Tackling complexity in modelling mountain hydrology: where do we stand, where do we go?

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Abstract The modelling of mountain hydrology is characterized by a series of challenges: continuous accessibility of sites is usually difficult, the accuracy of measurements is limited or even unknown, and their areal representativeness is highly variable in space and time. The spatial variability of many variables that serve as model input undergoes significant scale dependence, and the validation possibilities for model output are limited. Finally, the quantification of uncertainties is usually limited to ensemble simulations across reasonable parameter spaces. Even though sophisticated mountain hydrology modelling schemes have been developed recently, many early concepts have survived: temperature index snowmelt modelling, the neglect of snow sublimation, pragmatic gauge corrections, evapotranspiration estimations, and simple soil- and overland flow representations. Many of these models lack the ability to be transferable in space and time, and in scenario applications they produce artefacts. By means of combining physically-oriented parameterizations and statistical approaches, multi-scale sensitivity studies and integration of remote sensing data in the meantime we can compile improved versions of our models. This is additionally facilitated by an increasing number of new hydrometeorological observatories in mountain areas that are currently built up. As an example of the potential and limitations of modelling mountain hydrology, we present an approach to combine a distributed hydrological model, physically-based snow process parameterizations and an artificial neural network for an enhanced modelling of water fluxes in a high Alpine catchment in the Berchtesgaden Alps (Germany). The hydrology there is highly complex due to the very steep topographic gradients, related spatial variability of all meteorological variables, the very heterogeneous snow cover and the karst nature of the groundwater system. We demonstrate the benefit of single model enhancements, and provide a generally climate change scenario-capable application. With operational observatories, international cooperation and networking, new opportunities arise for joint mountain hydrological process and modelling studies. We conclude with an outlook of upcoming scientific challenges in coupled human–natural water systems.

Key words mountain hydrology; modelling; scale dependence; snowmelt; glacier response; operational observatory; process-oriented approach; complexity; society

INTRODUCTION

After PUB (Predictions in Ungauged Basins), the science-initiative that started in 2003 and ended in 2012, IAHS is now entering the decade of Panta Rhei (Everything flows: Change in Hydrology and Society). This new initiative officially started during the IAHS General Assembly in Göteborg, Sweden, 22–26 July 2013. The new common vision developed by the IAHS community focuses on the rapid environmental changes and an improved understanding of the processes governing the water cycle, their changing dynamics, and their mutual interaction with rapidly developing human systems. This new decade is seen as an exceptionally significant opportunity to strengthen the role of hydrological sciences in society. For hydrologists all over the world, this is a moment to pause and critically reflect the achievements the hydrological research community has accomplished during PUB, the state of the art of hydrological science today, and the next steps to undertake into Panta Rhei.

As for mountainous water systems, they are characterized by exceptionally fast and intense changes, impressively visible, be it the enormous spatial heterogeneity of the meteorological variables, efficient mass movements like avalanches, sediment transport, mudflows or rockfalls, enormously fast developing floods or changing hydrological regimes due to shrinking or even disappearing glaciers. Even the effects of climate change are easily recognizable. The extreme topography in Alpine regions accelerates and intensifies the hydrological and morphological processes, often leading to situations with effects that cause the status of a catastrophe for the population at first. Such events have an extreme level of awareness by the affected communities, find their attention in the media, and are understood in their significance by the public:

mountainous water systems are commonly understood in their importance, not to mention their central role as water towers.

In this article we reflect the development of the modelling of mountainous water systems, and make an attempt to provide a perspective of what could be important to scientifically investigate by the hydrological community within the framework of the new IAHS science initiative, Panta Rhei. After describing the perception of the challenges of hydrological modelling, we show how much of classical calibration methods have survived in our simulation methodologies used today. Then we provide examples of how the intrinsic complexity of mountainous water systems can be tackled in process-oriented parameterizations, and what beneficial role the equipment of long-term observatories in mountain basins can play. Finally, we highlight the importance of initiatives for cooperation and internationalization, and the role of society in current and future research action.

