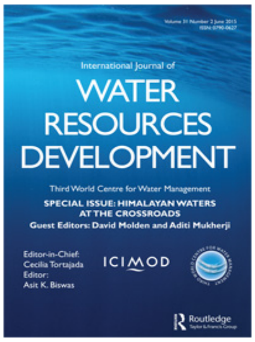

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Impact of climate change on the hydrological regime of the Indus, Ganges and Brahmaputra river basins: a review of the literature

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The Indus, Ganges and Brahmaputra river basins support 700 million people in Asia. The water resources are used for irrigation, drinking, industry, navigation and hydropower. This paper reviews the literature on the impact of climate change on the hydrological regime of these river basins and suggests that the different basins are likely to be affected in different ways. Climate change will have a marked affect on meltwater in the Indus Basin and may result in increased flood risk in the Brahmaputra Basin. The overall impact on annual discharge is likely to be low, but more studies are required to understand intra-annual changes and the impact of extreme events.

Keywords: climate change; water resources; Indus; Ganges; Brahmaputra

Introduction

The Indus, Ganges and Brahmaputra (IGB) river basins support the lives and livelihoods of some 700 million people to the south of the Hindu Kush Himalayan ranges (Eriksson et al., 2009). The water resources in these basins have been widely utilized for drinking, irrigation, navigation, industry and hydropower, and provide the basis for local livelihoods (Mirza, Warrick, & Ericksen, 2003). For example, around 144,900 ha of land is irrigated in the Indus Basin, 156,300 ha in the Ganges Basin, and 6000 ha in the Brahmaputra Basin (Immerzeel, van Beek, & Bierkens, 2010). In recent years, there has been increasing concern that the water resources of these river systems may be vulnerable in the context of global climate change (IPCC, 2007; Kundzewicz et al., 2007), which could have considerable implications for the livelihoods and well-being of the people in the region (Eriksson et al., 2009). Rising temperatures and changes in precipitation could affect the hydrological regime through factors such as changes in seasonal extremes, increased evapotranspiration, changes in glacier volume (Bolch et al., 2012), and changes in snow and glacier melt (Lutz, Immerzeel, Shrestha, & Bierkens, 2014). A number of authors have suggested that shrinking of glaciers in response to rising temperatures might result in a marked reduction in water availability in some rivers in the medium-to-long term (Bolch et al., 2012; Immerzeel, Beek, Konz, Shrestha, & Bierkens, 2012; Kääb, Berthier, Nuth, Gardelle, & Arnaud, 2012), following an initial increase in meltwater volume (Barnett, Adam, & Lettenmaier, 2005; Lutz et al., 2014). However, the type and extent of changes are still being investigated (Immerzeel et al., 2010; Lutz et al., 2014). The difficulties in assessing change are compounded by the fact that the river basins all have their origins in high mountain areas, and the effects of climate change in these areas, as well as the implications for downstream water availability, are complex (Nepal, Flügel, & Shrestha, 2014a).

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A number of authors have used climate models to estimate the likely changes in the main driving factors such as precipitation and temperature in the IGB river basins, and have used these projected data in hydrological models to assess the possible impacts on the hydrological regime and water availability. In this paper, we attempt to synthesize these results by looking at two questions: how the climate has changed in these river basins in recent times, and how future climate change (i.e. projected changes in precipitation and temperature) will affect the hydrological regime. The review focuses on the major papers on historical and projected climate change and impact on hydrology in the IGB river basins and selected sub-basins published in English in peer-reviewed journals since 1996. The threshold year was chosen to include only papers published after publication of the second assessment report of the Intergovernmental Panel on Climate Change.

The Indus, Ganges, and Brahmaputra river basins

The IGB basins extend across the southern slopes of the Himalayan mountain chain. Figure 1 shows the locations of the basins and the major catchments referred to in this study. The major characteristics of the basins are summarized in Table 1. All the basins extend across multiple countries; the river systems have distinct climate and flow regimes influenced to a large extent by the summer and winter monsoons.

