Journal of Hydrology (2008) **355**, 148–163

available at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/jhydrol

The impact of climate change on the water resources of Hindukush–Karakorum–Himalaya region under different glacier coverage scenarios

M. Akhtar [a,*], N. Ahmad [a], M.J. Booij [b]

[a] *Institute of Geology, University of the Punjab, Lahore, Pakistan*
[b] *Department of Water Engineering and Management, University of Twente, Enschede, The Netherlands*

Received 20 April 2007; received in revised form 20 February 2008; accepted 16 March 2008

KEYWORDS
Regional climate model;
Delta change approach;
HBV model;
Climate change;
Glacier coverage;
Hindukush–Karakorum–Himalaya region

Summary This paper presents estimates of water resources changes in three river basins in the Hindukush–Karakorum–Himalaya (HKH) region associated with climate change. The present climate (1961–1990) and future climate SRES A2 scenario (2071–2100) are simulated by the PRECIS Regional Climate Model at a spatial resolution of 25×25 km. Two HBV models (i.e. HBV-Met and HBV-PRECIS) are designed to quantify the future discharge. HBV-Met is calibrated and validated with inputs from observed meteorological data while HBV-PRECIS is calibrated and validated with inputs from PRECIS RCM simulations for the current climate. The future precipitation and temperature series are constructed through the delta change approach in HBV-Met, while in HBV-PRECIS future precipitation and temperature series from PRECIS RCM are directly used. The future discharge is simulated for three stages of glacier coverage: 100% glaciers, 50% glaciers and 0% glaciers. Generally temperature and precipitation shows an increase towards the end of 21st century. The efficiencies of HBV-Met during calibration and validation are higher compared to the HBV-PRECIS efficiencies. In a changed climate, discharge will generally increase in both models for 100% and 50% glacier scenarios. For the 0% glacier scenario, HBV-Met predicts a drastic decrease in water resources (up to 94%) in contrast to HBV-PRECIS which shows only a decrease up to 15%. Huge outliers in annual maximum discharge simulated through HBV-Met indicate that hydrological conditions are not predicted perfectly through the delta change downscaling approach. The results for HBV-Met simply confirm that the quality of observed data in this region is poor. The HBV-PRECIS model results are indicative of the higher risk of flood problems under climate change. The climate change signals in all three river basins are similar however, there are differences in the evaluated future water resources estimated through HBV-Met, whereas in HBV-PRECIS the changes in water resources are similar. This shows that the transfer of climate change signals into hydrological changes is more consistent

* Corresponding author. Tel.: +92 42 9231251.
E-mail address: akhtarme@yahoo.com (M. Akhtar).

0022-1694/$ - see front matter
doi:10.1016/j.jhydrol.2008.03.015

in HBV-PRECIS than in HBV-Met. One of the reasons of the poorer results of the delta change approach is that in this approach the frequency of rainy days is not changed and day to day variability in temperature is not correctly transferred. However more research is needed to evaluate the uncertainties in both downscaling approaches. Moreover, the dynamical downscaling approach needs to be tested with other RCMs and preferably to other river basins as well.

Introduction

Pakistan's economy is agro-based and highly dependent on the large scale Indus irrigation system (Snow and Ice Hydrology Project, 1990). Water issues hold a unique place in Pakistan's policymaking history. It has generated significant heated debate and controversy for a very long time as illustrated by issues such as the construction of the Kalabagh Dam and the unequal distribution of water resources among the provinces (Ghazanfar, 2007). Impacts of climate change and climate variability on the water resources are likely to affect irrigated agriculture and installed power capacity. Changes in flow magnitudes are likely to raise tensions among the provinces, in particular with the downstream areas (Sindh province), with regard to reduced water flows in the dry season and higher flows and resulting flood problems during the wet season. Therefore, in Pakistan future water resources estimation under climate change is important for planning and operation of hydrological installations.

To investigate the impact of climate change on future water resources a hydrological model can be driven with the output from a general circulation model (GCM) (Watson et al., 1996). However, the spatial resolution of GCMs (about 250 km) might be too coarse for hydrological modeling at the basin scale. One way to bridge this scale gap is through statistical downscaling (e.g. Wilby et al., 1999). In many hydrological studies (Bergström et al., 2001; Pilling and Jones, 2002; Guo et al., 2002; Arnell, 2003; Booij, 2005) statistical downscaling of different GCMs has been used to translate the assumed climate change into hydrological response. An alternative approach is dynamical downscaling (e.g. Hay et al., 2002; Hay and Clark, 2003), in which a regional climate model (RCM) uses GCM output as initial and lateral boundary conditions over a region of interest. The high horizontal resolution of a RCM (about 25—50 km) is more appropriate for resolving the small-scale features of topography and land use, that have a major influence on climatological variables such as precipitation in climate models. Moreover, the high resolution of the RCM is ideal to capture the variability of precipitation as input to hydrological models (Gutowski et al., 2003). Recent applications of this approach are presented by Kay et al. (2006a, b) and Leander and Buishand (2007).

To estimate the impact of climate change on river discharges different scenarios of the future meteorological conditions (e.g. temperature and precipitation) are used as input to a hydrological model of a river basin to calculate the corresponding discharges. Changes in downscaled temperature and precipitation series can be applied to observed temperature and precipitation series by simple transformation rules. We will refer to this approach as the delta change approach (Hay et al., 2002). In the delta change approach, an expected mean temperature change is added to the observed temperature record to obtain a future temperature time series. Precipitation is usually multiplied by a fraction. However, the adjustment of precipitation in this way is not ideal, as the results depend on the way in which the monthly factors are applied to the daily rainfall series (Reynard et al., 2001). Another way to estimate the future water resources is by using RCM outputs directly to force the hydrological model (Hay et al., 2002; Graham et al., 2007; Leander and Buishand, 2007). In these studies some bias corrections are made in the RCM outputs before using them into hydrological models calibrated and validated with observed meteorological data. The direct use of RCM output has the potential advantage that more complex changes in the probability density functions of the input variables of hydrological models are taken into account. Akhtar et al. (2008) used the RCM outputs directly in the hydrological model and estimated the parameters of the hydrological model for each source of input, i.e. outputs from different RCMs, separately.

One field of application of hydrological models is the creation of runoff scenarios for different climate and glaciation conditions. However, glacier storage is not handled well by current conceptual or physically-based hydrological models. Hence, holistic approaches to study and model glacier storage are of major importance to fully integrate glaciers into the hydrological balance to be used for water resources and river flow predictions at all time scales (Jansson et al., 2003). During the 20th century, most of the world's glaciers have shrunk (Paul et al., 2004; WGMS, 2002; Haeberli et al., 1999) and for a warming rate of 0.04 K a^{-1}, without increases in precipitation, few glaciers would survive until 2100. On the other hand, if the warming rate is limited to 0.01 K a^{-1} with an increase in precipitation of 10% per degree warming, it is predicted that overall loss would be restricted to 10—20% of the 1990 volume (Oerlemans et al., 1998). The glaciers of the Greater Himalaya are also retreating (Mastny, 2000), although Hewitt (1998) reports the widespread expansion of the larger glaciers in the central Karakorum, accompanied by an exceptional number of glacier surges.

The aim of our study is to examine the impact of climate change on the future water resources of three river basins of the Hindukush—Karakorum—Himalaya (HKH) region under different glacier coverage scenarios. To achieve this we make use of the output of the RCM PRECIS nested within the GCM HadAM3P as input into the HBV hydrological model to estimate the discharge of the three river basins in the present and future climate. The GCM uses the SRES A2 greenhouse gas emission scenario for the simulation of the future climate. The study area is described in section

'Description of study area'. The climatological inputs and HBV hydrological model are briefly described in section 'Methodology'. The results of the PRECIS RCM present and future simulations and impacts of climate change on the discharge are presented in section 'Results and discussion'. Finally, the conclusions and recommendations are given in section 'Conclusions and recommendations'.

Description of study area

Three river basins are selected for analysis: Hunza river basin, Gilgit river basin and Astore river basin. Table 1 lists some features of the study basins and Fig. 1 shows the location of the three river basins. These three river basins are situated in the high mountainous HKH region with many peaks exceeding 7000 m and contain a large area of perennial snow and ice. The HKH region is dominated by large glaciers and there is a fivefold to tenfold increase in precipitation from glacier termini (~2500 m) to accumulation zones above 4800 m. Maximum precipitation occurs between 5000 and 6000 m (Hewitt, 1993). Most glaciers are nourished mainly by avalanche snow. Westerly circulations and cyclonic storms contribute two third of high altitude snowfall (Hewitt et al., 1989), while one third derives from summer snowfall mainly due to monsoon circulation (Wake, 1989). A huge loss of ice mass and glacier recessions are observed in almost all Karakorum glaciers for most of the 20th century until the mid 1990s. Since then there has been thickening and advances in many glaciers but confined to the highest watersheds of the central Karakorum (Hewitt, 2005). In spite of surge type behavior of some glaciers in the HKH region (Diolaiuti et al., 2003), some others (e.g. the Baltoro glacier) are stable during the last 100 years (Mayer et al., 2006) and glaciers located in valleys are declining. A shift to a positive mass balance may be taking place, in accordance with weather-station records and gauging stations that show reduced runoff from the most heavily glacierized Hunza basin (Fowler and Archer, 2006; Archer and Fowler, 2004). However, the suddenness of the changes in glaciers and their confinement to the highest watersheds suggests that thermal and hydrological thresholds being crossed that trigger down slope redistribution of ice by normal as well as surging flow, with or without mass balance changes (Hewitt, 2007).

