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Challenges and Uncertainties in Hydrological Modeling of Remote Hindu Kush–Karakoram–Himalayan (HKH) Basins: Suggestions for Calibration Strategies

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Assessment of water resources from remote mountainous catchments plays a crucial role for the development of rural areas in or in the vicinity of mountain ranges. The scarcity of data, however, prevents the application of standard approaches that are based on data-driven models. The Hindu Kush–Karakoram–Himalaya mountain range is a crucial area in terms of water resources, but our understanding of the response of its high-elevation catchments to a changing climate is hindered by lack of hydro-meteorological and cryospheric data. Hydrological modeling is challenging here because internal inconsistencies—such as an underestimation of precipitation input that can be compensated for by an overestimation of meltwater—might be hidden due to the complexity of feedback mechanisms that govern melt and runoff generation in such basins. Data scarcity adds to this difficulty by preventing the application of systematic calibration procedures that would allow identification of the parameter set that could guarantee internal consistency in the simulation of the single hydrological components. In this work, we use simulations from the Hunza River Basin in the Karakoram region obtained with the hydrological model TOPKAPI to quantify the predictive power of discharge and snow-cover data sets, as well as the combination of both. We also show that short-term measurements of meteorological variables such as radiative fluxes, wind speed, relative humidity, and air temperature from glacio-meteorological experiments are crucial for a correct parameterization of surface melt processes. They enable detailed simulations of the energy fluxes governing glacier–atmosphere interaction and the resulting ablation through energy-balance modeling. These simulations are used to derive calibrated parameters for the simplified snow and glacier routines in TOPKAPI. We demonstrate that such parameters are stable in space and time in similar climatic regions, thus reducing the number of parameters requiring calibration.

Keywords: *Hydrological modeling; model calibration; multi-objective calibration; TOPKAPI; energy-balance modeling; enhanced-temperature-index melt model; glacier melt; Hunza River Basin; Pakistan.*

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Introduction

The Hindu Kush–Karakoram–Himalaya (HKH) region has often been referred to as the "third pole" (Qiu 2008) because of the large amounts of snow and ice that are stored in its high-elevation basins. These provide water resources to some of the most populous countries on Earth, sustaining the livelihoods of many hundred millions of people in the downstream areas. Water from the HKH is particularly important for drinking and agricultural uses (Akhtar et al 2009; Bookhagen and Burbank 2010; Immerzeel et al 2010), and changes in its quantity and timing will have dramatic effects on the downstream populations (Akhtar et al 2009). Little is known, however, about the changes that the climate, glaciers, and seasonal snow cover in the region are undergoing. Some of the evidence available seems to point to a distinct pattern of glacio-hydrological response of the region's basins along an east–west HKH transect, with glaciers in the Karakoram range that seem to be growing or in a phase of positive mass balance, while glaciers further east are experiencing negative mass balances (eg Hewitt 2005, 2011; Scherler et al 2011). Their future response is also unclear.

The HKH region is characterized by a striking scarcity of hydro-meteorological and glaciological data (eg Cogley 2011; Kargel et al 2011). This prevents both an understanding of the main physical processes that control runoff generation at high elevations (Hewitt 2011) and the correct characterization of such processes in glacio-hydrological models, including a sound identification of model parameters (Akhtar et al 2009). Application of physically based and distributed hydrological models is necessary both for prediction of the hydrological responses of basins over large spatial scales and for simulations of the basins' future responses. Physically based models, in particular, should guarantee that future predictions are more accurate, because they depend less on parameter calibration, and their parameters should have a physical meaning or basis. All models, however, including physically based ones, have parameters that need to be estimated or identified through calibration (Foglia et al 2009). Appropriate calibration is a key issue in modern hydrological science, and much attention has been recently devoted to it. Several studies, in particular, have questioned the use of a single integrated response variable (in general stream flow) for calibration, as this may result in more than one combination of parameters providing the best fit (Anderton et al 2002; Brooks et al 2007), which has been famously referred to in the literature as an "equifinality problem" (eg Beven 2001, 2002).

A way to avoid this undesired effect is to include additional data sets in the calibration procedure or in the estimate of model parameters (eg Bergstrom et al 2002; Cao et al 2006). Several recent studies have shown that inclusion of remotely sensed snow-cover images might help improve model performance and avoid compensation of model errors. Snow-cover maps provided by the Moderate Resolution Imaging Spectroradiometer (MODIS) have been used in the European Alps and North America both to study snow-cover evolution and to calibrate model parameters (Simic et al 2004; Parajka and Blöschl, 2006, 2008), and they have been shown to considerably improve both model performance (Parajka and Blöschl, 2008) and internal consistency (Finger et al 2011). Finger et al. (2011) showed that MODIS data—although providing no information on actual snow amount—can have similar predictive power as ground-based mass-balance observations. For this reason, they have been increasingly used also for calibration of models applied to the HKH region (Immerzeel et al 2009; Bookhagen and Burbank 2010; Immerzeel et al 2010; Konz et al 2010).

Existing glacio-hydrological modeling studies in the region, however, are limited, and they have mostly been conducted at the very large scale (Bookhagen and Burbank 2010; Immerzeel et al 2010). Immerzeel et al (2010) considered the 5 major Southeast Asian basins (Indus, Ganges, Brahmaputra, Yangtze, and Yellow River Basins) and modeled their response to a changing climate using a simple degree-day approach to simulate snowmelt and ice melt. Bookhagen and Burbank (2010) analyzed the partition of runoff components for 27 major catchments draining the southern Himalayan front, stretching from the Indus in the west to the Tsangpo/Brahmaputra River in the east, using remotely sensed data to drive a snowmelt model based on air temperature and solar radiation. The model parameters, however, were not calibrated but estimated, and no attention was paid to their impact on the model results.

