Modelling runoff and its components in Himalayan basins

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Abstract The hydrology of Himalayan basins is not well understood due to the complexities in the climate and geography, and the scarcity of data. The objective of this study is to quantitatively assess the contribution of various components of runoff in the Himalayan basins. To achieve this goal, the Hydrologiska Byråns Vattenbalansavdelning (HBV) model was used to simulate the runoff and its components on two Himalayan basins, the Beas River basin, India and the Wang Chhu basin, Bhutan. Four components: runoff from glacier melting, snow melting on glacier, snow melting outside glacier, and rainfall were identified by the HBV model. The simulation results show that the HBV model can give a fair estimation of the runoff of these two catchments and the effects of glaciers and snow are largely dependent on the catchment characteristics and the glaciated area. For the Wang Chhu basin, the largest contributor to runoff is rainfall, whereas melting of snow and glacier is dominant in the Beas River basin. This research will not only contribute to the improved understanding of the impacts of climate change on the hydrological response in the Himalaya area, but will also provide guidance for the development of hydropower potential and water resources assessment in these Himalayan basins.

Key words climate change; HBV; Himalayan basins; hydrological modelling; runoff components; snow and glacier

INTRODUCTION

It is reported that in many regions of the globe the glaciers are retreating and seasonal snowfalls are becoming less (Bolch *et al.*, 2012). As the largest cryosphere outside the polar area and the source of rivers supporting more than 800 million people, the Himalayan glaciers are of concern for both scientific research and public communities (Hagg *et al.*, 2007; Bolch *et al.*, 2012). However, due to difficult and expensive access, a complex geography and climate, the hydrology of this region is not well understood. The hydrology regime of Himalayan basins is mainly dependent on the monsoon and melting of snow and glaciers. To understand the contribution of glaciers to runoff is an indispensable step to knowing the impact of climate change on water resources, flooding and drought in glacier fed basins. Currently there are four methods to analyse the runoff components from rainfall, melting of snow and glaciers: the water balance analysis (Thayyen *et al.*, 2005; Kumar *et al.*, 2007), glacier degradation from observation or modelling as a contribution to runoff (Kotliakov, 1996; Kaser *et al.*, 2010), isotopic investigations (Dahlke *et al.*, 2013) and hydrological modelling (Hagg *et al.*, 2007; Naz *et al.*, 2013). However, the limitations of these methods cannot be neglected, especially for climate change studies. The water balance method can only approximately estimate the effects of glacier and snow monthly or larger time scales; and additionally this method cannot separate snowmelt and ice melting on glaciers. Approaches that compare glacier melt water production (obtained through measurements or modelling) with measured discharge further downstream are problematic because glacier melt water can be considered as a raw volume input into the runoff system, but the discharge further downstream has been modified by precipitation, evaporation, irrigation, damming, or exchange with subsurface flow regimes and groundwater (Kaser *et al.*, 2010). Isotopic investigation cannot be widely used as it demands large financial and laboratory support. However, the application of hydrological models to understand the glacier effects in hydrology is relatively new (Hagg *et al.*, 2007; Huss *et al.*, 2008; Koboltschnig *et al.*, 2008; Prasch, 2010; Nepal *et al.*, 2013). A practical challenge is the lack of long-term data of high quality to represent the hydrological dynamics of Himalayan rivers. Moreover, the rainfall–runoff models rarely describe the snow and ice melting (Singh, 2001) and glacier dynamics (Naz *et al.*, 2013) at basin scale.

The work reported in this paper has attempted to use a conceptual hydrological model to understand the glacier and snow effects on hydrologic response in the Himalayan region and has identified the contributions to runoff from glaciers melting, snowmelt inside the glacier area, snowmelt outside the glacier, and rainfall. The Hydrologiska Byråns Vattenbalansavdelning (HBV) model was selected due to its good performance in cold mountainous Scandinavian countries with appreciable glacier and seasonal snow coverage.