Table 1 Characteristics of study area

	River basins		
	Hunza	Gilgit	Astore
Gauging station	Dainyor	Gilgit	Doyian
Latitude	35° 56′	35° 56′	35° 33′
Longitude	74° 23′	74° 18′	74° 42′
Elevation of gauging station (m)	1450	1430	1583
Drainage area (km^2)	13925	12800	3750
Glacier covered area (km^2)	4688	915	612
% Glacier covered area	34	7	16
Mean elevation (m)	4472	3740	3921
% Area above 5000 m	35.8	2.9	2.8
No. of meteorological stations			
Precipitation	—	2	1
Temperature	—	2	1
No. of PRECIS grid points	12	10	4

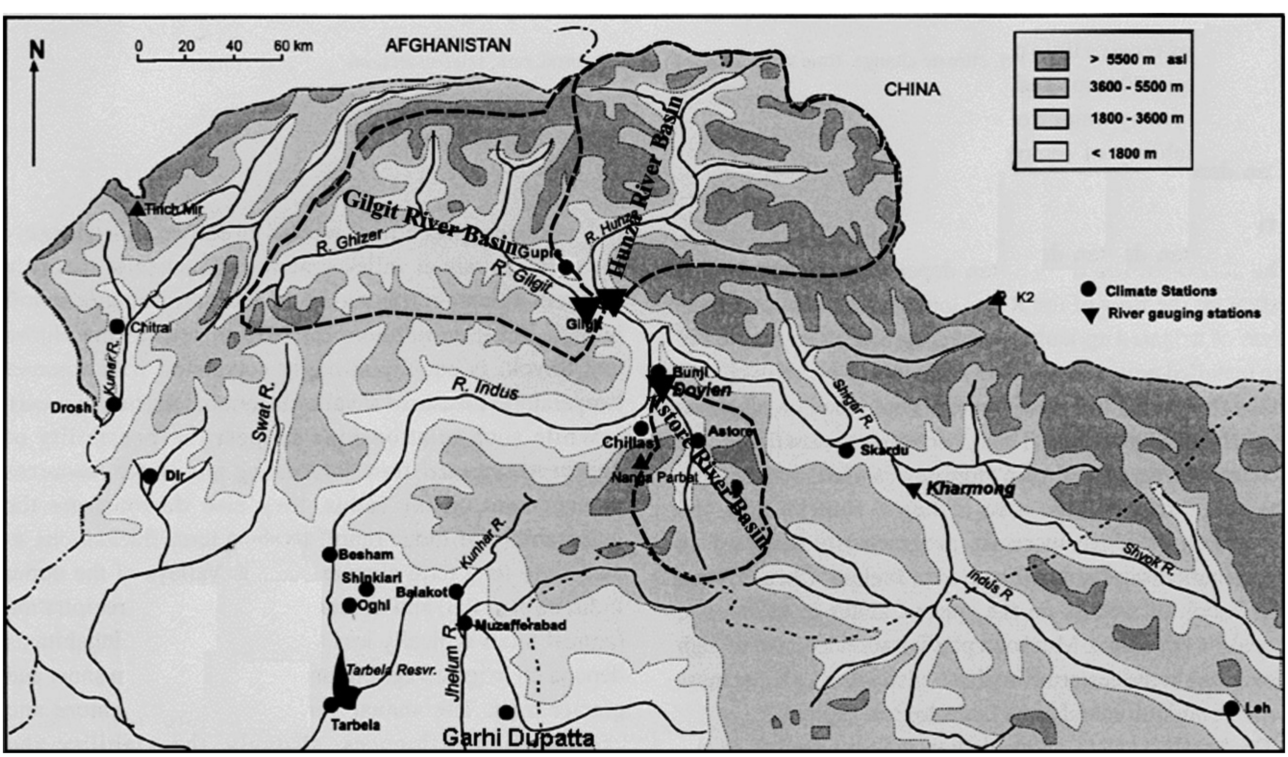

Figure 1 Location of three river basins.

Seasonal snow melt and melting of glacial ice are both large contributors in the discharge of the selected three rivers. In most winters, 80—90% of the area becomes snow covered (Snow and Ice Hydrology Project, 1990). Climatic variables are strongly influenced by altitude. The HKH region receives a total annual rainfall of between 200 and 500 mm, but these amounts are derived from valley-based stations and not representative for elevated zones. High-altitude precipitation estimates derived from accumulation pits runoff above 4000 m range from 1000 mm to more than 3000 mm. These estimates depend on the site and time of investigation, as well as on the method applied (Winger et al., 2005).

Methodology

Climatological input

Observed data

Daily observed meteorological data from the Gilgit and Astore meteorological stations are selected for the Gilgit and Astore river basins. There is no meteorological station in the Hunza river basin, therefore neighboring Skardu meteorological station is used for calibration and validation of HBV. The observed discharge data for the three river basins are available at the outlets of the basins. The length of the records in the three river basins is not the same and there are some missing years in the discharge data. Therefore, in some cases the calibration and validation periods in the three river basins are not same (see Table 3 in section 'Calibration and validation of HBV model').

Regional climate model outputs

The RCM used in this study is PRECIS developed by the Hadley Centre of the UK Meteorological Office. The PRECIS RCM is based on the atmospheric component of the HadCM3 climate model (Gordon et al., 2000) and is extensively described in Jones et al. (2004). The atmospheric dynamics module of PRECIS is a hydrostatic version of the full primitive equations and uses a regular longitude—latitude grid in the horizontal and a hybrid vertical coordinate. For this study, the PRECIS model domain (Upper Indus basin) has been set up with a horizontal resolution of 25×25 km, as compared to Akhtar et al. (2008) who used a horizontal resolution of 50×50 km. The domain is roughly stretched over the latitude 26°—39°N and longitude 67°—85°E. The HadAM3P global data set is used to drive the PRECIS model. The horizontal resolution of the HadAM3P boundary data is 150 km and for the present and future climate, it covers the period 1960—1990 and 2070—2100, respectively (Wilson et al., 2005). For the future climate, the SRES A2 greenhouse gas emission scenario is selected (Nakicenovic et al., 2000).

The first year in each PRECIS RCM experiment is considered as a spin-up period and these data are not used in any analysis. After post processing of each PRECIS RCM experiment the time series of temperature and precipitation are produced for further analysis.

Delta change approach to observed data

The delta change approach has been used in many climate change impact studies before (see e.g. Arnell, 1998; Gellens and Roulin, 1998; Middelkoop et al., 2001). In this approach, the observed climate time series are adapted with estimated monthly climate changes from the PRECIS RCM. The observational database used for the delta change approach covers the period 1981—1996. The future daily temperature ($T_{\mathrm{f,daily}}$) and daily precipitation ($P_{\mathrm{f,daily}}$) time series are constructed by Eqs. (1) and (2), respectively

$$T_{\mathrm{f,daily}} = T_{\mathrm{o,daily}} + (\overline{T_{\mathrm{f,monthly}}} - \overline{T_{\mathrm{p,monthly}}}) \tag{1}$$

$$P_{\mathrm{f,daily}} = P_{\mathrm{o,daily}} \frac{\overline{P_{\mathrm{f,monthly}}}}{\overline{P_{\mathrm{p,monthly}}}} \tag{2}$$

where $T_{\mathrm{o,daily}}$ is the observed daily temperature, $P_{\mathrm{o,daily}}$ is the observed daily precipitation, $\overline{T_{\mathrm{f,monthly}}}$ is the mean monthly PRECIS simulated future temperature, $\overline{T_{\mathrm{p,monthly}}}$ is the mean monthly PRECIS simulated present temperature, $\overline{P_{\mathrm{f,monthly}}}$ is the mean monthly PRECIS simulated future precipitation and $\overline{P_{\mathrm{p,monthly}}}$ is the mean monthly PRECIS simulated present precipitation.

Depending on the source of input data, i.e. observed meteorological data and PRECIS RCM simulations for the current climate, two HBV models (see Section 'HBV hydrological model') are calibrated and are hereafter referred to as HBV-Met and HBV-PRECIS, respectively. The climate change signal from the PRECIS RCM is transferred to HBV-Met through the delta change approach whereas in HBV-PRECIS the future simulated temperature and precipitation series are used directly. The effect of climate change on river discharge is simulated for the current glacier extent (100% glacier scenario) and for two stages of deglacierisation, i.e. after an areal reduction by 50% (50% glacier scenario) and after complete melting (0% glacier scenario).

HBV hydrological model

For river discharge simulation, the hydrological model HBV of the Swedish Meteorological and Hydrological Institute (SMHI) is used (Bergström, 1995; Lindström et al., 1997). Using inputs from RCMs this model has reproduced the discharge fairly well for e.g. the Suir river in Ireland (Wang et al., 2006). HBV has been widely used in Europe and other parts of the world in climate change studies (Liden and Harlin, 2000; Bergström et al., 2001; Menzel and Bürger, 2002; Booij, 2005; Menzel et al., 2006). This model is a semi-distributed, conceptual hydrological model using sub-basins as the primary hydrological units. It takes into account area-elevation distribution and basic land use categories (glaciers, forest, open areas and lakes). Sub-basins are considered in geographically or climatologically heterogeneous basins. The model consists of a precipitation routine representing rainfall and snow, a soil moisture routine determining actual evapotranspiration and controlling runoff formation, a quick runoff routine and a base flow routine which together transform excess water from the soil moisture zone to local runoff, a transformation function and a routing routine. A general description of the HBV model is given in SMHI (2005) and the application of HBV to the HKH region is extensively studied by Akhtar et al. (2008).