Few studies have been conducted at the catchment or river-basin scale (Akhtar et al 2009; Immerzeel et al 2011; Tahir et al 2011). Some of them have included in more detail specific glaciological processes (eg Immerzeel et al [2011], who accounted for changes in glacier geometry due to ice flow), but in others, glaciers were completely ignored (Tahir et al 2011; as well as Bookhagen and Burbank 2010, for the larger scale). None of them has looked at parameter calibration and multi-objective or multivariable calibration, with the exception of Konz et al (2007), who analyzed the internal consistency of simulations with different parameter sets against mass-balance observations. Akhtar et al (2009) analyzed how different input data sets result in different model parameters. Most of the models used in the studies cited here are conceptually rather than physically based (Konz et al 2007; Akhtar et al 2009; Immerzeel et al 2010; Tahir et al 2011) and lumped rather than spatially distributed (Konz et al 2007; Akhtar et al 2009).

Recent research has also looked at using local, point-scale simulations of glacier melt from accurate energy-balance models to determine the parameters of distributed hydrological models (Pellicciotti et al 2008; Ragettli and Pellicciotti 2012). This approach is based on the assumption that simulations of melt rates from physically based energy-balance models are very accurate when driven by high-quality measurements of the forcing meteorological variables, as they are available at the locations of Automatic Weather Stations (AWSs). Such simulations can be used as benchmarks and surrogates for high-resolution ablation data to calibrate the melt parameters of distributed hydrological models, in this way removing a number of model parameters from the global calibration against commonly available data such as runoff or MODIS images. This makes it possible to correctly reproduce melt processes at a variety of scales/locations and to reduce the ambiguity in calibrated parameters. Ragettli and Pellicciotti (2012) have shown that only few seasons of data are sufficient to identify the value of the parameters and determine those that are robust in time and space and thus can be left out of standard calibrations at the distributed scale.

The present paper describes possible strategies for calibration of hydrological models to reduce uncertainties in simulations of the response of

high-elevation catchments in the HKH region. We describe the use of snow-cover remote imagery and limited stream-flow data to constrain model parameter sets for simulations of discharge and other water-balance variables of remote Himalayan headwaters. We show how specific parameters can be determined outside of the distributed model calibration by means of point-scale, short-term energy-balance simulations, and we discuss their connection to the atmospheric forcing typical of different locations. We provide examples from various case studies, including from other mountainous regions of the world, to highlight the potential of different calibration strategies that could be applied to ungauged Himalayan basins. We make the point that there is uncertainty in both the data available and the modeling approaches, and that both uncertainties have to be minimized for a thorough assessment of water resources in the area and their changes under a changing climate. We conclude with recommendations for future modeling studies and comprehensive monitoring programs in the region, based on the evidence provided.

Methods

Hydrological model

In this work, we use simulations from the physically based, fully distributed TOPKAPI model. TOPKAPI was originally developed as a physically based and distributed hydrological catchment model (Todini and Ciarapica 2001; Liu and Todini 2002; Liu et al 2005). The model simulates all relevant components of the water balance and transfers the rainfall–runoff processes into nonlinear reservoir equations, which represent drainage of the soils, overland flow, and channel flow. Information about topology, surface roughness, and soil characteristics is obtainable from soil maps, digital elevation models (DEMs), and land-use maps. The model has been recently further developed to make it suitable for application to high-elevation basins where snow and ice are dominant components of the hydrological cycle (Finger et al 2011; Ragettli and Pellicciotti 2012).

A new snowmelt and ice melt routine based on the enhanced temperature-index model (ETI) by Pellicciotti et al (2005) has been implemented for the distributed simulation of snowmelt and ice melt. Routing of glacier surface meltwater into glacier runoff is conducted with linear reservoirs, and snow accumulation, which is based on extrapolation of point observations of precipitation, includes gravitational redistribution. The melting of snow and ice is computed using an intermediate-complexity approach between a full energy-balance model and a simple temperature-index model (see Hock [2005] and Pellicciotti et al [2005] for a definition of the 2 approaches). If air temperature in cell i T_i (°C) exceeds the threshold air temperature T_T, melt is computed as (Pellicciotti et al 2005):

$$M_i = TF \cdot T_i + SRF \cdot I_{Gi} \cdot (1 - \alpha_i), \quad (1)$$

where M_i is melt in mm water equivalent (w.e.) d^{-1} of cell i, TF is the temperature factor in mm w.e. K^{-1} d^{-1}, SRF is the shortwave radiation factor in mm w.e. m^2 W^{-1} d^{-1}, I_{Gi} is the incoming shortwave radiation in Wm^{-2}, and α_i is the surface albedo (for daily calculations).

Case study

In this work, we apply TOPKAPI to the Hunza River Basin in Pakistan (Figure 1). The Hunza River Basin is located in the high Karakoram Range at about 36°N, 75°E in the Northern Territory of Pakistan. The basin has an area of around 14,234 km^2 and an altitude range from 1494 masl to 7788 masl. Runoff is measured at only one gauging station (Dainyor Bridge), located on the Hunza River immediately above the confluence with the Gilgit River, which in turn is tributary to the upper Indus. Three meteorological stations with daily precipitation and temperature data are located within the basin (Figure 1). Data are scarce, both in space and in time, and only 3 years of measurements were available at the stations for this study (2001 to 2003). No observations of other meteorological variables, such as snow height or additional meteorological data, were available, and our understanding of the mechanisms controlling snow and ice ablation is also limited.

