfall) as well as a modified cloud cover regime and higher temperatures can affect the seasonal snowmelt runoff patterns and the »effective« long-term evolution of glaciers. Such a sensitivity analysis could finally provide some clues about the existence of threshold mechanisms related to climate variability, which can apparently trigger irreversible retreating trends of glacier mass-balance.

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