As input, the model needs the distribution of the basin area by altitude and land use categories, where the glaciated parts have to be treated as a separate land use class and glacier mass balance is determined for each elevation zone. For running the daily model, the only required data are daily means of temperature and daily total precipitation (potential evapotranspiration is calculated using a simplified version of Thornthwaite's equation with temperature as input). Daily discharge is needed for calibration. Parameters of the HBV model are calibrated using a manual calibration procedure (SMHI, 2005). In previous HBV studies, much experience has been gained in parameter estimation, which is used to acquire the range of parameters in our study (Uhlenbrook et al., 1999; Krysanova et al., 1999; SMHI, 2005; Booij, 2005). A univariate sensitivity analysis is performed to assess the sensitivity of the discharge regime to the parameters. For the three river basins, parameters GMELT (glacier melting factor), FC (maximum soil moisture storage), PERC (percolation from upper to lower response box), TT (threshold temperature), DTTM (value added to TT to reach threshold temperature for snowmelt), and CFMAX (factor for snow melt) are found to be most sensitive and there is a strong interdependence among these parameters. Therefore, a multivariate sensitivity analysis is performed to calibrate the parameters of the HBV-MET and HBV-PRECIS models for each river basin.

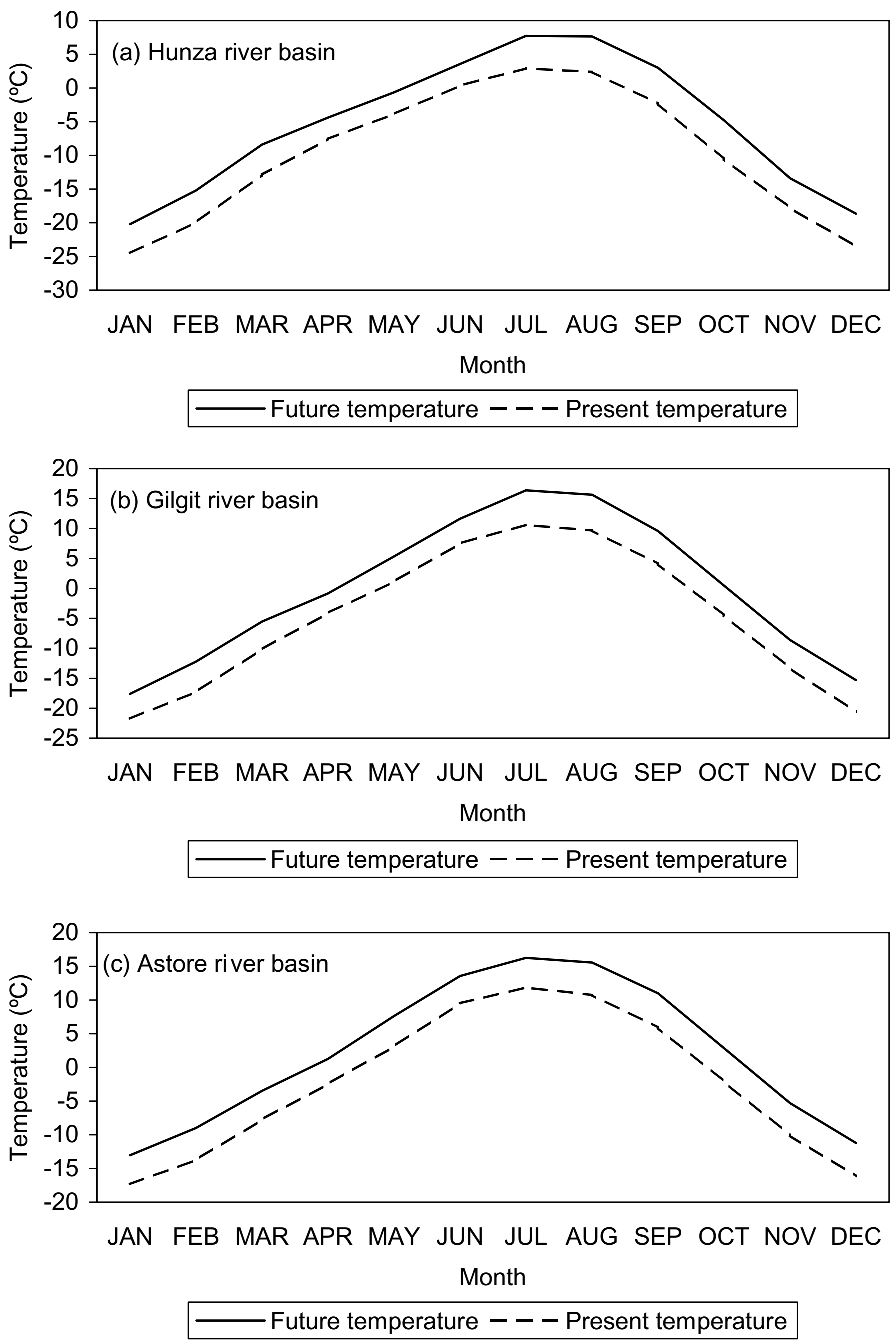

Figure 2 Mean annual cycle of temperature over (a) Hunza river basin (b) Gilgit river basin (c) Astore river basin as simulated with PRECIS for present (1961—1990) and future (2071—2100) day climate (°C).

In order to assess the performance of the model, the Nash–Sutcliffe efficiency coefficient NS (Nash and Sutcliffe, 1970) and the relative volume error RE are commonly calculated by Eqs. (3) and (4):

$$NS = 1 - \frac{\sum_{i=1}^{i=N}[Q_s(i) - Q_o(i)]^2}{\sum_{i=1}^{i=N}[Q_o(i) - \bar{Q}_o]^2} \quad (3)$$

$$RE = 100\frac{\sum_{i=1}^{i=N}[Q_s(i) - Q_o(i)]}{\sum_{i=1}^{i=N}Q_o(i)} \quad (4)$$

where i is the time step, N is the total number of time steps, Q_s represents simulated discharge, Q_o is observed discharge and $\bar{Q}_o$ is the mean of Q_o over the calibration/validation period. For a favorable model performance, the efficiency NS should be as high as possible (maximum value of 1) and the RE value should be close to zero.

Results and discussion

Changes of temperature and precipitation during 2071–2100

For three river basins, the mean annual cycles of temperature and precipitation for the present and future climate

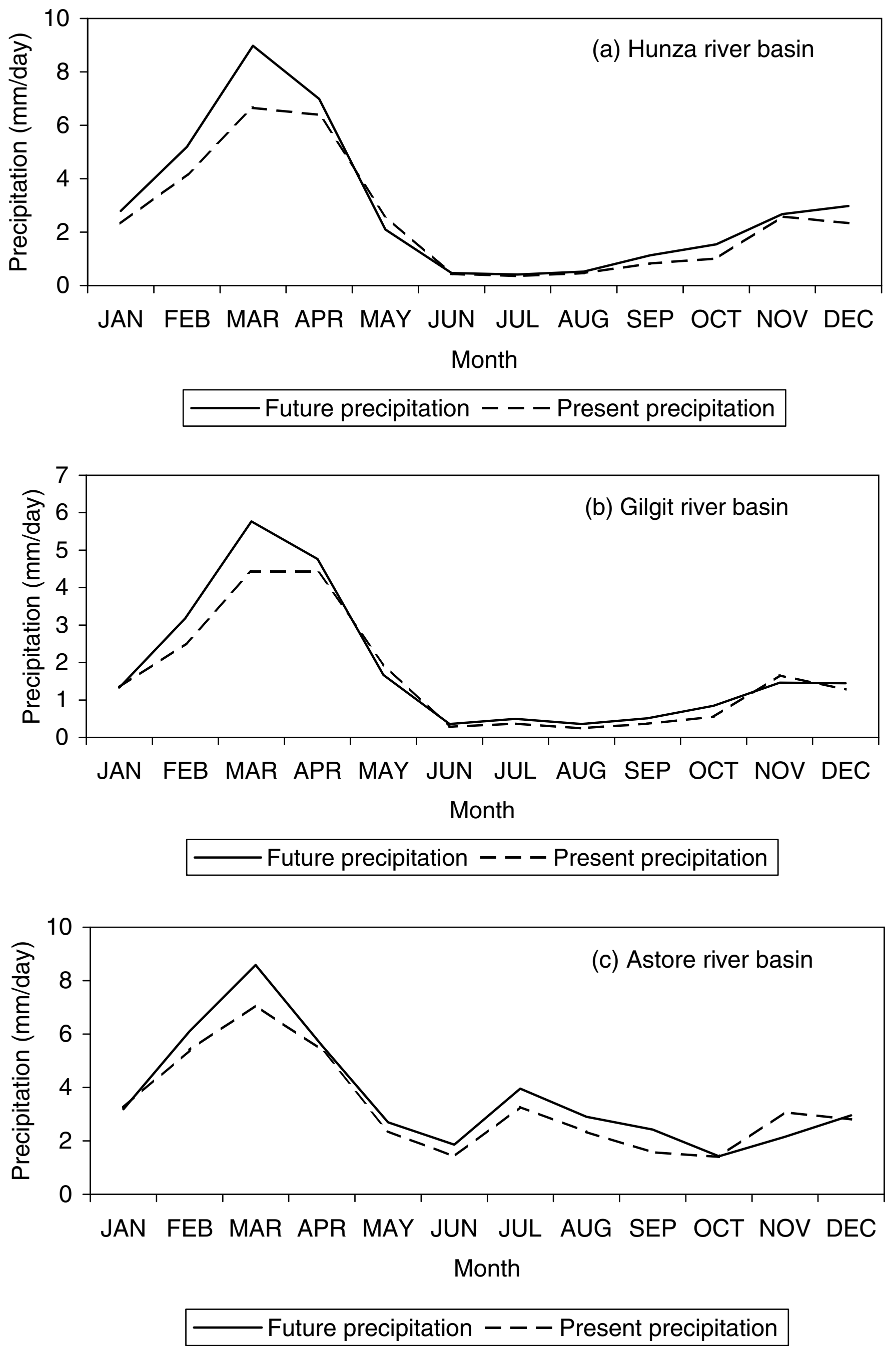

Figure 3 Mean annual cycle of precipitation over (a) Hunza river basin (b) Gilgit river basin (c) Astore river basin as simulated with PRECIS for present and future day climate (mm/day).

simulated with PRECIS are presented in Figs. 2 and 3, respectively. These indicate a general increase in temperature and precipitation during the period 2071–2100. The warming is uniformly distributed over the three river basins. Both in the present and future simulated climate the highest temperature is reached in the month of July and lowest temperature is observed during the month of January. Table 2 presents the seasonal changes in temperature and precipitation in the three river basins with climate change. The annual mean temperature rise by the end of the century is up to 4.8 °C. The warming is stronger during the winter season compared to the summer season.