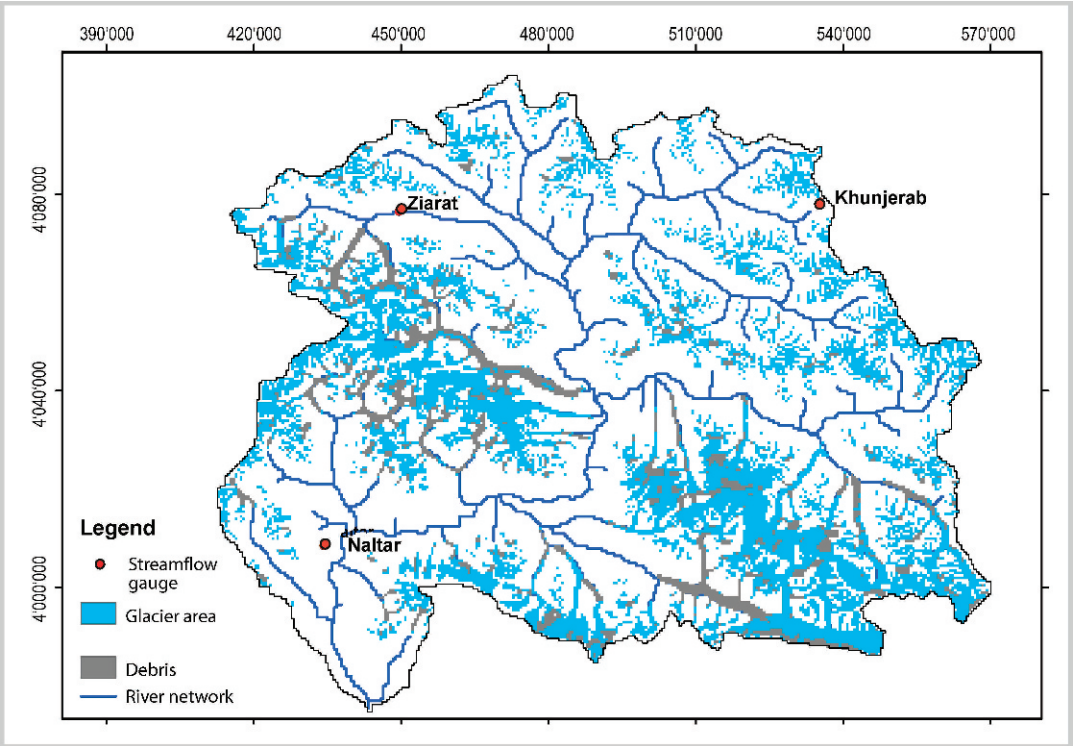
In this work, we use the year 2001 for calibration and the 2 years 2002 and 2003 for validation. We also use the MODIS daily snow product for the same years (http://modis-snow-ice.gsfc.nasa.gov). The daily MODIS maps are used for model calibration by comparing them to the snow-cover extent simulated by TOPKAPI. Agreement between the two is evaluated using an efficiency criterion (S_{eff}) that measures the goodness of fit as the ratio between correctly predicted cells and total available cells after having removed pixels that were cloud covered or had no measurements (Konz et al 2007).

Model calibration

Ragettli and Pellicciotti (2012) have shown that measurements such as snow height and meteorological variables other than air temperature (ie relative humidity, wind speed, global radiation) can substantially contribute to constraining model parameters by allowing determination of those parameters related to the melting of snow and ice (see also next section). Since no such additional data were available for the basin, we investigated the value of different data sets and best-of-fit measures for calibration of TOPKAPI.

Given the scarcity of data, calibration is challenging, especially with the growing number of parameters that are typical of complex models such as TOPKAPI, since this type of model attempts to describe the physics of each component of the basin hydrological cycle. As a response to this, we investigated the suitability of

FIGURE 1 Map of the Hunza River Basin showing the position of the 3 meteorological stations as well as the river network and the glacier borders. Both clean-ice and debris-covered glaciers are indicated. (Map by Silvan Ragettli)



different data sets to calibrate the model, together with various combinations of goodness-of-fit measures. The idea behind this is that, when data are limited, one should maximize their information content by way of the most appropriate model performance criterion or combination of them. We analyzed the predictive power of the 2 data sets available in the region—runoff and MODIS snow-cover images—and of their combination, and of 5 evaluation criteria or goodness-of-fit-measures—(1) the Nash and Sutcliffe efficiency criterion (R_{eff}); (2) the logarithmic Nash and Sutcliffe efficiency criterion (R_{logeff}); (3) volume error (VE); (4) coefficient of determination (R^2); and (5) the snow cover efficiency (S_{eff})—together with various combinations of these criteria.

Calibration was conducted using the optimization algorithm PEST (Doherty 1995), which allows combination of various criteria and data sets within the algorithm objective function. We looked at the ability of each data set to reproduce correctly runoff and snow cover, but also at the corresponding partition of runoff components that resulted from using each of them. We recalibrated 12 model parameters, with initial ranges taken from the literature and similar case studies, and based also on an initial sensitivity analysis of the model (Buergi 2010). The initial conditions were obtained by running TOPKAPI for 10 years with the initial parameter values. Details can be found in Buergi (2010).

Constraining melt model parameters through short-term energy-balance simulations

We discuss here the potential of constraining some of the parameters of distributed, physically based hydrological models against simulations at the point scale from more sophisticated models. This is applicable for melt parameters, which can be optimized against energy-balance simulations, following the approach suggested by Ragettli and Pellicciotti (2012), and previously used also by Pellicciotti et al (2005), Pellicciotti et al (2008), and Carenzo et al (2009) at the point scale.

Energy-balance models compute melt as the residuals of all energy fluxes at the glacier–atmosphere interface:

$$Q_{\text{M}} = Q_{\text{I}} + L + Q_{\text{H}} + Q_{\text{L}} + Q_{\text{S}} \qquad (2)$$

where Q_I is the net shortwave radiation flux, L is the net long-wave radiation flux, Q_H is the turbulent sensible heat flux, Q_L is the turbulent latent heat flux, and Q_S is the conductive energy flux in the snow/ice, or subsurface flux (eg Hock 2005). All fluxes are defined as positive when directed toward the surface. The single fluxes are computed from physically based equations that describe the thermodynamic exchange at the glacier surface using measurements of wind speed, relative humidity, and radiative fluxes. They also require knowledge of surface characteristics such as albedo and surface roughness.