METHODS

The HBV model concept was developed by the Swedish Meteorological and Hydrological Institute in the early 1970s (Bergström, 1976), and has been modified to create many versions (Ehret *et al.*, 2008; Wrede *et al.*, 2013). The main routines are snow accumulation and melting, ice melting, soil moisture accounting and runoff generation. A degree-day method is used for snow and ice melting calculation; evapotranspiration is calculated based on field capacity and permanent wilting point. The runoff is simulated by two nonlinear parallel reservoirs representing the direct discharge and the groundwater response with the spatial distribution of soil saturation controlling the response described by a nonlinear distribution function. The model performs water balance calculations for every discretized element. Furthermore, the distributed HBV is also able to simulate the sub-grid variability with fractions of land classes within one element. Every element has a sub-grid scale distribution, accumulation and ablation of snow, interception storage, evapotranspiration, groundwater storage, runoff response, and glacier mass balance. Detailed information can be found in the references (Lindström *et al.*, 1997; Li *et al.*, 2013).

HYDROLOGIC SIMULATION

The HBV model was set up on two Himalayan basins, viz. the Beas River basin, India and the Wang Chhu basin, Bhutan. A model-independent nonlinear parameter estimation and optimization package called PEST (Doherty & Johnston, 2003) was used for model calibration. The objective function was set to obtain the best value of Nash-Sutcliffe efficiency (NSE) in respect of discharge. Three criteria were used to evaluate the model performance: the NSE, the correlation coefficient (R), and the relative mean error (RME) (Table 1). NSE is sensitive to high peaks (Nash & Sutcliffe, 1970); RME is for the relative error; and R represents the overall trend between observation and simulation (Krause *et al.*, 2005). Therefore, the combination of these three criteria can give an appropriate evaluation of the model performance in runoff simulation.

Table 1 Evaluation criteria and their corresponding formulation. O_i and S_i are the observed and simulated flow, respectively; *i* is the time series index; *n* is the total number of time steps; *cov(O,S)* is covariance of observation and simulation; σ_o and σ_s are the standard deviations of observation and simulation, respectively.

Criterion	Formula	Value range	Perfect value
NSE	$1-\frac{\sum_{i=1}^{n}(O_i-S_i)^2}{\sum_{i=1}^{n}(O_i-\overline{O}_i)^2}$	$-\infty,1$	1
R	$\frac{\mathrm{cov}(O,S)}{\sqrt{\sigma_O\times\sigma_S}}$	$-1,1$	1
RME	$\frac{\sum_{i=1}^{n}(S_i-O_i)}{\sum_{i=1}^{n}O_i}$	$-\infty,+\infty$	0

The Wang Chhu basin

The Wang Chhu basin with an area of 3580 km^2 is located in west-central Bhutan (Fig. 1). As one of the four major rivers in Bhutan, the Wang Chhu rises in Tibet and flows south-easterly. The lower course is called the Raidak River in India, which is one of the main right tributaries of the Brahmaputra River. The average elevation of the basin is 3609 m a.m.s.l., ranging from 1817 to 7078 m a.m.s.l. The average slope of the basin is 26.5°. The main land cover is forest; approximately 4.4% of the area is covered by glaciers or permanent snow, mainly in the northern part. The climate is as varied as its altitude and affected by monsoons from the south to the north. The monsoon season is from June to September. The records (1995–2009) from Drugyel Dzong climate station (the upper left station in Fig. 1) show that the average annual precipitation is 3493 mm, with 61% in the monsoon season. The contemporary average temperature of the same station is 12.8°C, with the highest being 20.0°C in July and the lowest being 4.7°C in January.

The model was calibrated from 1 January 1998 to 31 December 2003, and validated from 1 January 2004 to 31 December 2008 at a daily time step. The results for the calibration and validation periods are shown in Table 2. For illustrative purpose, the observed and simulated discharge in the validation period is shown in Fig. 2. It clearly shows that the model can fairly simulate hydrologic response of the Wang Chhu basin and give a good fit of the low flow, although it somewhat underestimates the high flow in the monsoon season which is common in hydrological modelling.