PRECIS estimates a rise in annual mean precipitation (up to 19%) by the end of the 21st century. The increase in precipitation is observed in all seasons. Generally, the changes in precipitation during the summer season are larger than during the winter season. This is because of the fact that the HKH region receives a very small amount of precipitation during the summer season and a small absolute increase in summer precipitation compared to winter precipitation gives a larger percentual precipitation change during the summer. The mean annual precipitation changes in the Hunza (19%), Gilgit (21%) and Astore (13%) river basins are similar. The general increase in temperature and precipitation is consistent with the projected increase in temperature and precipitation in neighboring areas such as southwest China and northwest India (Yinlong et al., 2006; Kumar et al., 2006).

Calibration and validation of HBV model

Table 3 presents the efficiencies, relative volume error and mean observed and simulated discharge for the two HBV models during calibration and validation periods for the three river basins. The average simulated discharge and average observed discharge is equal during the calibration period for each HBV model and for each river basin and consequently the relative volume error is zero. General testing of conceptual models (Rango, 1992) has shown that NS values higher than 0.8 are above average for runoff modeling in glaciated catchments. Therefore, model efficiencies during calibration are satisfactory for the two HBV models. The efficiencies of HBV-Met are higher than those of HBV-PRECIS. Since the calibration period for the two models are different and the efficiency values highly depend on the time period for which the model is run, the smaller efficiency of HBV-PRECIS might be due to the events that are not captured by the model during that period. During the validation period NS values, RE values and visual inspection of hydrographs (Figures are not given) show that performance of the two HBV models is satisfactory. The values of the performance criteria show that during the validation period overall performance of HBV-Met (e.g. $0.71 < NS < 0.91$) is somewhat better compared to the calibration period (e.g. $0.67 < NS < 0.86$), while overall performance of HBV-PRECIS during validation (e.g. $0.58 < NS < 0.72$) is somewhat less compared to the calibration period (e.g. $0.74 < NS < 0.82$). Although in this study we used PRECIS RCM outputs at 25 km resolution (for Upper Indus Basin domain) yet on average the efficiency of HBV-PRECIS is similar to that of Akhtar et al. (2008) achieved by using PRECIS RCM outputs at 50 km resolution (for South Asia domain). This shows that increasing the resolution of data does not necessarily increase the efficiency of the hydrological model.

Table 2 Seasonal changes of mean temperature and precipitation under SRES A2 scenario from PRECIS in 2071–2100 over three river basins relative to 1961–1990

River basins	Temperature change (°C)			Precipitation change (%)		
	Annual	Winter	Summer	Annual	Winter	Summer
Hunza	4.5	4.8	4.2	19	27	10
Gilgit	4.8	4.8	4.8	21	19	24
Astore	4.5	4.7	4.4	13	1	25

(Summer = April–September; Winter = October–March).

Table 3 Performance of two HBV models during calibration and validation in different river basins

	River basin	Calibration					Validation				
		Period	$\bar{Q}_o$ m^3/s	$\bar{Q}_s$ m^3/s	NS	RE %	Period	$\bar{Q}_o$ m^3/s	$\bar{Q}_s$ m^3/s	NS	RE %
HBV-Met	Hunza	1981–1990	306.5	306.5	0.86	0	1990–1996	281.1	275.1	0.91	−2
	Gilgit	1981–1990	266.8	266.9	0.83	0	1990–1996	295.6	256.7	0.77	−13
	Astore	1981–1990	133.4	133.4	0.67	0	1990–1996	171.2	152.3	0.71	−11
HBV-PRECIS	Hunza	1971–1980	370.6	369.8	0.74	0	1981–1990	306.5	364.9	0.72	19
	Gilgit	1961–1970	288.7	288.6	0.82	0	1981–1990	266.8	264.8	0.72	0
	Astore	1975–1983	120.6	121.6	0.79	0	1983–1990	140.5	109.5	0.58	−22

The NS values are for daily model runs.

Future annual discharge cycle

Fig. 4 shows the mean annual discharge cycle simulated by HBV-Met for the present and future climate for three stages of glacier coverage: 100% glaciers, 50% glaciers and 0% glaciers. The amplitude of the annual discharge cycle is increased in a changed climate under the 100% glacier scenario. Snow melting starts one month earlier and discharge rises towards its peak in summer (August). However, this case has to be regarded as a hypothetical one because future 100% glacier extent is not realistic with climate change. If the glacierised area is reduced by 50%, snowmelt still begins one month earlier and discharge is increased during March, April and May in the Astore river basin, while it is decreased in the Hunza and Gilgit river basins in this period. The discharge under 50% glacier scenario is also increased in September and October in the Hunza river basin. The qualitative changes in monthly runoff for the 0% glacier scenario

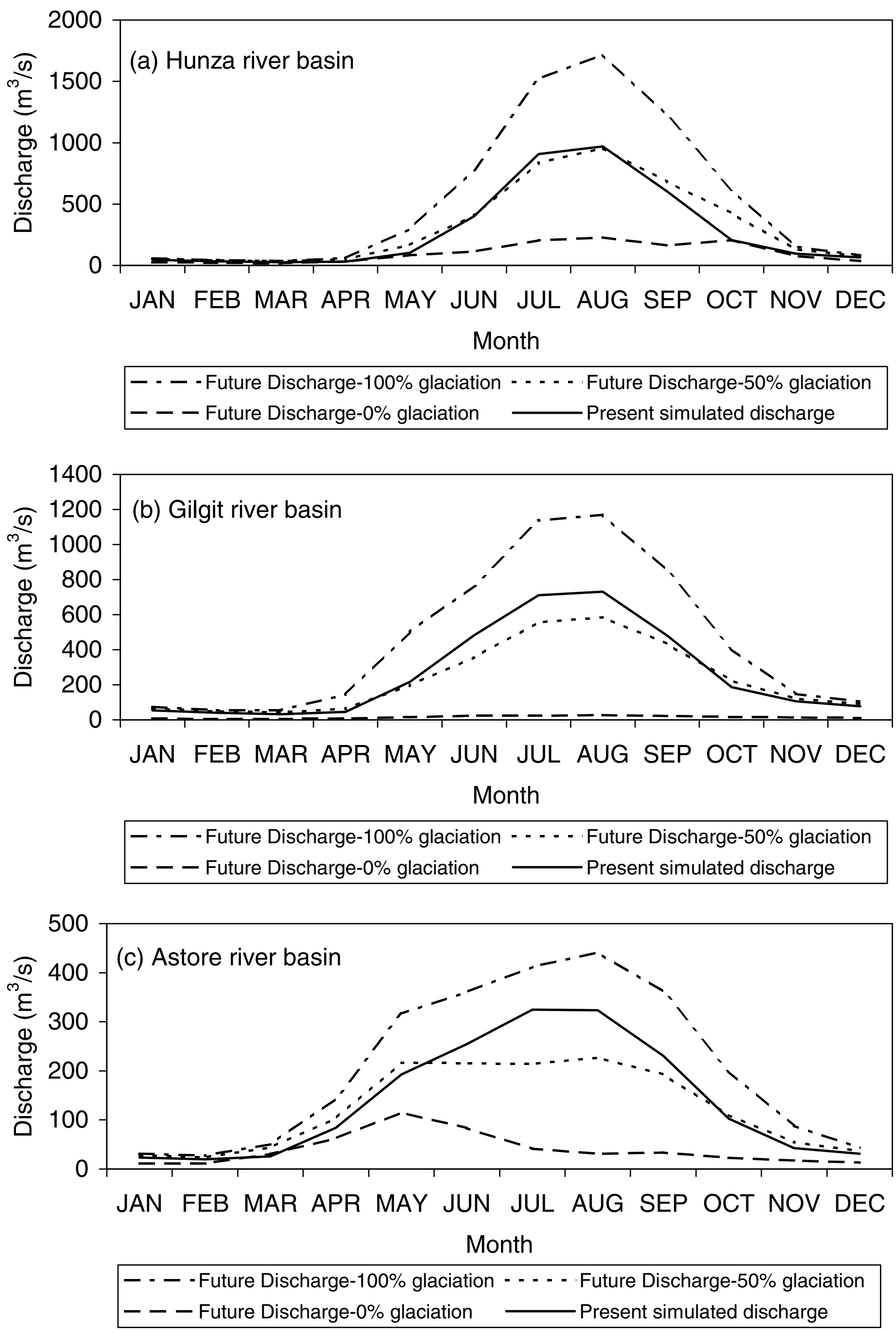

Figure 4 Annual discharge cycle simulated by HBV-Met for the present climate and future climate for three stages of glaciation for three river basins.

are more controversial. The discharge is reduced drastically in all three river basins. HBV-Met shows that the major contribution in these river basins is because of glacial melt, although the exact contribution is not known.