If these measurements are of high quality, energy-balance simulations can be very accurate, and get closest to reality as possible at high temporal resolution. The drawback, obviously, is that they require extensive and specific measuring campaigns on glaciers or in their close proximity, which can be difficult in high elevations and remote areas. Ragettli and Pellicciotti (2012) used hourly energy-balance simulations together with additional meteorological and surface data to calibrate some of the parameters of TOPKAPI for a glacierized basin in central Chile. They showed that the parameters calibrated in this way respond very clearly to the climate settings typical of the dry Andes of Chile. The authors also succeeded in identifying parameters that—once recalibrated—were transferable from one season to the other and from one basin to the other and could therefore be left out of subsequent recalibration at the distributed scale. These parameters are *MF*, *SRF*, and T_T of Equation 1 and the parameters of albedo parameterizations.

Pellicciotti et al (2005) and Carenzo et al (2009) used energy-balance simulations to calibrate the parameters of the ETI model for one and several glaciers in the Alps, respectively, and looked at their spatial and temporal variability, while Pellicciotti et al (2008) used the same approach to recalibrate the melt model parameters for a glacier in the climatic setting of the dry Andes of Chile. Following their approach, we recalibrate the three parameters of the ETI model (see Equation 1) for a number of sites in the Andes, the European Alps, and the Himalaya, using the surface energy-balance model described in detail by Pellicciotti et al (2008, 2009), Carenzo et al (2009) and Pellicciotti et al (2010), by minimizing the differences between the energy-balance (EB) and ETI melt simulations. We use the Nash and Sutcliffe efficiency criterion (last column in Table 1) as the goodness-of-fit criterion. The input data sets used to run both models were described in detail by Carenzo et al (2009) for the European Alps and by Pellicciotti et al (2008) for the dry Andes, while the data for the Nepal Himalaya were recorded at the Pyramid Automatic Weather Station (AWS), which is located at 5035 masl beside the Khumbu Glacier in Sagarmatha National Park, Nepal (27°57′33″N; 86°48′47″E). More than 2 years of data are available from October 2002 to December 2004, with hourly measurements of air temperature, precipitation, relative humidity, atmospheric pressure, wind speed and direction, incoming and outgoing shortwave and long-wave radiation, and snow depth. Data are freely available from the CAMP project homepage (http://data.eol.ucar.edu/codiac/dss/id=76.113). More details about the data and energy-balance simulations can be found in Normand (2010).

Results

Predictive capabilities of different data sets and evaluation criteria

Figure 2 shows runoff simulated by calibrating the model against runoff only (blue, red, and brown lines), MODIS snow cover only (turquoise line), and a combination of the 2 (green lines), together with measured runoff. The best performance is obtained when a combination of runoff and MODIS images is used and all criteria are used (green line). It is also evident that using MODIS images alone (turquoise line) leads to the worst performance of all data sets, with strong underestimation of runoff except for the raising limb of the hydrographs in the months of April and May. The good performance of this parameter set for the beginning of the melt season is due to a good representation of snow cover at the end of the winter season, which leads to correct melt simulations in the beginning of the season. MODIS images provide only information about the areal extent of snow cover, but not its depth/volume. Our results point clearly to the fact that this data set alone cannot be used for model calibration. In combination with runoff, however, it significantly increases the model performance, as shown by comparison with simulations obtained using all 3 runoff criteria (brown line). The use of all three criteria (R^2, R_{eff}, and R_{logeff}) applied to the same data set of daily runoff seems to deteriorate the model performance (with overestimation of observed discharge). Our results also clearly indicate that if only one criterion is to be used, the most appropriate is the Nash and Sutcliffe R_{eff} (red line). The volume error, finally, results in a very good performance against runoff but fails to reproduce the temporal evolution of snow cover (low S_{eff} values).

Analysis of the partition of the 3 main hydrological components that determine runoff (precipitation, snowmelt, and ice melt) corresponding to each data set and criterion (or combination of them) is shown in Figure 3. There is large variability in the components' magnitude among the 7 cases discussed here, with the largest differences associated in particular with using only snow (Figure 3E) and with using all three runoff criteria (Figure 3F). If we assume the more realistic partition to be the one corresponding to the combination of the two data sets (Figure 3G), as justified also by results of the overall objective function (Figure 2), then it is clear that the choice of the best-fit-criterion has a strong effect on the magnitude of rain and melt components: If we use the coefficient of determination for model calibration (Figure 3C), then precipitation is overestimated, ice melt is underestimated over the entire period, and snowmelt is overestimated at the beginning of the season. If we use all 3 runoff criteria (Figure 3F), conversely, precipitation is underestimated and ice melt is overestimated. Each criterion and data set corresponds to sets of parameters that vary largely among themselves, so that predictions in a changing climate might differ considerably even though agreement for the present is similar. Our conclusions should be looked at in view of the lack of knowledge about the real processes due to the little data available about snowmelt and ice melt in the region, and point once more

TABLE 1 Values of the temperature factor (*TF*), shortwave radiation factor (*SRF*), and threshold temperature for melt (T_T) (see Equation 1) recalibrated against energy-balance simulations at several sites in the Swiss Alps (Arolla and Gorner, indicating Haut Glacier d'Arolla and Gornergletscher in the Swiss Alps), central Andes of Chile (Juncal, indicating Juncal Norte Glacier), and at one location in Nepal (Pyramid site) for various seasons and conditions. Details about locations and data sets are provided in the text. Units are as follows: *TF* is in mm w.e. K^{-1} d^{-1}, *SRF* is in mm w.e. m^2 W^{-1} d^{-1}, and T_T is in °C.