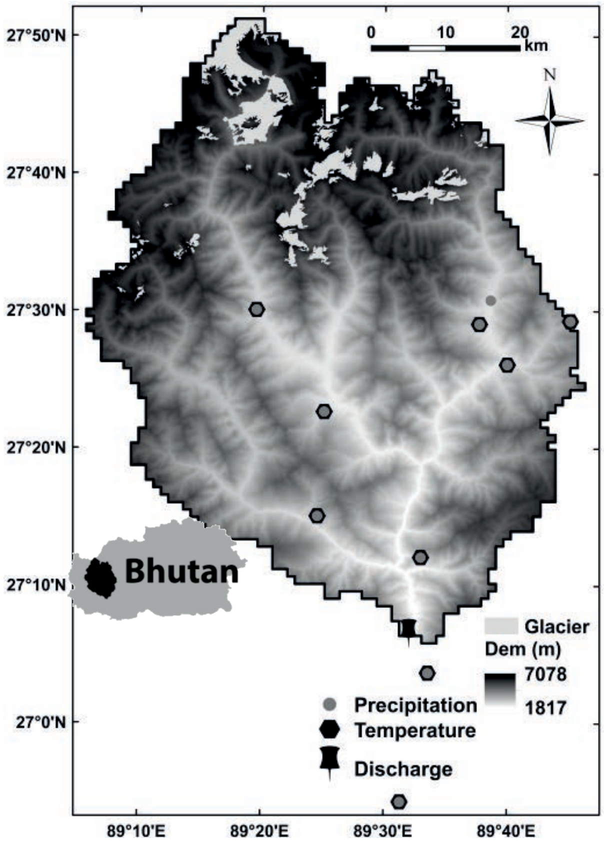

Fig. 1 A representation from DEM of the Wang Chhu basin, Bhutan, showing location of stations and glaciated area.

Table 2 Model efficiency at daily time step of calibration and validation periods on Wang Chhu basin.

Period	NSE	R	RME
Calibration	0.80	0.89	–0.05
Validation	0.76	0.88	–0.09

The Beas River basin

The Beas River in northern India is an important river of Indus River system. The Beas River basin at the Thalout discharge station covers an area of 4883 km^2, of which more than 500 km^2 is under permanent snow cover (Prasad & Roy, 2005; Kumar *et al.*, 2007). The upper part of the basin is occupied by permanent show and glaciers (Singh & Kumar, 1997). Like the Wang Chhu basin, the climate varies with the elevation and is affected by the monsoon. Winter (January to March), pre-monsoon (April to June), monsoon (July to September) and post-monsoon (October to December) are the four seasons in the Beas River basin (Singh & Kumar, 1997). In this study, seven precipitation stations and seven temperature stations are used (see Fig. 3).

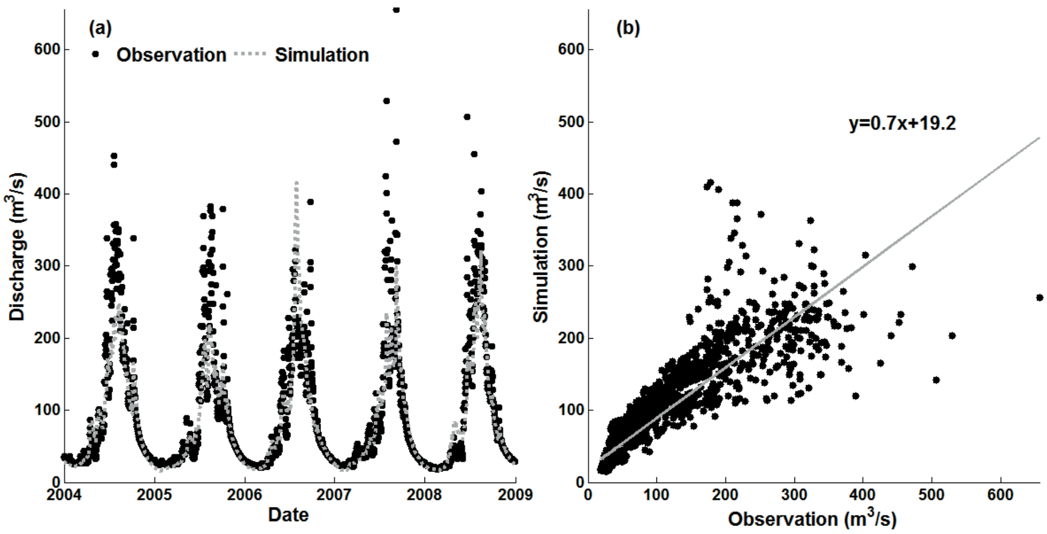

Fig. 2 Observed and simulated daily discharge in validation period (a) and the scatter plot (b), Wang Chhu basin.