Fig. 5 shows the mean annual discharge cycle simulated by HBV-PRECIS for the present and future climate for three stages of glacier coverage: 100% glaciers, 50% glaciers and 0% glaciers. The amplitude of the seasonal discharge cycle is increased in a changed climate under the 100% glacier scenario as well. Snowmelt starts one month earlier, i.e. it starts in March. There is an increase in river discharge throughout the year and in all river basins. The highest peak is observed in July. For the 50% glacier scenario the discharge is increased during March—July while during August—October the shape of the hydrograph is generally the same as in the present climate. After complete reduction

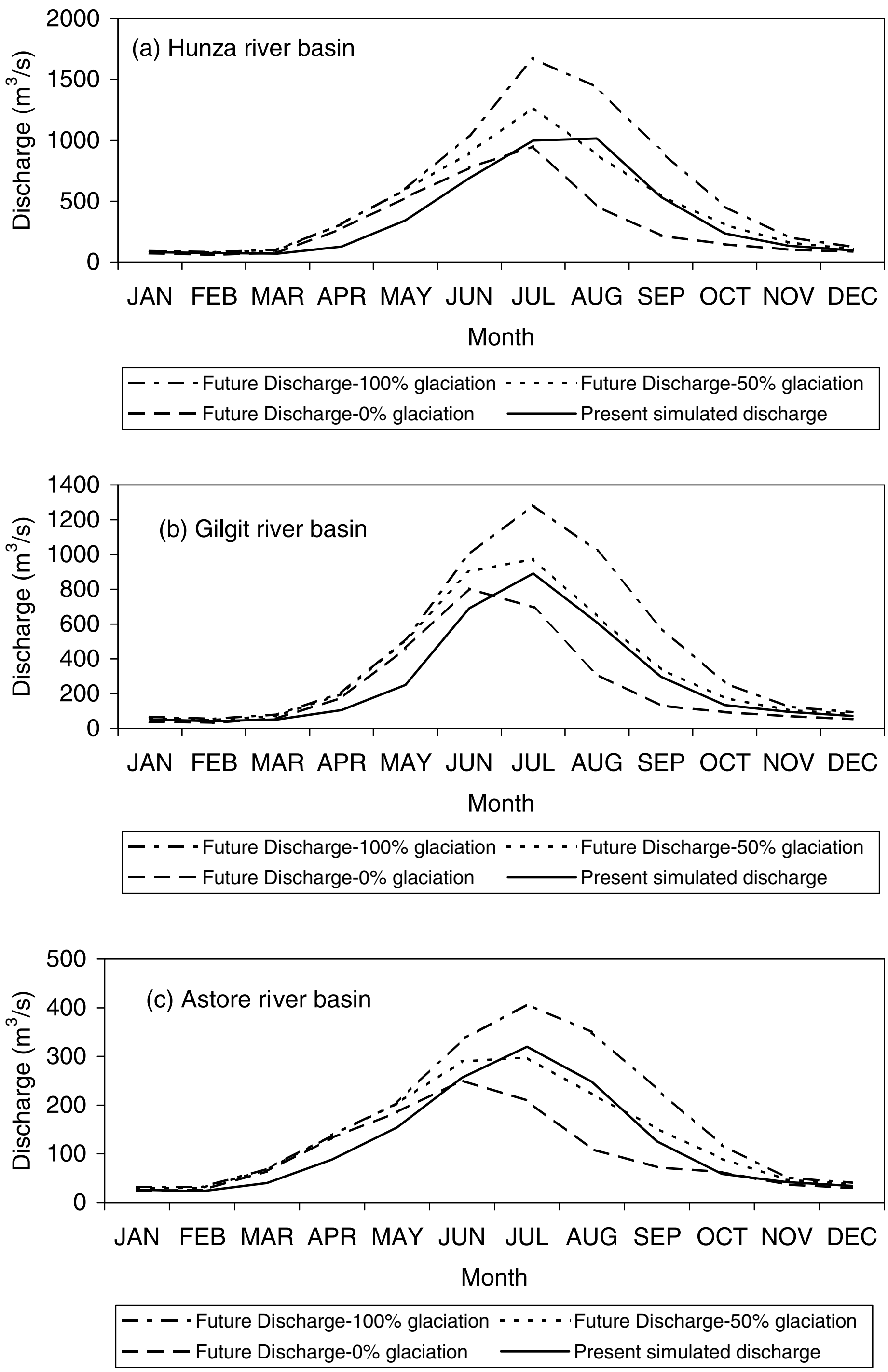

Figure 5 Annual discharge cycle simulated by HBV-PRECIS for the present climate and future climate for three stages of glaciation for three river basins.

Table 4 Mean relative change in future discharge (2071—2100) in a changed climate relative to the present discharge (1961—1990) for three glaciations stages and for three river basins

Model	River basin	Mean change in discharge (%)		
		100% glacier	50% glacier	0% glacier
HBV-Met	Hunza	88	10	−65
	Gilgit	70	−12	−94
	Astore	48	−12	−72
HBV-PRECIS	Hunza	59	21	−15
	Gilgit	60	24	−12
	Astore	41	13	−15

of the glaciers, snowmelt still starts one month earlier and there is an increase in discharge during March—May. There is a considerable decrease in discharge during July—September.

Table 4 presents the mean relative changes in future discharge (2071—2100) in a changed climate relative to the present discharge (1961—1990) for the three glaciations stages and for three river basins. There is a big discrepancy between the results of changes in discharge simulated by HBV-Met and HBV-PRECIS. Under the 100% glacier scenario both models predict an increase in water resources. However the increase is higher in HBV-Met compared to HBV-PRECIS. Under the 50% glacier scenario HBV-Met predicts an increase in the discharge in the Hunza river basin, while in the Gilgit and Astore river basins the discharge is expected to decrease. HBV-PRECIS predicts an increase in all river basins under the 50% glacier scenario. Without glaciers, HBV-Met predicts a drastic decrease in the discharge (65—94%) in all river basins, whereas HBV-PRECIS predicts about a 15% decrease in the discharge. There is neither forest nor any major lake present in the three river basins and glaciers and fields (area without forest) are considered as the only two land use classes in the hydrological model framework. Therefore, the effect of complete melting of glaciers on the hydrological cycle will depend on the degree of glaciation in the river basins and response of the river basins to climate change. For instance looking at the similar patterns of climate change in the three river basins the highly glaciated Hunza river is expected to react more severely compared to the least glaciated Gilgit river basin. However, HBV-Met shows that more drastic changes are expected in the Gilgit river basin compared to the Hunza river basin. This is may be because of the inaccurate transfer of climate change signals through the delta change approach. The decrease in discharge predicted by HBV-PRECIS is consistent with the complete melting of glaciers, because the net annual ice losses due to wastage of glaciers represents between 12% and 15% of the annual water yield from melting ice (Hewitt et al., 1989). The transfer of climate change signals into hydrological changes seems to be more consistent in HBV-PRECIS. The temperature and precipitation changes are almost similar in all three river basins. The resulting changes in water resources conditions under all glaciation scenarios are also more similar in HBV-PRECIS compared to HBV-Met. Although these basins have similar geology and hydrology, there is a chance that due to potential biases in PRECIS RCM simulated temperature and precipitation series for the current climate, the parameters of HBV-PRECIS are adjusted in such a way that the impacts on water resources are similar. However, transferring the climate change signals to the hydrological model through the direct use of RCM simulations preserves future extremes which is an advantage over the delta change approach (Graham et al., 2007).

Future discharge peaks

Extreme value analysis based on the Gumbel extreme value distribution is carried out to estimate the impact of climate change on floods for three river basins with two HBV models and for three glaciation stages. For this, the maximum discharge per hydrological year is determined from both measured and simulated discharge series of three river basins. Fig. 6 shows the extreme value distribution of floods derived from observed discharge data and simulated discharge data from HBV-Met and HBV-PRECIS. Observed discharge data from the period 1981—1996, simulated discharge data for HBV-Met from the period 1981—1996 and simulated discharge data for HBV-PRECIS from the period 1961—1990 are used. Since the extreme discharge return values are influenced by the period of study, it is difficult to compare the observed extreme values with HBV-PRECIS simulated extreme values. Moreover, observed and HBV-Met simulated extreme values are based on relatively few extreme flood events, which makes the extrapolation to large return periods highly susceptible to errors. Anyhow, the general trend of present day simulated annual maximum discharge from both HBV models is an underestimation at all return levels. The highest differences between observed and modeled extreme discharges are found in the Astore river basin.

The flood frequency results under climate change for three glacier stages estimated through HBV-PRECIS and HBV-Met models are presented in Figs. 7 and 8, respectively. In all river basins, HBV-PRECIS shows an increase in flood magnitude for all return periods under climate change in the 100% and 50% glacier scenarios. The magnitude of flood frequency under climate change in the 0% glacier scenario is increased in the Hunza and Gilgit river basins whereas in Astore river basin it is comparable with the current magnitude of floods at least at higher return periods. The change in peak discharge at 20-year return level in the 100% glacier scenario is 68%, 36% and 34% in the Hunza, Gilgit and Astore river basins, respectively. These results are consistent with the study of Milly et al. (2002) who found an overall increase in flood peaks during the twentieth century and this trend is expected to continue in the future. HBV-Met predicts an increase in flood magnitude for all return period under climate change in the Hunza and Gilgit river basins for the 100% glacier scenario whereas for the 50% and 0% glacier scenarios, the magnitude of peak discharges is decreased. The flood frequency is increased in the Astore river basin for the 100% glacier scenario for all return periods and for 50% glacier