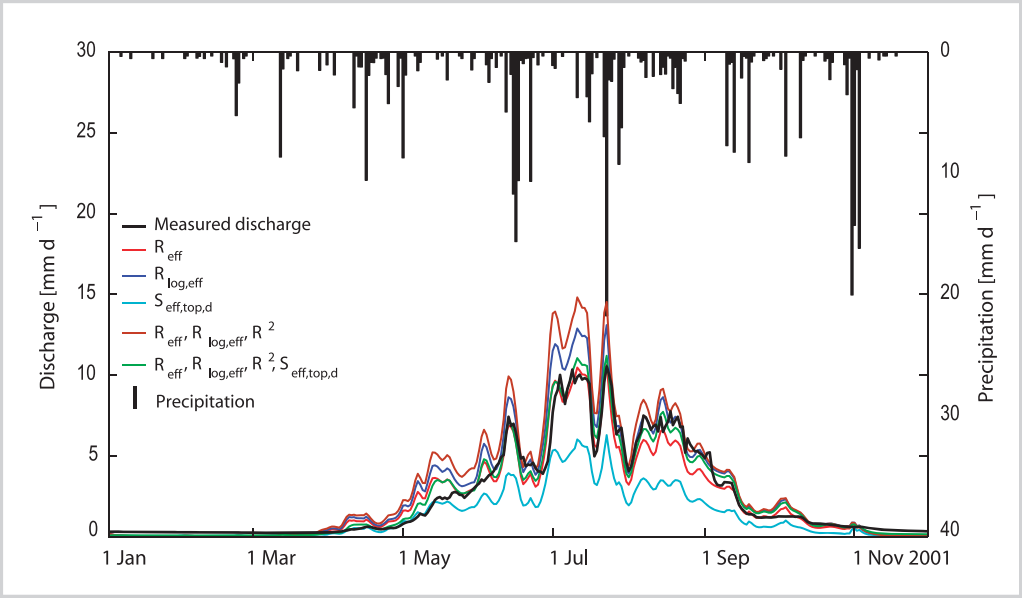
Station	T_T	*TF*	*SRF*	Nash–Sutcliffe
Pyramid (Nepal)				
2003 complete	−4.66	0.152	0.00713	0.81
2003 shorter	−4.66	0.136	0.00690	0.77
2005 complete	−5.97	0.104	0.00805	0.85
2005 shorter	−4.27	0.160	0.00759	0.84
2006 complete	−4.97	0.088	0.00667	0.78
2006 shorter	−5.37	0.088	0.00598	0.68
2007 complete	−5.37	0.080	0.00552	0.64
2007 shorter	−4.67	0.048	0.00483	0.50
Arolla (Switzerland)				
Lowest, May–Jun 2001	−0.17	0.016	0.00621	0.74
Lowest, Jul–Sep 2001	−0.37	0.048	0.00966	0.96
Lowest, 2001	−0.37	0.040	0.00943	0.94
Lowest, 2005	−1.57	0.088	0.00920	0.95
Lowest, 2006	0.63	0.048	0.00989	0.96
Central, May–Jul 2001	−0.47	0.032	0.00759	0.82
Central, Jul–Sep 2001	0.73	0.000	0.00943	0.93
Central, 2001	0.13	0.008	0.00897	0.90
Uppermost, 2001	−0.77	0.008	0.00828	0.87
North-central, Jul–Sep 2001	1.03	0.016	0.00966	0.95
North-central, 2001	0.63	0.024	0.00920	0.92
South-central, 2001	−0.67	0.000	0.00828	0.86
Gorner (Switzerland)				
2005	−2.27	0.040	0.00943	0.95
2006	−0.27	0.032	0.00989	0.96
Juncal (Chile)				
AWS1 2008–2009	6.20	0.016	0.01035	0.98
AWS3 2008–2009	4.19	−0.032	0.01035	0.97
AWS1 2005–2006	6.30	−0.008	0.01058	0.99

to the need for acquiring more detailed information about the current status of the cryosphere in the region.

Constraining melt model parameters through short-term energy-balance simulations

The values of the recalibrated parameters of the ETI model (Equation 1) are reported in Table 1, together with their corresponding Nash and Sutcliffe efficiency criterion values. The parameters in Table 1 are clearly correlated to the climatic setting of the region, with high *SRF* values in the dry Andes of Chile, characterized by very intense solar radiation and absence of clouds, and high T_T in the same region because of the strong radiative cooling at night, favored by absence of clouds, which cools the snowpack (see Pellicciotti et al 2008, 2010; Ragettli and Pellicciotti 2012).

FIGURE 2 Runoff simulated by TOPKAPI for the Hunza River Basin for the calibration year 2001, using different data sets and best-of-fit criteria for calibration (indicated in the legend), together with measured runoff and precipitation.



At the Pyramid site in the Everest region in Nepal, we obtained negative threshold temperature values, high *TF*, and relatively low *SRF*. The T_T values of Pyramid can be explained by the very low air temperatures, with melting occurring also for negative temperatures. The low *SRF* in comparison with values in the European Alps might be related to the occurrence of the monsoon and corresponding high cloudiness. Melt occurs during the entire year, but mainly during monsoon. There is clear clustering of parameters for the 3 regions analyzed, and 3 main patterns can be identified:

1. For *TF*, the highest values are for the Pyramid site, lower for the European Alps, and very low or negative for the dry Andes of Chile.
2. For T_T, high and positive values are evident for Chile, low T_T values around 0°C are found for the European Alps, and negative T_T is found for the Pyramid site.
3. The *SRF*s increase clearly from the Pryramid site to the dry Andes site, with intermediate values in the Swiss Alps (Table 1).

Data uncertainty

In the two sections above, we have discussed at some length the uncertainty associated with model calibration. We would like to conclude this section by describing uncertainty in predictions related to the input data using the same Hunza River Basin example discussed in the corresponding methods and results sections.

Of the total glacier area (14,234 km^2), 3930 km^2 are glacierized; 32% of glaciers are debris covered. We reconstructed the glacier volume using the method developed by Immerzeel et al (2011). The average initial ice thickness of the glaciers reconstructed in this way is 39 m, and total ice storage equals 153 km^3. In contrast, total annual precipitation is around 330 mm (average value over the period of record available 2001 to 2003), which corresponds to 4.7 km^3 of ice storage. If we compare the input to the basin in form of precipitation with the total water stored in ice, this is 33 times larger than the annual precipitation. The average discharge at the basin outlet for 2001 to 2003 is 9.8 km^3.