THE ULTIMATE CHALLENGE

It is now almost 25 years since the IAHS President at that time, Vit Klemeš, published his well-known article "The modelling of mountain hydrology: the ultimate challenge", an outcome of the Štrbské Pleso workshop which was held in Czechoslovakia in 1988 (Klemes, 1990). In this paper, modelling mountain hydrology was not only seen as fitting some more or less plausible mathematical expressions to given sets of data so as to minimize the difference between the modelled and recorded times series of runoff, but it was regarded as synthesis of observed empirical facts and their theoretical understanding. Hence, this synthesis requires both observations of the state of nature, and consideration of processes covering the widest range. From the perspective of the late 1980s, the observations were "the most difficult to make", and the processes governing mountain hydrology "posing the greatest demands on theoretical understanding".

In the article, the problems of accessibility of mountain sites on a continuous basis, and observation of, e.g. a precipitation profile over a mountain range or streamflow in a mountain creek, are impressively portrayed. A second problem is the one of accuracy, e.g. of the recordings of precipitation due to wind effects or malfunction of the device, or of streamflow, due to the high instability of the channel cross-sections, to name only two examples. The third problem, the areal representativeness of point observations, is of course a general and pervasive problem in hydrology, but it is most serious in mountainous terrain. Here the topography, soil, and the ground cover come together with extreme variability of hydrological and meteorological variables. Klemeš states "only remote sensing is a promising technique to support areal distributions of the point measurements" (Klemeš, 1990). Remote sensing can be employed for topographic surveying, land-use and soil type mapping, and, "most significantly for mountain hydrology, [for] the mapping of snow cover and lately in the mapping of snow water equivalent".

In this period, the retrieval, processing and analysis of remotely sensed data was a demanding and expensive task, mastered only by a few specialists.

The theoretical understanding of the processes shaping mountain hydrology is complicated by their intrinsic theoretical complexity, combined with the aformentioned difficulties encountered in connection with gathering the empirical knowledge – to be brought together by means of interdisciplinary cooperation, due to the interplay of the corresponding processes.

In mountainous settings, more complicating problems arise. A crucial one is the meaning of scale, here going far beyond the usual connotation of areal size: both the vertical and the horizontal aspects of scale have a direct relevance to the effective structuring of a hydrological model, to its parameterization, and to the extent and type of lumping.

There are more features in mountain hydrology that make modelling such systems different from the classical rainfall–runoff modelling: providing adequate input data can be a challenging modelling task itself. The structure of a mountain hydrology model should also account for non-linearities and threshold effects in the various processes, like the release of meltwater from saturated firn or avalanches which accelerate melt in the lower zones to which the snow is transported. Mountain hydrology models have to be properly adjusted in their spatial and temporal resolution, in their physical representativeness according to the intended purpose, in the complexity of the parameterizations applied (according to the nature of the modelled system, and the available input data). Increasing the number parameters does not necessarily mean improvement.

Klemeš concludes that "mountain hydrology modelling highlights some important problems of contemporary hydrology and points the way to their solution more clearly than it would be otherwise apparent" (Klemeš, 1990). He supports a focus on the processes that shape the hydrological cycle, and on the importance of areal mapping of hydrological variables to overcome the inadequacy of the traditional point measurements.

Most interestingly, even the human perspective is considered as a challenge, in fact with respect to the intrinsic relativity of the scale and the terms "lumped" or "distributed". The notions of scale and size are influenced by the national origin of the modeller: what is a catchment of relative prominence in one country may be identified as the basin of a small creek in another.

PERILS OF CALIBRATION

A comprehensive review on the state of modelling mountainous water systems was given by Burlando *et al.* (2002). Special consideration was directed to modelling snow accumulation and redistribution, since the spatial distribution and temporal dynamics of the snow water storage controls the mechanisms of runoff generation and provides the main input for the melting season streamflow. Hence, the processes leading to the spatio-temporal heterogeneity of the mountain snow cover are crucial for the prediction of the water resources availability (Marsh, 1999), be it for the natural streamflow generation, or for the release of meltwater into reservoirs for hydropower generation. Whereas the accumulation process of both solid and/or liquid precipitation in mountainous basins is an extremely complex and scale-dependent process, its quantification has been much improved with the availability of airborne laserscanning imagery time series, which at least enable the derivation of winter accumulation patterns, the resulting total of preferential deposition, erosion and deposition, and avalanches (Warscher *et al.*, 2011). Explicit modelling and remote sensing have provided evidence that the resulting snow patch patterns in spring are highly persistent (Bernhard *et al.*, 2010). The resulting quantities are also an essential prerequisite for the understanding and robust modelling of glacier mass balances, i.e. simulating the long-term glacier response to a changing climate without producing artefacts (Strasser, 2008).