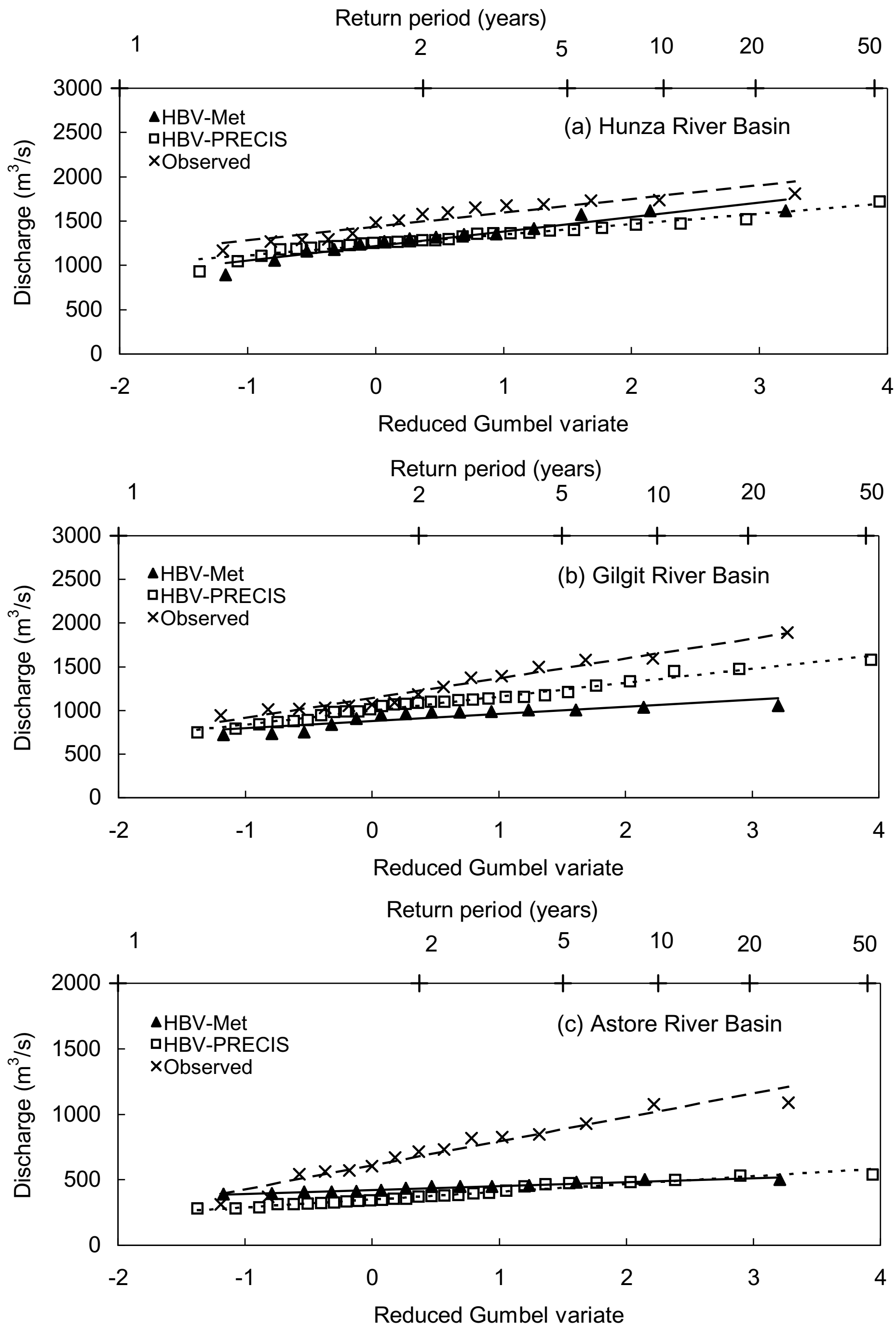

Figure 6 Observed, HBV-Met simulated and HBV-PRECIS simulated annual maximum discharge as a function of return period for three river basins.

scenario at least at higher return periods. For this river basin the magnitude of the peak discharge is decreased for the 0% glacier scenario. The change in peak discharge at 20-year return level in the 100% glacier scenario is 54%, 32% and 73% in the Hunza, Gilgit and Astore river basins, respectively. For the 50% and 0% glacier scenarios the flood peaks at 20-year return level decrease in the Hunza (10% and 54%, respectively) and Gilgit (27% and 83%, respectively) river basins. In the Astore river basin the flood peaks at 20-year return level are increased (43%) for the 50% glacier scenario and are decreased (19%) for the 0% glacier scenario.

The characteristics of future annual maximum discharge values are given in Table 5. There are huge outliers in HBV-Met simulated future annual maximum discharge values in all river basins (not shown in the figures). The outliers are also present in HBV-PRECIS simulated future annual maximum discharge values in the Astore river basin. Some

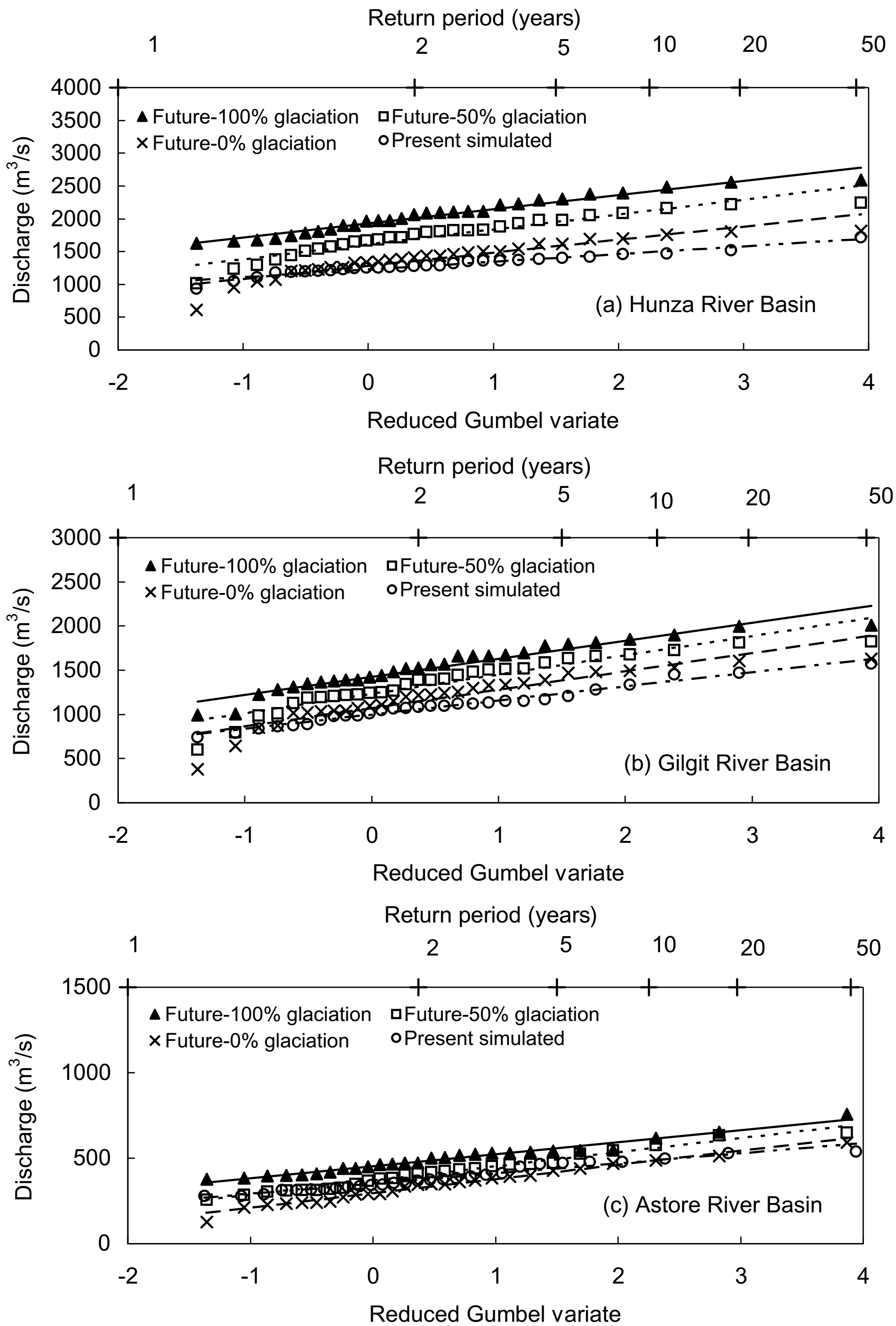

Figure 7 HBV-PRECIS simulated annual maximum discharge as a function of return period for current and changed climate for three glacier stages for three river basins.

of these outliers in both HBV-Met and HBV-PRECIS may be because of the high variability of runoff due to the small size of the river basin. The outliers in HBV-Met are explained by the fact that in each river basin only one meteorological station is used for temperature and precipitation input into HBV-Met. Observed precipitation is considered as areally averaged precipitation but actually point precipitation. Unfortunately, sufficient precipitation stations are not available to assess the areally averaged basin scale precipitation in a right way. Consequently, observed precipitation shows too much variability and extreme behavior. Parameters are estimated under too variable and extreme conditions. For example in Hunza river basin at Skardu meteorological station there are three heavy rainfall spells