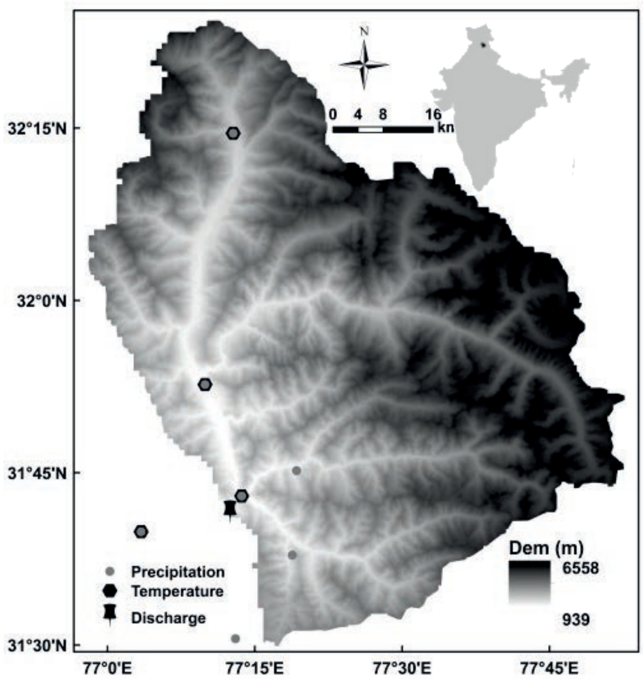

Fig. 3 DEM of the Beas River basin, India, and locations of stations.

The model was calibrated from 1 January 1987 to 31 December 1996 by the same calibration process as the Wang Chhu basin and validated from 1 January 1997 to 31 August 2005 at a daily time step. The results were analysed at a monthly time step, shown in Table 3 and Fig. 4. The model is able to give a good estimation of the monthly runoff. However, the model overestimates the low flow and some flood peaks.

Table 3 Model efficiency at monthly time step of calibration and validation periods on the Beas River basin.

Period	NSE	R	RME
Calibration	0.78	0.89	0.07
Validation	0.70	0.90	0.25

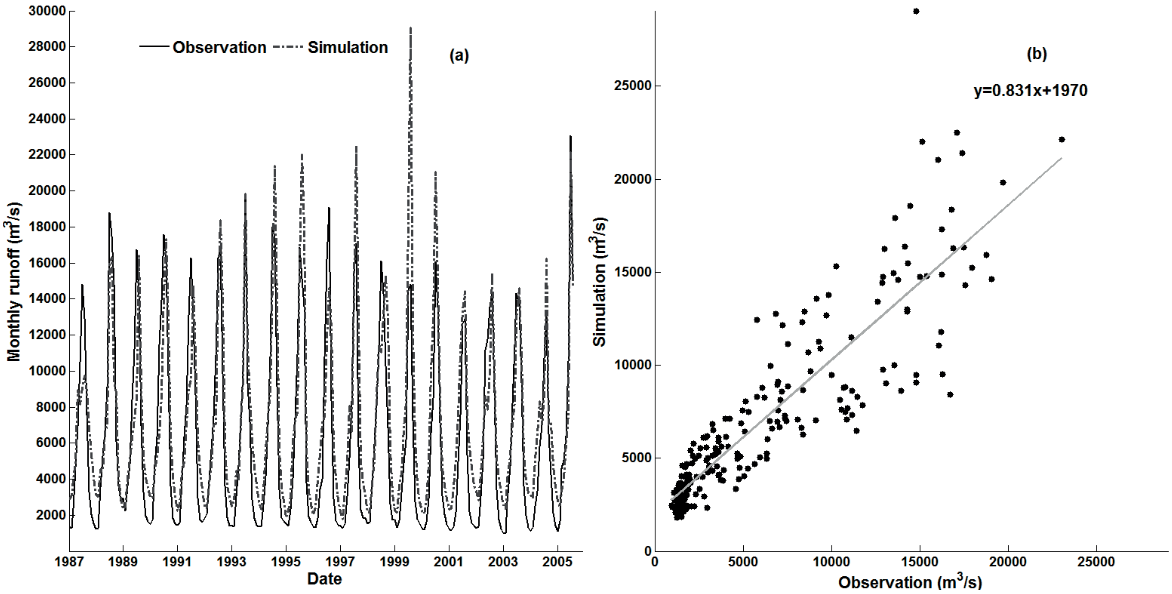

Fig. 4 The simulated and observed monthly runoff (a) and their scatterplot (b) from 1 January 1987 to 31 August 2005. The calibration period is from 1 January 1987 to 1 January 1996, Beas basin.