With respect to snowmelt modelling, temperature-index based conceptual approaches like SRM (Martinec *et al.*, 1983) or HBV (Bergström, 1992) are still widely used, mainly in remote regions with sparse data availability (e.g. Hagg *et al.*, 2011). Originally only utilizing temperature as input, these models have been extended to include modelled radiation (Hock, 1999) and, later, albedo (Pellicciotti *et al.*, 2005). Where the required data is available (i.e. primarily in special observatory sites with structured research programmes), energy balance approaches have been developed, applying more or less complex methods to distribute the weather station recordings to the basin scale (i.e. Pomeroy *et al.*, 1998; Escher-Vetter, 2000). Successful attempts have also been made to apply the multi-layer models for avalanche risk prediction for hydrological applications (Brun *et al.*, 1992; Lehning *et al.*, 1998; Etchevers *et al.*, 2004). However, in many cases the runoff generation process is still simulated by means of simple linear reservoir approaches (Kirnbauer *et al.*, 2009), and snow-canopy interaction is mostly neglected, even though parameterizations exist to both quantify the amount of snow that evaporates from the trees, and the evolution of the beneath-canopy snow cover (Liston & Elder, 2006; Strasser *et al.*, 2011). The need for robust, easy-to-operate hydrological models is nevertheless high, in order to fulfil the needs of short- to medium range water resources management including planning purposes, flood forecasting and hydropower generation. In most cases, the water system is modified by man-made technical structures and manifold water use strategies. Burlando *et al.* (2002) also accentuate the importance of data distribution and representativeness, and proper model validation. They conclude that "identifying the representative elementary time and space scales and developing distributed models are key points …", rather than evoking a dualism between the physically-based and the conceptual modelling philosophy. It has been shown that the former does not necessarily produce the better results, but elaborate calibration techniques can enable the conceptual models to produce results which match observations with a very high degree (Zappa *et al*., 2003). However, these models are neither transferable in space, nor in time, since the calibration factors include all unconsidered processes and characteristics of the site and time of calibration.

However, even in so-called physically-based modelling, many older concepts that have generally already been dismissed by the scientific community, still exist (Pomeroy *et al*., 2011): if radiation is not explicitly estimated, simple assumptions have to be made for the amount of evapotranspiration, snowmelt and soil thaw (frozen soils are mostly not considered anyway). Snow sublimation is mostly neglected, and lateral redistribution processes alike: hence, the required gauge corrections include the latter process as well. Soils are mostly represented as uniform porous media and subjected to more or less clever mathematical manipulations. Finally, all land surface areas are assumed to freely drain into the streams with overland flow velocities. Pomeroy *et al.* (2007) point out that multi-scale modelling, field studies and remote sensing can help us to develop appropriate parameterizations, reduce the need for calibration from streamflow and define an appropriate model structure with optimal spatial representation. These can be transferred from research basins for use in basins with limited data. Learning from the failures of the uncalibrated models can be seen as instructive and supporting the development of enhanced scientific process understanding. Still, the streamflow information can be used to improve the model performance in streamflow prediction, but the perils of calibration to make a model work and “just somehow” reproduce the observations, should be avoided.

TACKLING COMPLEXITY

In recent years, significant effort has been invested in the development of enhanced process-oriented hydrological models, including less parameterizations for many of the complex processes that govern a particular basin’s water balance. Much of the motivation herein has its origin in the requirement of climate change scenario applications where derived parameterizations might not be valid under future climate conditions anymore, particularly if it comes to applications of the modelling for scenario horizons of several decades. The respective models have grown to frameworks consisting of many modules which can be variably combined, depending on the location and purpose of their application. Prominent examples of such modular systems include ALPINE3D (Lehning *et al*., 2006). Typically, ALPINE3D includes a meteorological preprocessor to provide time series of the meteorological variables as spatially distributed fields, including the simulation of radiation. The model also includes a drifting snow module solving a diffusion equation for suspended snow and a saltation transport equation. These atmospheric processes are coupled to the 1-D model of vegetation, snow and soil (SNOWPACK), and a conceptual runoff module. Using ALPINE3D for the Dischma Valley (Switzerland), it has been shown that terrain influence on the radiation balance has a much larger influence on the runoff generation than vegetation or the spatial variability of the soil (Lehning *et al*., 2006). Apart from the seasonal snow-cover distribution for a glacierized catchment (Mott *et al*., 2008), the model has also been applied for glacier mass balance and glacier runoff studies (Michlmayr *et al*., 2008). Like ALPINE3D, AMUNDSEN is a process-oriented mountain hydrology model that is capable of longer-term scenario simulation runs (Strasser *et al*., 2008, 2011). It is comprised of a sophisticated radiation transfer scheme, snow-canopy interaction modelling according to the algorithms of SNOWMODEL (Liston & Elder, 2006), lateral redistribution of snow by avalanches and wind (Warscher *et al*., 2011), and a stochastic weather generator. AMUNDSEN has been validated in many modelling experiments, i.e. the two *Snowmip* projects (Etchevers *et al*., 2004; Rutter *et al*., 2009).