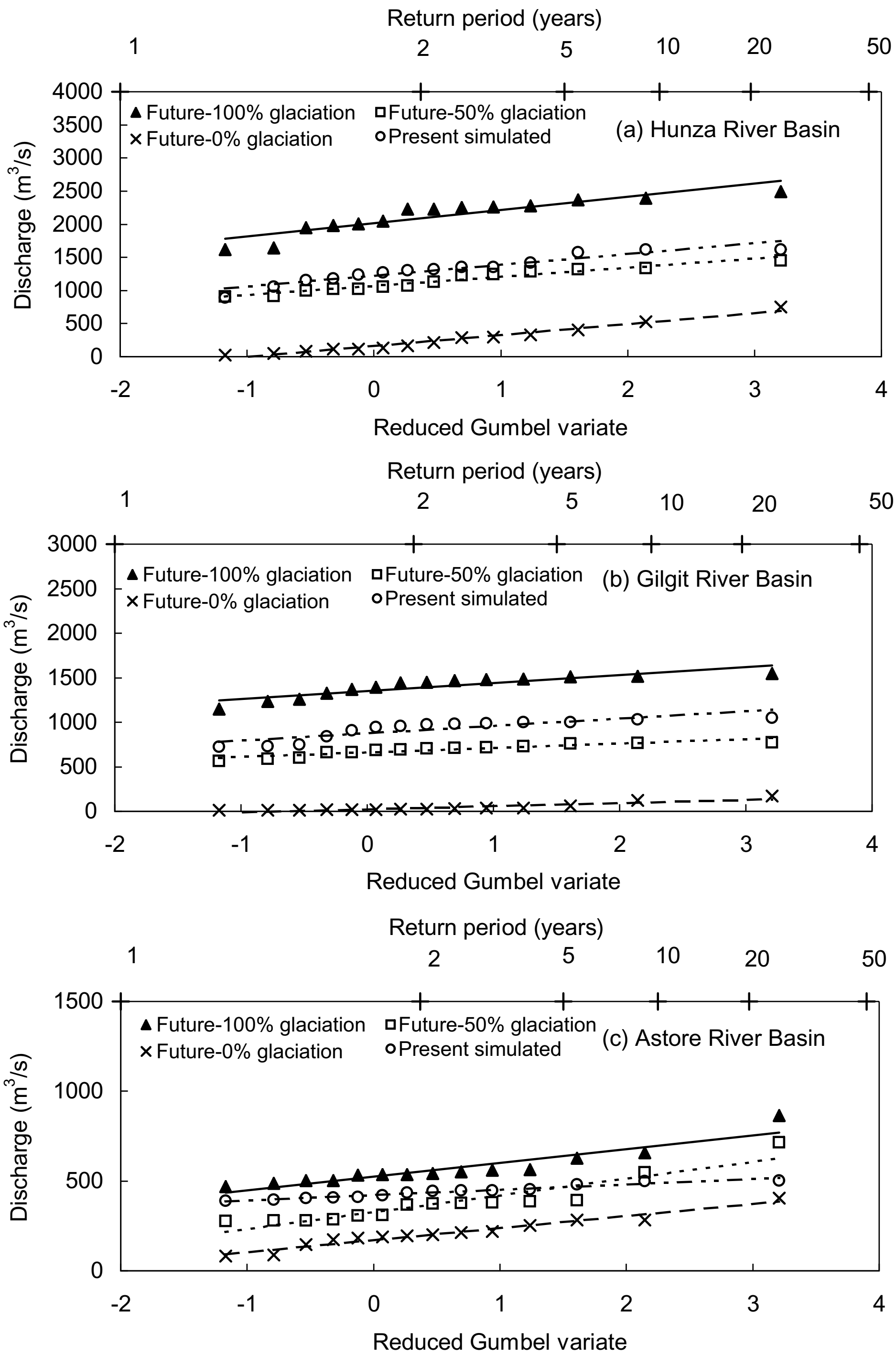

Figure 8 HBV-Met simulated annual maximum discharge as a function of return period for current and changed climate for three glacier stages for three river basins.

in the month of October 1987 (average rainfall is 37.0 mm in October, 1987 while the climate normal for October is 6.4 mm). When we use climate change scenarios derived from PRECIS (in October there is an increase in precipitation of 57%) HBV-Met gives extremely high peaks in October 1987 (an increase in mean discharge of 289% in October 1987). Therefore, the quality of input data used in HBV-Met seems to be too poor to simulate extreme discharge behavior.

The modeled changes in flood frequency under climate change are just estimations that are based on simulations using input data from only one RCM run, using one emission scenario and one single GCM for the boundary data. Other GCMs could result in quite different flood frequency predictions. Despite all uncertainties, the behavior of peak discharges predicted by the two HBV models supports the direct use of RCM output as input to hydrological models in this area.

Table 5 Characteristics of future annual maximum discharge simulated by two HBV models in a changed climate for the three glaciations stages and for three river basins

Model	River basin	Glaciation scenario					
		Means (m^3/s)			Standard deviation (m^3/s)		
		100%	50%	0%	100%	50%	0%
HBV-PRECIS	Hunza	2052.5	1738.0	1391.9	272.2	294.9	266.5
	Gilgit	1540.5	1351.6	1186.0	261.1	288.1	276.6
	Astore	549.8 (613.3)	473.9 (536.2)	394.7 (451.7)	321.3 (465.3)	324.1 (462.2)	305.6 (429.2)
HBV-Met	Hunza	2123.7 (2837.4)	1140.3 (1887.7)	249.9 (915.5)	265.1 (2775.9)	169.4 (2899.3)	203.5 (2585.1)
	Gilgit	1400.2 (1430.5)	688.3 (709.9)	42.9 (53.5)	120.0 (165.0)	65.9 (104.8)	47.3 (61.3)
	Astore	566.2 (591.7)	377.8 (401.0)	207.9 (231.3)	99.5 (137.6)	121.2 (147.3)	82.5 (120.5)

The values in parentheses are for future annual maximum discharge with outliers.

Conclusions and recommendations

The PRECIS RCM present climate and future SRES A2 climate scenarios presented in this paper include detailed regional information (25×25 km) and is very important for climate impact assessment in various sectors. This paper includes only the basic aspects of simulated present and future climate (i.e. future changes in temperature and precipitation). Generally, temperature and precipitation shows an increase towards the end of the 21st century spread monotonously over the three river basins. There are several uncertainty sources in the PRECIS RCM simulations which are not discussed here. However, we plan to evaluate and quantify these uncertainties in this region in PRECIS RCM simulations in our future work.

In a changed climate, HBV does not calculate the new glacier area size automatically. To bridge this deficiency, we have used three glacier coverage scenarios as applied by Hagg et al. (2007) while modelling the hydrological response to climate change in glacierized Central Asian catchments. However, future glacier extent may be predicted separately by using a simple hypsographic modelling approach (e.g. Paul et al. 2007). The use of such a predicted future glacier extent in HBV would give a more realistic hydrological change. To quantify the future water resources, the delta change approach is used for HBV-Met and direct use of PRECIS RCM data is done for HBV-PRECIS. There are differences in the results of both approaches. In a changed climate, the discharge will generally increase both in HBV-PRECIS and HBV-Met in the 100% glacier scenario (up to 60% and 88%, respectively) and in the 50% glacier scenario (up to 24% and 10%, respectively). For the 0% glacier scenario under climate change, a drastic decrease in water resources (up to 94%) in HBV-Met is present, whereas HBV-PRECIS shows a decrease up to 15%.

There are huge outliers in annual maximum discharge simulated with HBV-Met. This shows that the prediction of hydrological conditions through the delta change approach is not ideal in the HKH region. HBV-PRECIS provides results on hydrological changes that are more consistent with RCM changes. This shows that the climate change signals in HBV-PRECIS are transmitted more realistically than in HBV-Met. Therefore, the direct use of RCM outputs in a hydrological model may be an alternative in areas where the quality of observed data is poor. The direct use of RCM outputs (HBV-PRECIS model) has shown that the magnitude of annual maximum flood peaks is likely to increase in the future. Hence, overall results are indicative of a higher risk of flood problems under climate change. The modeled changes in future discharge and changes in flood frequency under climate change are not conclusive because more research is needed to evaluate the uncertainties in this approach. Moreover, this technique needs to be tested with other RCMs and preferably to river basins in other parts of the world as well.

Acknowledgements

Part of this study was completed at ICTP, Trieste, Italy, which provided funding for two months fellowship for this work. The Higher Education Commission of Pakistan has also provided financial funding. The authors would like to thank the PRECIS team at Hadley Centre, Met Office, UK, for their comments and suggestions during the PRECIS simulations. The boundary data of different GCMs have been kindly supplied by David Hein on behalf of Hadley Centre, Met Office, UK. The daily river discharge data and meteorological data have been taken from WAPDA, Pakistan and Pakistan Meteorological Department, respectively. The authors also thank the HBV support team at SMHI for their useful comments and suggestions during the study.

References

Akhtar, M., Ahmad, N., Booij, M.J., 2008. Use of regional climate model simulations as input for hydrological models for the Hindukush—Karakorum—Himalaya region. Hydrology and Earth System Sciences Discussions 5, 865—902.

Archer, D.R., Fowler, H.J., 2004. Spatial and temporal variations in precipitation in the upper Indus Basin, global teleconnections and hydrological implications. Hydrology and Earth System Science 8, 47—61.

Arnell, N.W., 1998. Climate change and water resources in Britain. Climatic Change 39, 83—110.

Arnell, N.W., 2003. Relative effects of multi-decadal climatic variability and changes in the mean and variability of climate