RUNOFF COMPONENTS

The multi-year average monthly results are shown in Fig. 5. For the Wang Chhu basin, the rainfall is the largest contributor to the runoff, especially during April to September, followed by the snowmelt outside glaciers. Due to the relatively small fraction of glaciated area, the runoff from glaciers is quite small. Therefore, glacier retreating caused by climate change is not expected to greatly influence the annual runoff of the basin. However, if the total precipitation amount does not change, less snow will marginally increase the risk of flooding because of the absence of the delaying effects of snow melt. For the Beas River basin, over 60% of the runoff is from cold water (snow and ice), of which over one third comes from glaciated area. The rainfall is the largest contributor only in August. The melting of glaciers would significantly reduce the base flow and more precipitation falling as rain is likely to cause heavy flooding. Beas River basin is prone to droughts in winter and post-monsoon, and floods in the monsoon.

The uncertainty of these results cannot be ignored. The sources of the uncertainty are data used in the calibration and validation, and the current model structure. Among the observed data of precipitation, temperature and discharge, the precipitation data are expected to be the largest source of uncertainty because most stations are located at lower elevations, while information about precipitation at higher elevations is missing. In this study, a degree-day method for glacier melting was used and the glacier area was not updated or modelled. By doing this, there is an inexhaustible ice volume available for melting, which is not realistic in a long term simulation and may lead to a too high estimation of water from glaciers. However, for the relatively short time periods used in this study this effect is probably negligible (Huss *et al.*, 2008). Additionally, the ice melting only happens when it is not covered by snow, which possibly results in lower estimation of glacier ice melting. Further research including modification of the model and data collection (both radar rainfall and reanalysis data) is needed to improve the accuracy of model simulation in the study region.

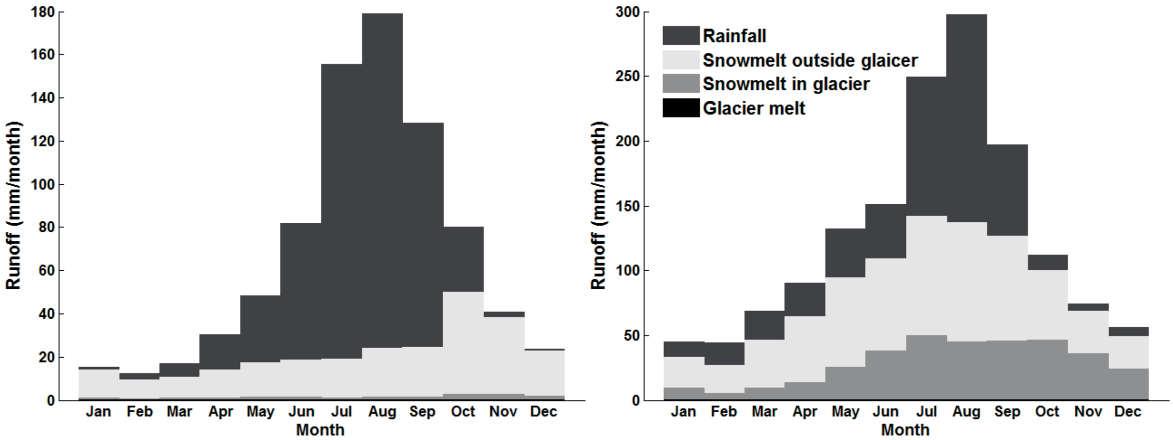

Fig. 5 Multi-year averaged monthly runoff components of the Wang Chhu basin (left) and Beas River basin (right).

CONCLUSIONS

To simulate the runoff and its contribution components in Himalayan regions, the HBV model was used to identify the runoff proportions from rainfall, snowmelt outside of glaciers, snowmelt in glaciers and glaciers' melting in two Himalayan basins: the Wang Chhu basin, Bhutan and the Beas River basin, India. The results show that the HBV model is able to give a fair estimation of runoff on these two catchments. For the Wang Chhu basin, the largest contributor to runoff is rainfall, whereas melting of snow and glacier is markedly dominant in the Beas River basin. The more precipitation that falls as rain is likely to raise the high flows and glacier retreat is likely to reduce the base flow, which possibly leads to more droughts and floods. In summary, these two study basins are vulnerable to climate change.

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