Recently, an enhanced linear reservoir module has been added to consider the runoff generation from new and old snow, firn, potential glacier ice and bare soil in small Alpine headwater catchments. In addition, the model comprises a module for the production of technical snow in skiing areas, and one for the representation of hydraulic connections for the simulation of reservoir inflows (Hanzer *et al*., 2013). For sub-Arctic regions in Canada, the modular process model system CRHM has been developed (Pomeroy *et al.*, 2007). This system covers a range of complexities in the physical representativeness of the parameterizations and can be flexibly configured for prairie, mountain, boreal and arctic settings.

Several new, process-oriented mountain hydrology models have been developed by merging existing models covering particular process types, e.g. the French multilayer snow evolution model CROCUS (Brun *et al.*, 1992) has been coupled with the regional runoff model ISBA to provide an appropriate modelling system for the quantification of the runoff generation and streamflow of the Rhone River (Habets *et al.*, 1999). For operational flood forecasting in the Austrian Inn River catchment, the physically-based snow cover model SES was coupled to the conceptual hydrological model HQSiM (Kirnbauer *et al.*, 2009). The operational mode is enabled through real-time connection with the output of the Austrian weather model, INCA (ZAMG, 2013).

In a recent effort, an attempt has been made to model the hydrologic behaviour of the high Alpine catchment of the Berchtesgadener Ache (Berchtesgadener Alpen, SE-Germany) (Nationalpark Berchtesgaden, 2013). This catchment is characterized by a complex karst-type system of drainage, and extreme vertical gradients of both meteorological variables and process heterogeneities: from the lowest point, the water body of the Königssee (603 m a.s.l.), the mountain slopes stretch more than 2100 m in the vertical to the summit of Mount Watzmann (2712 m a.s.l.), but they do so in a horizontal distance of only 4 km. Consequently, the hydrological system is mainly driven by precipitation distribution and its phase, lateral redistribution of snow, topography-dependent radiative energy input, and the karst pathways of the meltwaters. Even two glaciers and a perennial snowfield have survived in the area, far below the climatological snow line, but lateral redistribution of snow has locally enabled positive mass balances (now the two glaciers are continuously retreating). Hence, the modelling of the water fluxes in the Berchtesgadener Ache catchment can be interpreted as a prototype case study for the "ultimate challenge" identified by Klemeš (1990) at that time. This catchment is equipped with a unique setting of meteorological observation infrastructure (Marke *et al.*, 2013), well distributed in the area and across the elevation range. For the quantification of the observed karst water storage a neural network approach has recently been developed, capable of nonlinear reproduction of spring response and stream discharge by training and application of a parameter adjustment procedure (Kraller *et al.*, 2012). With this approach, the strong heterogeneity and discontinuity of the medium can be described. The artificial neural network (ANN) approach for the karstic part of the hydrologic system was coupled to the WaSiM-ETH (Schulla, 2012) which provides the framework for the model set-up as a whole. WaSiM is applied here in 50-m spatial resolution because of the steep topography of the catchment. WaSiM has already been successfully applied in other Alpine catchments like the Mangfall (Kunstmann & Stadler, 2005) and the Ammer (Kunstmann *et al.*, 2004, 2006). However, in its standard version, karstic flows could not be accounted for. Figure 1 shows the improvement in the streamflow runoff dynamics that could be achieved by the introduction of the neural network approach for the subcatchment of the Königsseetal. The Nash-Sutcliffe efficiency of the modelled runoff increases from 0.34 to 0.65. These improved streamflow characteristics propagate downwards and accordingly have positive effects on the modelling of the water fluxes at regional scale.