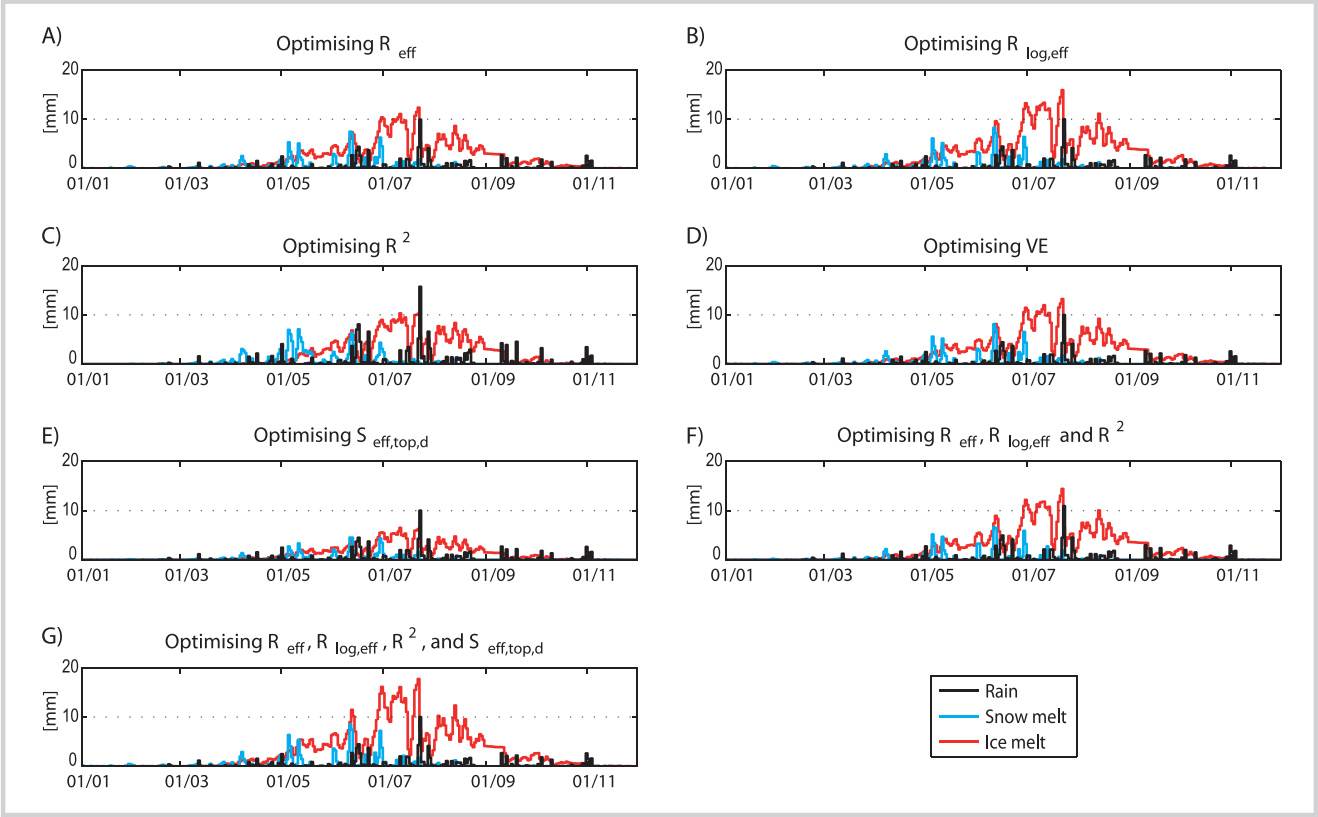
Assuming that the measurements of precipitation and discharge are correct—and if we ignore evapotranspiration—then the net negative mass balance of the catchment is 5.1 km^3 y^{-1}, which is equal to −1.29 m y^{-1} over the glacier area. These are very high melt rates, which seem unlikely and seem to suggest that either precipitation is underestimated or discharge is overestimated. Based on evidence from previous work, we tend to favor the option that basin-averaged precipitation is underestimated (see Immerzeel et al [2012] in this issue for an in-depth discussion). We will come back to this issue in the Discussion section.

Discussion

Predictive capabilities of different data sets and evaluation criteria

In the results section, we have shown that use of MODIS snow-cover data can improve the calibration of the TOPKAPI hydrological model by increasing internal consistency, while these observations alone cannot be used for parameter calibration. Results were shown only for the calibration year 2001, but we obtained the same results also for the 2 validation years 2002 and 2003 (Figure 4A, B).

FIGURE 3 The 3 components, rain, snowmelt, and ice melt, contributing to total runoff simulated by TOPKAPI for the Hunza River Basin for the year 2001, when different data sets and best-fit-criteria are used for calibration.



Our findings cannot be easily compared with similar studies in the region because few authors have looked explicitly at model internal consistency. This also depends on the structure of the model used, as representation of single components of the glacio-hydrological system is much more permissible in physically based models, which reproduce each of the components through a more or less physical description, in comparison, for instance, with the reservoir approach used by many conceptual models such as the Hydrologiska Byråns Vattenbalansavdelning (HBV) (used in this region by, among others, Akhtar et al 2009).

In general, however, most studies in the region have agreed on the usefulness of additional information provided by MODIS by using it as input to the models or for calibration (Immerzeel et al 2009, 2010; Bookhagen and Burbank 2010; Konz et al 2010). Our results also point out the limitation of using correlation-based measures alone for model calibration and assessment of model performance, since use of the correlation coefficient does not allow one to discriminate between different parameter sets, as pointed out clearly already by Legates and McCabe (1999).