The Indus Basin

The Indus originates in the high Himalayan mountains of China, India and Pakistan in the north and extends to the dry alluvial plains of Sindh Province in Pakistan in the south, finally draining into the Arabian Sea (Ali & De Boer, 2007; FAO, Aquastat, 2011a). The major part of the basin lies in arid-to-semi-arid climatic zones, but there is considerable temporal and spatial climatic variation across the area. Short spells of heavy precipitation occur in the summer (June to September), while westerlies bring precipitation in the winter and spring (Ali & De Boer, 2007). Rajbhandari, Shrestha, Kulkarni, Patwardhan, and Bajracharya (2014), using the APHRODITE (Asian Precipitation Highly-Resolved Observational Data Integration Towards Evaluation of Water Resources) data-set, estimated that nearly 50% of the precipitation falls during the monsoon and 40% during winter and spring. The northern parts have significant snowfall, while the southern parts have comparatively mild weather. The average annual rainfall ranges from less than 100 mm to 500 mm in the lowlands, and up to 2000 mm in the mountains (FAO, Aquastat, 2011a).

The Indus has the largest irrigation network in the world. The water is regulated by two major storage dams in the upper Indus Basin (the Tarbela Dam on the Indus and the Mangla Dam on the Jhelum) that are fed predominantly by meltwater (Immerzeel et al., 2010; Laghari, Vanham, & Rauch, 2012).

The Ganges Basin

The Ganges originates in the high-altitude areas of the Himalayas and the Tibetan Plateau, with tributaries flowing south from China, Nepal and India into the Indo-Gangetic Plain. The Ganges merges with the Brahmaputra in an extensive delta area in India and Bangladesh, finally emerging in the Bay of Bengal.

The basin encompasses diverse topography, ecosystems and biodiversity, from the alpine arid rain-shadow areas of the Tibetan Plateau through the steep topography of the