Apart from the karst effects on the streamflow generation, enhanced snow process descriptions were implented into WaSiM-ETH in a step-wise approach (Warscher *et al.*, 2013). First, the existing temperature-index snowmelt routine was replaced with an energy balance scheme. In a second step, gravitational snow slides were introduced to laterally transport the snow from luff to the leeward sides of the steep slopes beneath the summits and ridges. And finally, the snow process descriptions were completed with a directed sky-view factor-based approach to include wind-driven redistribution of snow. All snow process descriptions have been adopted from AMUNDSEN (Etchevers *et al.*, 2004; Strasser, 2008; Strasser *et al.*, 2008), hence they represent validated modules that have proven their robustness in different settings already. Again, the improvement of the streamflow runoff simulation can be illustrated for each single enhanced process description (Fig. 2): for the investigated period, the Nash-Sutcliffe efficiency of the modelled runoff increases from 0.52 to 0.58 by introduction of the energy balance approach, the latter

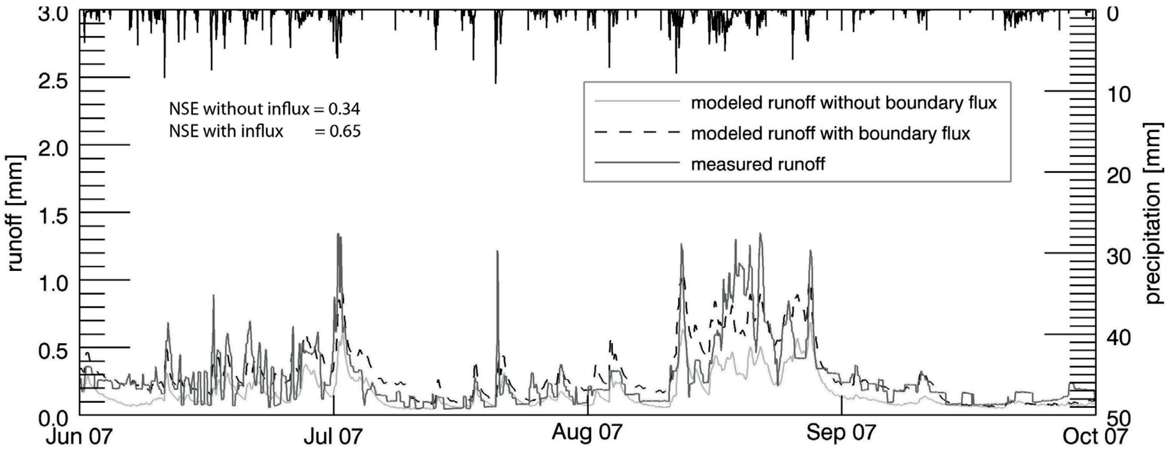

Fig. 1 Measured runoff, modelled runoff and modelled runoff with implemented boundary flux (20-day time increment) for June to October 2007 for subbasin Königsseetal. Linear Nash Sutcliffe Efficiency shows model performance from June to October 2007. From Kraller *et al.* (2012).