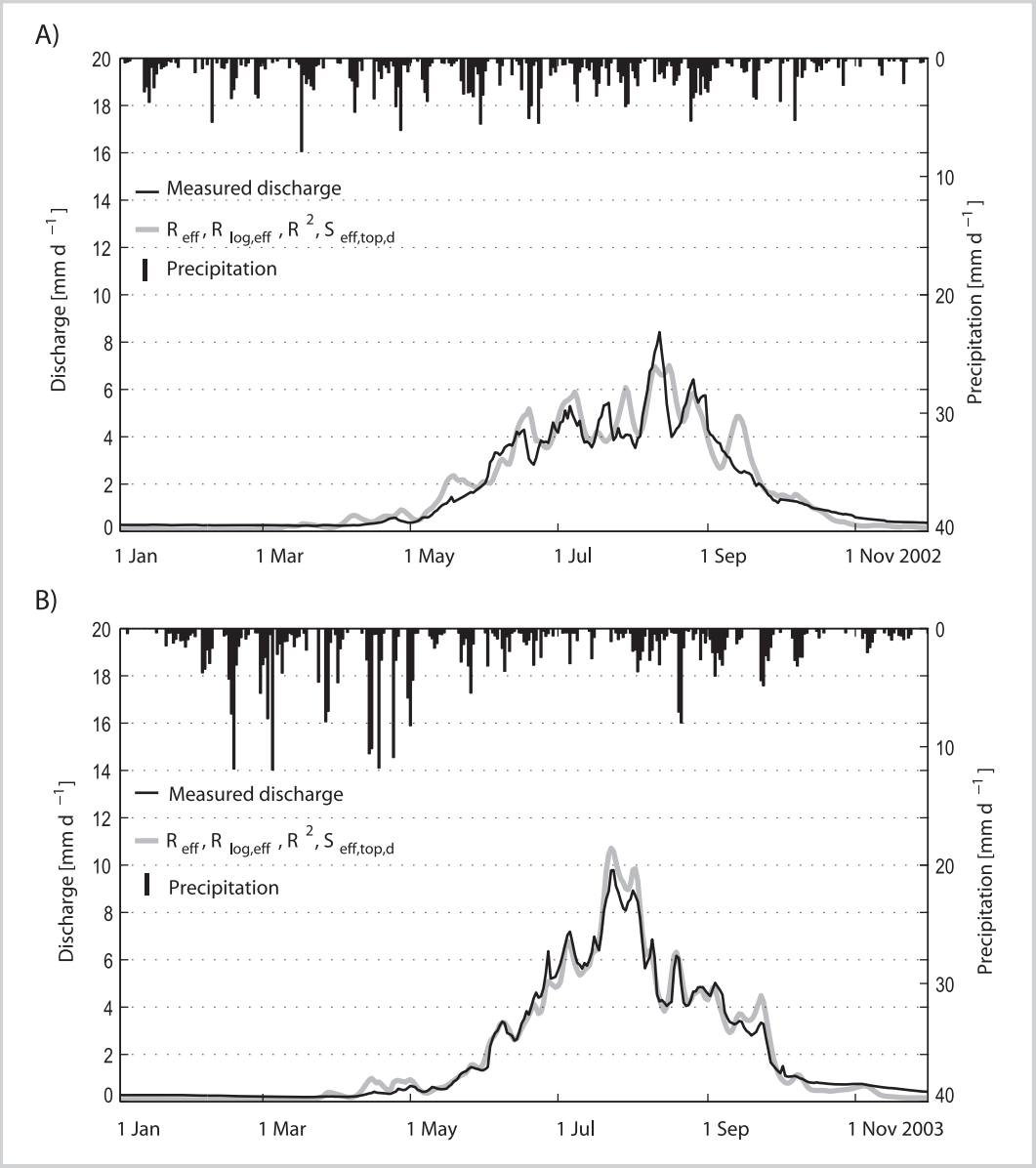
To complete this analysis, attention should also be paid to the different ways of weighting the single data sets into the objective function. While this is beyond the scope of this paper, it is an important issue that is currently being addressed by the present authors in work in progress. In general, we think that findings about the hydrological response of catchments in the HKH region, and their response to changes in climate in particular, should be accompanied by a thorough assessment of calibration strategies and sensitivity of the results to the model parameters, which might represent a larger source of uncertainty than assumed until now. However, sensitivity studies are rare (Immerzeel et al 2010).

Constraining melt model parameters through short-term energy-balance simulations

The results presented herein show that the parameters of the ETI model depend on the specific climate of one region and can be explained through knowledge of the dominant processes in that region (see also Pellicciotti et al 2008). In light of these results, it seems, therefore, that the value of short-term observations, which would allow us to understand the main high-elevation processes and characterize parameters of distributed, simpler models, by far exceeds their demand in terms of time, logistics, and manpower, and we recommend using energy-balance simulations as a viable way to reduce equifinality in large and remote glacierized area.

One issue that should be considered in such an assessment is the sensitivity of the ETI model to its main parameters. In a recent study of model sensitivity and

FIGURE 4 Runoff simulated by TOPKAPI for the Hunza River Basin for the validation year 2002 (A) and 2003 (B) using the combination of both data sets (runoff and snow cover) and all best-of-fit criteria for calibration (indicated in the legend), together with measured runoff and precipitation.



uncertainty, Heynen et al (2011) showed that the parameters to which the ETI model is most sensitive are *SRF* and T_T of Equation 1, and the coefficients controlling parameterization of albedo for application of the model at the distributed scale, thus indicating that these are the parameters that should be carefully determined. The authors also showed that the sensitivity of the model is the same in different climatic contexts and for glaciers of different sizes and characteristics, thus illustrating the consistency and robustness of their results (see also Heynen 2011). One of their main findings that might be relevant for application in remote HKH catchments is that the model was very sensitive to the temperature lapse rate used for extrapolation of air temperature from point measurements to the basinwide scale, which confirms the evidence provided in this and other studies about the importance of correctly extrapolating the input meteorological variables (see also following section).