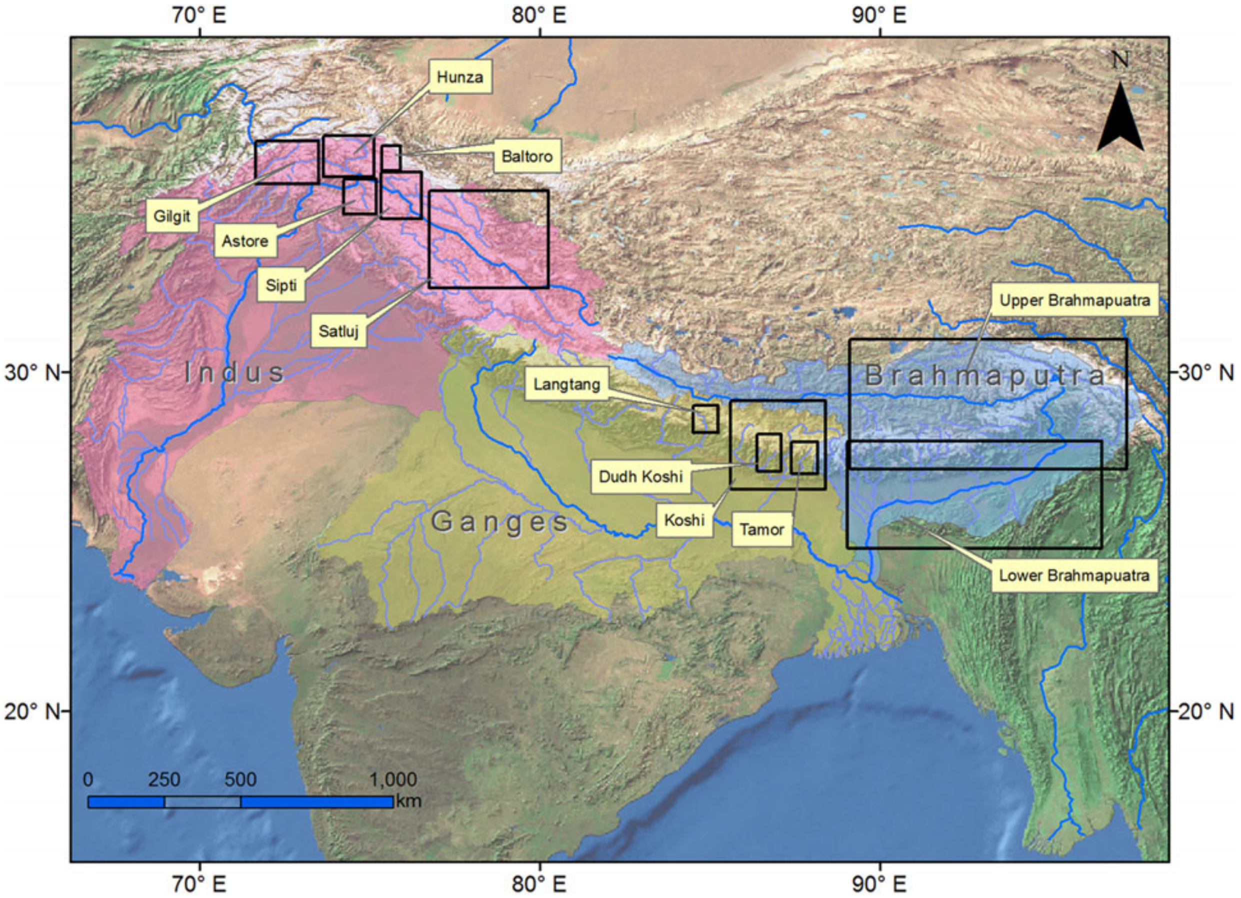

Figure 1. Location of the Indus, Ganges, and Brahmaputra river basins, and selected individual catchments.

Table 1. Basic characteristics of the Indus, Ganges and Brahmaputra river basins.

Basin	Countries	Area (km^2)	Length (km)	Population (thousands)	Population density ($persons/km^2$)	Annual discharge (m^3/sec)	Water availability (m^3 per person per year)	Net irrigation water demand (mm)
Indus	Afghanistan 6%, China 8%, India 39%, Pakistan 46%	1,120,000	3180	178,483	160	5533	978	908
Ganges	China 3%, India 79%, Nepal 14%, Bangladesh 4%	1,087,300	2515	407,466	375	12,037	932	716
Brahmaputra	Bangladesh 7%, Bhutan 7%, China 50%, India 36%	543,400	2840	118,543	218	21,261	5656	480

Sources: IUCN, IWMI, Ramsar Convention, WRI (2003); FAO, Aquastat (2011a; 2011b); Eriksson et al. (2009); Immerzeel et al. (2010); Molden, Vaidya, Shrestha, Rasul, & Shrestha, (2014).

high mountains, including the world's highest point, Mt Everest (8848 m asl), to the flat plains. The combination of young and fragile geology and intense monsoon rainfall leads to high rates of erosion; and the resultant sediment is deposited in the Indo-Gangetic Plain, resulting in a shifting of the position of the river channels. Most of the basin is strongly influenced by the summer monsoon with the eastern part receiving the highest rainfall. The effect of the monsoon weakens from east to west; the Koshi catchment in the east receives 72–81% of rainfall during the monsoon season (June to September) (Nepal, 2012), while the Bhagirathi and Mandakini sub-basins to the west receive only 55–65% (Molden et al., 2014; Shrestha, 2008). The headwaters area is dominated by snow, glaciers and permafrost, with precipitation in the form of snow year-round. The meltwater runoff accelerates from the pre-monsoon to the post-monsoon season.

The Brahmaputra Basin

The Brahmaputra (Yarlung Zhanbo in China; Jamuna in Bangladesh) also originates in the Himalayan mountain range, flowing east through the southern part of China into eastern India and thence to Bangladesh, where it merges with the Ganges (FAO, Aquastat, 2011b).

With the exception of the upper reaches, which lie in the Himalayan rain-shadow area, the basin is heavily influenced by the summer monsoon, with annual rainfall ranging from 1200 mm in parts of Nagaland (India) to over 6000 mm on the southern slopes of the Himalayas, with a mean annual value of 2300 mm. Some 60–70% of annual rainfall falls in the monsoon from June to September with a further 20–25% in the pre-monsoon from March through May. At least some precipitation falls as snow at elevations above 1500 m asl. The basin is characterized by high seasonal variability in flow, sediment transport and channel configuration (Goswami, 1985). Floods are quite common during the monsoon in the plains areas of India, while in the low-flow period, the river becomes a multiple-channel stream with sand bars and channels shifting back and forth between the main stream banks (FAO, Aquastat, 2011b).