due to global warming: future streamflow in Britain. Journal of Hydrology 270, 195—213.
Bergström, S., 1995. The HBV model. Chapter 13 of Computer models of watershed hydrology. Water Resource Publications, 443—476.
Bergström, S., Carlsson, B., Gardelin, M., Lindström, G., Pettersson, A., Rummukainen, M., 2001. Climate change impacts on the runoff in Sweden-assessments by global climate models, dynamical downscaling and hydrological modelling. Climate Research 16, 101—112.
Booij, M.J., 2005. Impact of climate change on river flooding assessed with different spatial model resolutions. Journal of Hydrology 303, 176—198.
Diolaiuti, G., Pecci, M., Smiraglia, C., 2003. Liligo Glacier, Karakoram, Pakistan: a reconstruction of the recent history of a surge-type glacier. Annals of Glaciology 36, 168—172.
Fowler, H.J., Archer, D.R., 2006. Conflicting signals of climate change in the upper Indus Basin. Journal of Climate 19, 4276—4293.
Ghazanfar, M., submitted for publication. Kalabagh Dam and the Water Debate in Pakistan. Lahore Journal of Policy Studies.
Gellens, D., Roulin, E., 1998. Streamflow response of Belgian catchments to IPCC climate change scenarios. Journal of Hydrology 210, 242—258.
Gordon, C.C., Cooper, C., Senior, C.A., Banks, H., Gregory, J.M., Mitchell, J.F.B., Wood, R.A., 2000. The simulation of SST, sea ice extents and ocean heat transport in a version of the Hadley centre coupled model without flux adjustment. Climate Dynamics 16, 147—168.
Graham, L.P., Andreasson, J., Carlsson, B., 2007. Assessing climate change impacts on hydrology from an ensemble of regional climate models, model scales and linking methods-a case study on the Lule River basin. Climatic Change 81, 293—307.
Guo, S., Wang, J., Xiong, L., Yin, A., Li, D., 2002. A macro-scale and semi-distributed monthly water balance model to predict climate change impacts in China. Journal of Hydrology 268, 1—15.
Gutowski, W.J., Decker, S.G., Donavon, R.A., Pan, Z., Arritt, R.W., Takle, E.S., 2003. Temporal-spatial scales of observed and simulated precipitation in central US climate. Journal of Climate 16, 3841—3847.
Haeberli, W., Frauenfelder, R., Hoelzle, M., Maisch, M., 1999. On rates and acceleration trends of global glacier mass changes. Geografiska Annaler 81, 585—591.
Hagg, W., Braun, L.N., Kuhn, M., Nesgaard, T.I., 2007. Modelling of hydrological response to climate change in glacierized Central Asian catchments. Journal of Hydrology 332, 40—53.
Hay, L.E., Clark, M.P., 2003. Use of statistically and dynamically downscaled atmospheric model output for hydrologic simulations in three mountainous basins in the western United States. Journal of Hydrology 282, 56—75.
Hay, L.E., Clark, M.P., Wilby, R.L., Gutowski, W.J., Leavesley, G.H., Pan, Z., Arritt, R.W., Takle, E.S., 2002. Use of regional climate model output for hydrological simulations. Journal of Hydrometeorology 3, 571—590.
Hewitt, K., Wake, C.P., Young, G.J., David, C., 1989. Hydrological investigations at Biafo Glacier, Karakoram Himalaya: an important source of water for the Indus River. Annals of Glaciology 13, 103—108.
Hewitt, K., 1993. The altitudinal distribution of Karakoram geomorphic processes and depositional environments. In: Shroder, Jr., J.F., (Ed.), Himalaya to the Sea: geology, geomorphology and the Quaternary. NY, Routledge, pp. 159—183.
Hewitt, K., 1998. Glaciers receive a surge of attention in the Karakoram Himalaya. EOS, Transactions. American Geophysical Union 79, 104—105.
Hewitt, K., 2005. The Karakoram anomaly? Glacier expansion and the elevation effect, Karakoram Himalaya. Mountain Research and Development 25, 332—340.
Hewitt, K., 2007. Tributary glacier surges: an exceptional concentration at Panmah Glacier, Karakoram Himalaya. Journal of Glaciology 53, 181—188.
Jansson, P., Hock, R., Schneider, T., 2003. The concept of glacier storage: a review. Journal of Hydrology 282, 116—129.
Jones, R.G., Noguer, M., Hassell, D.C., Hudson, D., Wilson, S.S., Jenkins, G.J., Mitchell, J.F.B., 2004. Generating High Resolution Climate Change Scenarios Using PRECIS. Met Office Hadley Centre, Exeter, UK, p. 40.
Kay, A.L., Jones, R.G., Reynard, N.S., 2006a. RCM rainfall for UK flood frequency estimation. I. Method and validation. Journal of hydrology 318, 151—162.
Kay, A.L., Jones, R.G., Reynard, N.S., 2006b. RCM rainfall for UK flood frequency estimation. II. Climate change results. Journal of hydrology 318, 163—172.
Krysanova, V., Bronstert, A., Muller-Wohlfeil, D.I., 1999. Modelling river discharge for large drainage basins: from lumped to distributed approach. Hydrological Sciences Journal 44, 313—331.
Kumar, R.K., Sahai, A.K., Kumar, K.K., Patwardhan, S.K., Mishra, P.K., Revadekar, J.V., Kamala, K., Pant, G.B., 2006. High-resolution climate change scenarios for India for the 21st century. Current Science 90, 334—345.
Leander, R., Buishand, T.A., 2007. Resampling of regional climate model output for the simulation of extreme river flows. Journal of Hydrology 332, 487—496.
Liden, R., Harlin, J., 2000. Analysis of conceptual rainfall-runoff modelling performance in different climates. Journal of Hydrology 238, 231—247.
Lindström, G., Johansson, B., Persson, M., Gardelin, M., Bergström, S., 1997. Development and test of the distributed HBV-96 model. Journal of Hydrology 201, 272—288.
Mastny, L., 2000. Melting of Earth's Ice Cover Reaches New High. World Watch Institute, Washington, DC, <www.Worldwatch.org/alerts/000306.html>.
Mayer, C., Lambrecht, A., Belo, M., Smiraglia, C., Diolaiuti, G., 2006. Glaciological characteristics of the ablation zone of Baltoro glacier, Karakoram, Pakistan. Annals of Glaciology 43, 123—131.
Menzel, L., Bürger, G., 2002. Climate change scenarios and runoff response in the Mulde catchment (Southern Elbe, Germany). Journal of Hydrology 267, 53—64.
Menzel, L., Thieken, A.H., Schwandt, D., Bürger, G., 2006. Impact of climate change on the regional Hydrology-Scenarios-Based modelling studies in the German Rhine Catchment. Natural Hazards 38, 45—61.
Middelkoop, H., Daamen, K., Gellens, D., Grabs, W., Kwadijk, J.C.J., Lang, H., Parmet, B.W.A.H., Schädler, B., Schulla, J., Wilke, K., 2001. Impact of climate change on hydrological regimes and water resources management in the Rhine Basin. Climatic Change 49, 105—128.
Milly, P.D.C., Wetherald, R.T., Dunne, K.A., Delworth, T.L., 2002. Increasing risk of great floods in a changing climate. Nature 415, 514—517.
Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models 1: a discussion of principles. Journal of Hydrology 10, 282—290.
Nakicenovic, N., Alcamo, J., Davis, G., de Vries, B., Fenhann, J., Gaffin, S., Gregory, K., Grübler, A., Jung, T.Y., Kram, T., La Rovere, E.L., Michaelis, L., Mori, S., Morita, T., Pepper, W., Pitcher, H., Price, L., Riahi, K., Roehrl, A., Rogner, H-H., Sankovski, A., Schlesinger, M., Shukla, P., Smith, S., Swart, R., van Rooijen, R., Victor, N., Dadi, Z., 2000. IPCC Special Report on Emission Scenarios, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
Oerlemans, J., Anderson, B., Hubbard, A., Huybrechts, Ph., Johannesson, T., Knap, W.H., Schmeits, M., Stroeven, A.P., van de Wal, R.S.W., Wallinga, J., Zuo, Z., 1998. Modelling the

response of glaciers to climate warming. Climate Dynamics 14, 267—274.

Paul, F., Maisch, M., Rothenbuhler, C., Hoelzle, M., Haeberli, W., 2007. Calculation and visualisation of future glacier extent in the Swiss Alps by means of hypsographic modelling. Global and Planetary Change 55, 343—357.

Paul, F., Kaab, A., Maisch, M., Kellenberger, T., Haeberli, W., 2004. Rapid disintegration of Alpine glaciers observed with satellite data. Geophysical Research Letters 31, L21402. doi:10.1029/2004GL02081.

Pilling, C.G., Jones, J.A.A., 2002. The impact of future climate change on seasonal discharge, hydrological processes and extreme flows in the upper Wye experimental catchment, mid-Wales. Hydrological Processes 16, 1201—1213.

Rango, A., 1992. Worldwide testing of the snowmelt runoff model with applications for predicting the effects of climate change. Nordic Hydrology 23, 155—172.

Reynard, N.S., Prudhomme, C., Crooks, S.M., 2001. The flood characteristics of large UK rivers: potential effects of changing climate and land use. Climatic Change 48, 343—359.

SMHI., 2005. Integrated hydrological modelling system (IHMS), Manual version 5.6, SMHI, Norrkoping.

Snow and Ice Hydrology Project, 1990. Snow and Ice Hydrology Project, Upper Indus Basin, Overall. Report, WAPDA- IDRC-Wilfrid Laurier University, p. 179.

Uhlenbrook, S., Seibert, J., Leibundgut, C., Rodhe, A., 1999. Prediction uncertainty of conceptual rainfall-runoff models caused by problems in identifying model parameters and structure. Hydrological Sciences Journal 44, 779—797.

Wake, C.P., 1989. Glaciochemical investigations as a tool for determining the spatial and seasonal variation of snow accumulation in the Central Karakorum, Northern Pakistan. Annals of Glaciology 13, 279—284.

Wang, S., McGrath, R., Semmler, T., Sweeney, C., Nolan, P., 2006. The impact of the climate change on discharge of Suir river catchment (Ireland) under different climate scenarios. Natural Hazards and Earth System Sciences 6, 387—395.

Watson, R.T., Zinyowera, M.C., Moss, R.H., 1996. Climate Change 1995: Impacts, Adaptations, and Mitigations of climate change. Cambridge University Press, 889 pp.

WGMS, 2002. World Glacier Monitoring Service, Glacier Mass Balance Data 2000/01, <www.geo.unizh.ch/wgms/>.

Wilby, R.L., Hay, L.E., Leavesley, G.H., 1999. A comparison of downscaled and raw GCM output: implications for climate change scenarios in the San Juan River Basin, Colorado. Journal of Hydrology 225, 67—91.

Wilson, S., Hassell, D., Hein, D., Jones, R., Taylor, R., 2005. Installing and using the Hadley Centre regional climate modelling system, PRECIS (version 1.4), Met Office Hadley Centre, Exeter, UK.

Winger, M., Gumpert, M., Yamout, H., 2005. Karakorum—Hindukush—western Himalaya: assessing high-altitude water resources. Hydrological Processes 19, 2329—2338.

Yinlong, X., Xiaoying, H., Yong, Z., Wantao, L., Erda, L., 2006. Statistical Analysis of climate change scenarios over China in the 21st century. Advances in Climate Change Research 2, 50—53.