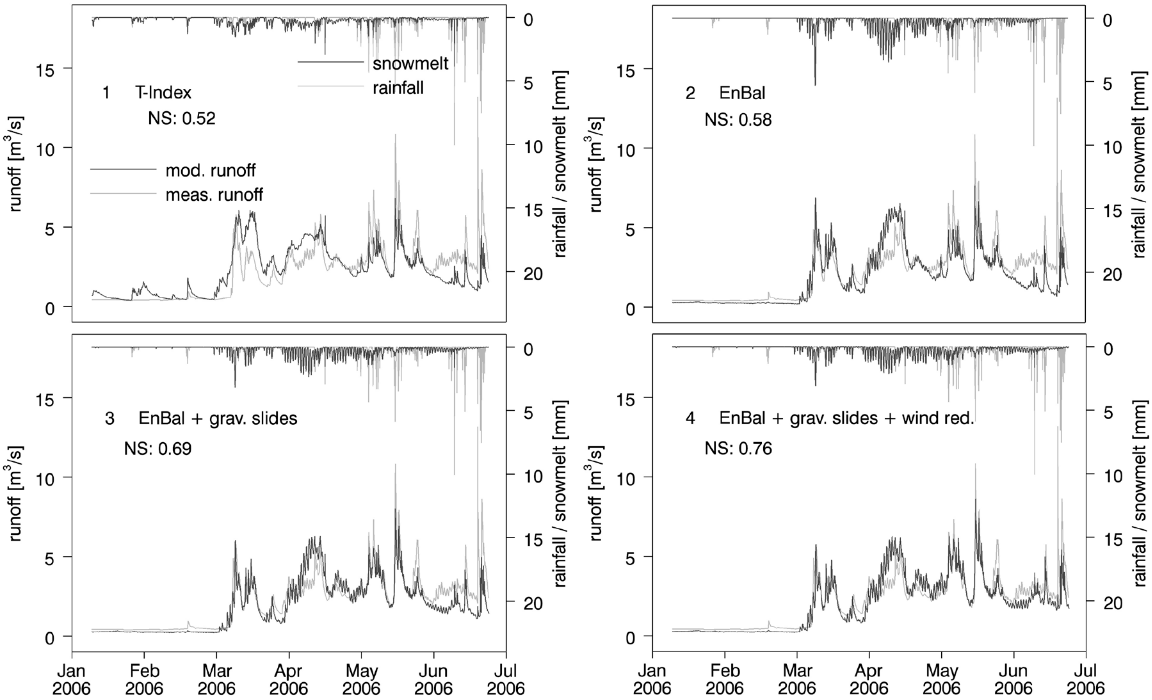

Fig. 2 Modelled and measured runoff at gauge Hintersee from February to June 2006 and according Nash-Sutcliffe coefficients (NS). Increasing snow model complexity from top to bottom: 1 temperature index, 2 energy balance, 3 energy balance and snow slides, 4 energy balance, snow slides, and wind redistribution. From Warscher *et al.* (2013).

generating the typical daily fluctuations which are observed due to the course of the radiative energy input (top left and right). The consideration of lateral transport in the form of gravitational slides leads to a downslope transport of snow, and consequently additional accumulation at the foot of the slopes where the snow was entrained. The effect of this redistribution is a prolonged melting out in these areas (bottom left). Nash-Sutcliffe efficiency now rises to 0.69. Likewise, the inclusion of the wind redistribution scheme leads to an improvement in the modelling, the Nash-Sutcliffe efficiency finally rising to 0.76 (bottom right). Without the two latter parameterizations, the model could not be used for scenario simulations, since too much snow would remain on the summits and higherelevated ridges, remaining there during summer and accumulating to high snow towers over the years. In contrast, the accumulation in the lower elevation karst areas in the catchment would not receive enough snow masses to explain the existence of the two glaciers in the area.

The Berchtesgaden project experiment shows that in a joint effort with both karst and snow process expertise and comprehensive observation infrastructure, the water fluxes of even a highly complex mountain system can be efficiently investigated. However, an enormous preparatory effort in the analysis of tracer experiments (for the general design of the artificial neural network), remote sensing image evaluation (for the parameterization of the lateral snow processes) and meteorological station installation (for the provision of high quality forcing data for the modelling) has already been invested. Now the new version of WaSiM-ETH has proven its reliability and will be given back to the scientific community in the near future.

The significant enhancement of the modelling performance in the Berchtesgadener Ache catchment could only be achieved through the availability of a continuous time series of meteorological observations from a dense, automatic measurement network, including sensors for precipitation, radiation and snow water equivalent, apart from temperature, humidity and wind speed that are commonly available and comparably easy to distribute to the catchment scale (at least the former two, wind speed and direction, are highly dependent on topographic structures). For further scientific development and improvement of our modelling skills, such operational observatories provide the necessary prerequisites to: (a) improve our understanding of the spatial (horizontal and vertical) variability of the meteorological conditions, (b) support correct regionalization of the recordings to areal fields, (c) enable isolation of single processes to correctly parameterize our submodels, and validate them, (d) allow for adequate model comparison, and (e) provide valuable data pools to be mutually exchanged and interpreted with other operational observatories. Such observatories can serve multiple purposes such as weather prediction, avalanche risk assessment, agrometeorological monitoring, water resources management, operation of hydrological structures and skiing resorts, protected area documentation, aviation, recreation and touristic purposes, and many more. In the best case, an operational mountain observatory is jointly managed by representatives from different disciplines, ensuring that a broad collection of variables is captured, processed and stored.