Historical and projected trends in precipitation

The Indus Basin

Archer and Fowler (2004) analyzed precipitation in the upper Indus Basin from 1895 to recent times; they did not identify any significant long-term trends although they suggested a statistically significant increase in annual precipitation at several stations over the period 1961–1999, with an upward trend in winter rainfall at all stations north and south of the Himalayan divide, and a statistically significant increase in summer rainfall between 1961 and 1999 at stations north of the Himalayan divide. It was unclear whether the latter was due to increased incursions of the monsoon or a stronger influence of the westerlies. Khattak, Babel, and Sharif (2011) found no clear trends in precipitation at 20 stations in the upper Indus Basin (Pakistan) between 1967 and 2005 using non-parametric trend analysis. The difference between these results may be due to the different periods covered, different methods of trend analysis, and/or differences in the stations chosen. For example, only 8 of the 20 stations in the study by Khattak et al. (2011) are the same as in the study by Archer and Fowler (2004). Another problem is that most of the precipitation stations in the mountainous regions are located in the river valleys (Barry, 2008), where precipitation maybe lower than higher upslope due to leeward effects.

Precipitation in the upper Indus Basin is projected to increase by 25% compared to the baseline by 2046–2065, based on five general circulation models (GCMs) (for A1B scenarios) (Immerzeel et al., 2010), while Akhtar, Ahmad, and Booij (2008) projected an increase of up to 21% using data from the PRECIS high-resolution regional climate model (RCM). Rajbhandari et al. (2014) also projected an increase in precipitation over the upper part of the basin for the A1B scenario by the end of the century using PRECIS, but they projected a decrease over the lower part and thus no overall pattern for the whole basin; they also projected a decrease in winter precipitation, particularly over the southern part of the basin. Forsythe et al. (2014) also projected an increase in precipitation in the upper Indus Basin (maximum seasonal mean +27%, annual mean change +18%) using a stochastic rainfall model, with increased intensity in the wettest months (February, March and April).

The values of future climate projections depend primarily on the GCMs used as a driver. The studies by Akhtar et al. (2008), Forsythe et al. (2014), and Rajbhandari et al. (2014) all use HadCM3, which was then also used in the PRECIS RCM. All these studies predict a general increase in precipitation, although the details differ.

Overall, the analyses of past precipitation by the various authors do not indicate any significant long-term trends over the last century, but they do suggest that there has been an increase in annual and seasonal precipitation in recent decades, while the climate projection data further indicate that precipitation may increase by the end of the present century. The differences reported in the extent and distribution of changes are likely to be due to differences in methods, data periods, and sources of the climate projection data. However, a detailed review of the different approaches and methods and their strengths and weaknesses lies outside the scope of this paper.

The Ganges Basin

Singh, Kumar, Thomas, and Arora (2008) reported that historically annual precipitation in the Ganges Basin has remained stable. Other authors have reported similar findings, but with localized differences. Shrestha, Wake, Dibb, & Mayewski, (2000) found no distinct trends in precipitation in the Nepal Himalayas between 1959 and 1994. Nepal (2012), in an analysis of precipitation trends in the Koshi catchment, found an increasing trend in annual precipitation at 22 of 36 stations and a decreasing trend at 14 stations, but the results were significant at only three stations (two increasing and one decreasing). Sharma, Vorosmarty, and Moore (2000) also found localized trends in precipitation in the Koshi catchment, but they lacked basin-wide significance.

Pervez and Henebry (2014) downscaled GCM projections using the Statistical Downscaling Model for the twenty-first century. They projected an overall increase in monsoon precipitation of 12.5% and 10% over the Ganges Basin compared to baseline for the A1B and A2 emission scenarios, respectively, with a decrease during the pre-monsoon and increase during the post-monsoon seasons. Immerzeel et al. (2010) projected an 8% increase in upstream precipitation in the Ganges Basin based on five different GCMs and the A1B scenario. Agarwal, Babel, and Maskey (2014) developed projections for future precipitation in the Koshi catchment in Nepal based on 10 GCMs under three scenarios (A1B, B1 and B2). The results indicated an increase in summer, autumn and annual precipitation, but a decrease in spring precipitation. The authors cautioned that differences exist among the GCMs that are small in the near future (2020s) but become significant during mid and late century. Kumar et al. (2011) projected an increase in summer monsoon precipitation over India by 9–16% towards the end of the century compared to baseline, under warming conditions.