Uncertainty in input data

There are indications that precipitation observed at rain gauges in rough topography and high elevations can be far off from reality, depending on the method used to measure precipitation, the type of gauge, and the position of the gauge (Rubel and Hantel 1999; Cheema and Bastiaanssen 2012). Various authors have suggested

methods for correcting measurements to take into account the effect of wind and evapotranspiration (eg Zweifel and Sevruk 2002). In addition to this, there is a problem of representativeness of low-elevation meteorological stations for the upper areas, where precipitation regimes can differ considerably (Winiger et al 2005; Hewitt 2011; Immerzeel et al 2012). Our results, together with those discussed by Immerzeel et al (2012, in this issue) and supported by evidence provided in other studies, seem to point to the fact that basinwide precipitation estimates obtained with traditional extrapolation methods from point observations are not appropriate for high-elevation catchments—and the Hunza River Basin in particular—due to the strong verticality and elevation dependency of climatic forcing (Hewitt 2011). If this is the case, then model parameters that are calibrated using a climatic forcing that is so far off will reflect such large error and compensate for it, thus making predictions based on climate change scenarios strongly unreliable. Our estimates are affected by uncertainties in the reconstruction of the glacier volumes, which are based on a lack of knowledge of glacier-bed topography and the assumption of negligible evapotranspiration, but their validity remains despite this. This simple example provides strong evidence for the need to improve and enlarge the monitoring networks available in the region, prove the quality of the measurements, and foster modeling of the basins. As this example shows and as discussed in greater detail by Immerzeel et al (2012, in this issue), models can often provide a quality check of the measurements and tell us where to measure by indicating where the uncertainty in the simulations is largest.

Conclusion

In this paper, we discussed various strategies to improve the simulations of the current and future response of remote HKH basins. In particular, we discussed the importance of multiple criteria calibration to obtain internally consistent parameter sets, which are the prerequisite for reliable water-resources assessments in mountainous environments. We investigated the predictive power of MODIS snow-cover data and discharge observations using a fully distributed hydrological model with a strong physical basis. The simulations were evaluated with different efficiency criteria in order to identify the most suitable combination of evaluation criterion and calibration data set. We also investigated the role that short-term observations of detailed cryospheric processes can play in enhancing our understanding of processes, and the ways in which they can be used to constrain model parameters to avoid equifinality. Finally, we considered the way in which a major uncertainty, liable to jeopardize any serious modeling attempt, can be found in the input data used to drive the models.

Our main conclusions are as follows:

1. We showed that MODIS snow-cover data are useful to improve model performance and identify parameter sets for modeling glacierized catchments, when used in combination with runoff data. On its own, however, the MODIS data set cannot be used for model parameter selection because it lacks quantitative information about the amount of snow on the ground, and therefore results in underestimation of total seasonal runoff.

   We also show that there is a clear problem of multiplicity of parameter sets, or equifinality problem, which should be addressed by calibrating the model against multiple variables, which allow assessment of the internal consistency of the model.
2. Calibration of model parameters depends not only on the data set used for it, but also on the evaluation criteria used in the optimization procedure to assess the agreement between simulations and observations. We have demonstrated that different evaluation criteria applied to the same data set, be this stream flow or snow cover, lead to different simulations of runoff and partition of the runoff components and corresponding model performances. We suggest that if only one criterion is to be used, then the Nash and Sutcliff efficiency criterion seems to be the one with best predictive power compared to the logarithmic efficiency criterion and to the correlation coefficient.

   These findings, however, should be corroborated by further analysis using additional data sets and seasons. Our findings are limited by the lack of real data in the region about the single contributions to total runoff, and this makes it difficult to estimate the actual composition of total runoff from glacierized catchments in this area. This clearly points to the need for additional measurements of cryospheric components in the region.
3. Short-term observations of the components of the energy balance can be useful to determine the parameters of the melt components of hydrological models. With accurate measurements of radiative fluxes, wind speed, and relative humidity, physical energy-balance models can be used to simulate melt with high accuracy. These melt simulations enable a precise determination of the parameters of more conceptual melt models, such as the ETI model discussed in this paper. We have shown that the ETI parameters obtained for different mountainous regions of the world cluster in main groups that depend strongly on the climatic forcings of the regions. Our results suggest that once we have identified the right parameter values of the ETI model for one region, they are stable over the seasons, confirming results by Ragettli and Pellicciotti (2012). Subsets of model parameters identified in this way reduce the number of parameters of distributed hydrological models, thus

contributing to minimize ambiguity in the optimal parameters of complex models. Parameters determined outside of calibration procedures such as those discussed in this paper can be used directly as such in the hydrological model or can help in defining the range used in the optimization. Preliminary findings of follow-up work show that results of most optimization techniques in fact depend heavily on the initial range used in the calibration.

4. The data sets and calibration techniques discussed here are useful for improving parameter estimation and increasing the internal consistency of hydrological models. However, the importance of maintaining and strengthening existing hydro-meteorological networks, by increasing the number of measuring locations and extending the length of records, should not be neglected, even if remotely sensed data sets are becoming increasingly applicable to hydrological modeling studies. In remote areas, short-term specific monitoring programs to quantify the actual status of the cryospheric components of the water balance of the region are meaningful alternatives to long-term observations.
5. Our answer to the question of how to calibrate hydrological models for simulations of remote HKH catchments is therefore to use a combination of different data sets obtained from ground observations and remote sensing, and to avoid simple calibration against discharge data only because they might result in an internally inconsistent model. This in turn would lead to an incorrect assessment of water resources, especially if scenarios are to be simulated. We also would like to stress once more the importance of setting up well-established monitoring programs in the region, with a special focus on the cryosphere. In combination with modeling studies based as much as possible on physically based, state-of-the-art models, this would allow verification of the quality of the observations, and it would fill gaps in time and space where observations are not available. We therefore call for an integrated approach to understanding the cryospheric response of the HKH region that is based on a combination of monitoring and modeling as the key for assessing the water resources in the region under a changing climate.

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