An example of such a joint initiative is the interdisciplinary cooperation platform “John’s creek” in the Austrian Alps (Strasser *et al.*, 2013), where the infrastructure is acquired and maintained from several institutions; the data will be made available via the internet portal of the WegenerNet (www.wegenernet.org). Further prominent examples for operational observatories are the TERENO observatories (www.tereno.net) (Zacharias *et al.*, 2012) with four sites in distinct regions in Germany. All of these observatories have in common that the envisaged period of operation is long-term, i.e. in the range of decades.

Such observatories particularly allow quantification of radiative fluxes from the sun (direct) and the atmosphere (diffuse). This information is crucial for interpolation algorithms as they are e.g. implemented in ALPINE3D, AMUNDSEN, or WaSiM-ETH. However, recordings of actual radiative input is required to deduce the absorption and scattering effects due to clouds. Only then can the simulated potential radiation be corrected for real conditions. Correct measurement of precipitation will remain a problem. However, the application of multiple airborne laser scanning data will allow us to indirectly infer the amount of winter precipitation by subtracting snow surface topographies of different date. Beneficially, this can be done in a spatially-distributed approach with high spatial resolution. With the availability of more upcoming operational observatories, international cooperation and mutual exchange of what we are learning from the measurements and the modelling alike, we will keep on allowing for valuable scientific progress in modelling mountain hydrology.

WHERE DO WE GO: THE ROLE OF SOCIETY

Apart from the technical infrastructure, the networking of hydrologists in their international community becomes increasingly important. Cooperation with partners focusing on similar research questions in the same mountain range, or working in similar political research areas such as the ERA (European Research Area), becomes a prerequisite for successful funding of collaborative research projects on larger scales. Only in such a way are structured and systematic comparisons of data, modelling and results ensured. Spreading the investigations across the elevation zones of a mountain range allows investigation of the variability of the considered processes, and the heterogeneity of the distribution of water resources, be it the instantaneous water fluxes, or the seasonal storage of water as snow. The response of glaciers to climate change, is locally and regionally very different. Long-term observatories help us to understand the climate-, energy- and mass fluxes interaction with all modifications stemming from the local topographical features, and their effect on the meteorological conditions and glacier motion. The wealth of data captured is beneficially stored and systematically documented in central databases with well-defined interfaces and transparent rules for public access.

In the most recent years, the urgent need to integrate the natural sciences part of hydrology with the social one has been recognized and identified as an important step ahead in scientific advance; many of the hydrological systems investigated today are modified by man, and the use of water is a political, economic and societal issue. Large integrated programs such as the NFP 61 in Switzerland (http://www.nfp61.ch), or GLOWA in Germany (http://www.glowa.org) have brought together scientists from both the natural and the social worlds of science to produce added value in the scientific outcomes of the projects, going far beyond the aspects of applied research only. The goal is to truly integrate the knowledge and methods of the various disciplines, as much as possible in true inter- and transdisciplinary cooperation. Nowadays, the general need for joint research across disciplines, including participatory aspects of stakeholder participation, is part of most funding calls open for hydrologists. It is no coincidence that immediately after the EGU General Assembly in Vienna 2013 a symposium (the Vienna Catchment Science Symposium) was held on the theme: Socio-hydrology – a new science of people and water (VCSS, 2013), with the goal of improving our understanding of two-way coupled dynamic human and water systems.

The new IAHS Science Decade Panta Rhei can become the global leading framework for the coming joint scientific work of the hydrological community in this direction: “The identification of common science targets and questions for the next 10 years will provide an exceptionally significant opportunity to strengthen the role of hydrological sciences in society and to profit from the immense knowledge of the IAHS community for solving the current and future challenges related to water resources” (Montanari *et al*., 2013), particularly in mountain water systems.

Acknowledgements We gratefully acknowledge the valuable contributions of Gabriele Kraller (Traunstein/Germany), Michael Warscher (Garmisch-Partenkirchen/Germany) and Thomas Marke (Innsbruck/Germany) from the WaterNPB research project (Nationalpark Berchtesgaden, 2013), and the continuous funding and collaborative support provided by Helmut Franz and Michael Vogel from the Park Administration (Berchtesgaden/Germany).

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