Overall, the various studies suggest that there has been no overall change in precipitation in the Ganges Basin over the past 50 years although localized trends have been observed. The projected data indicate that the monsoon precipitation might increase in future, although the magnitude of the projected change varies, primarily due to differences in the driving GCMs and the study domains.

The Brahmaputra Basin

Flügel et al. (2008) studied the variation in annual mean and seasonal precipitation in the upper Brahmaputra River basin from 1961 to 2005 and found a slight increase in mean annual precipitation as well as in autumn, spring and summer, but no statistically significant trends. Immerzeel (2008) also analyzed historic trends using global 100-year monthly high-resolution data for 1900–2002 and concluded that the precipitation did not show any clear trend and was mainly determined by the monsoon.

Pervez and Henebry (2014) projected an overall 12% and 16% increase in monsoon precipitation over the Brahmaputra Basin compared to baseline for the A1B and A2 emission scenarios, respectively, using the Statistical Downscaling Model, with a decrease during the pre-monsoon and increase during the post-monsoon season. They also suggested that the peak of monsoon precipitation is likely to shift from July to August, which could impact the livelihoods of a large population in the region. Immerzeel (2008) projected future precipitation based on six different GCMs and found an accelerated increase in precipitation with a greater increase over the Tibetan Plateau than over the plains areas; the increase in precipitation in summer could indicate a potential increase in extreme events.

Overall, the studies suggest that there has been no statistically significant change in precipitation in the Brahmaputra Basin over the past 50–100 years, although there is some indication of a small overall increase. The projections indicate an increase in monsoon and post-monsoon precipitation over the basin, decrease in pre-monsoon precipitation, and a shift in the timing of peak monsoon precipitation.

Historical and projected trends in temperature

The Indus Basin

The temperature trends reported in the Indus Basin are not homogeneous, with different studies showing different results (Bhutiyani, Kale, & Pawar, 2007). Fowler and Archer (2006) reported a consistent lowering of mean and minimum summer temperatures, but no consistent trend in maximum summer temperatures, between 1961 and 2000. They suggested similar results in north-west India and at lower-level stations in Nepal. Winter mean and maximum temperatures showed statistically significant increases, but winter minima showed no significant trend. Similarly, Khattak et al. (2011) also reported an increase in winter maximum temperatures between 1976 and 2005 in the upper, middle and lower parts of the Indus Basin of 1.79, 1.66 and 1.20 °C, respectively. Chaudhry and Rasul (2007) identified a significant increase in annual mean temperature in Balochistan, Punjab and Sindh Provinces in Pakistan between 1960 and 2007 of 1.15, 0.56 and 0.44 °C, respectively. They also observed an increasing but not significant trend in annual mean temperature over the mountainous areas of the upper Indus Basin, with seasonal differences. There was a rise in summer temperatures but a fall in winter temperatures, and thus an increase in the seasonal temperature range. The authors suggested that the seasonal differences resulted from relatively clearer skies than in the past, but more detailed studies of daily temperature and cloud cover would be needed to confirm this (Khattak et al., 2011). Chaudhry and Rasul (2007) carried out an area-weighted analysis of temperature trends in the upper Indus Basin using re-analyzed data from the past 100 years from the Climatic Research Unit of the University of East Anglia. The trend showed an overall gradual rise in temperature but with periods of rise and fall. The last decade of the twentieth century was the warmest ever in the northern mountainous areas, which is consistent with global trends. Bhutiyani et al. (2007) also concluded that the north-western Himalayan region has warmed significantly during the last century, at a rate higher than the global average.

Kazmi et al. (2014) generated future temperature scenarios using statistical downscaling based on HadCM3 for the A2 and B2 scenarios for Pakistan, which includes part of the Indus Basin. They projected increasing trends for minimum and maximum temperatures throughout Pakistan, particularly in the northern (Upper Indus) and south-western areas, over the three decades of 2001–2030. Similarly, Islam, Rehman, Sheikh, and Khan (2009) projected an increase in temperature in both northern and southern Pakistan under the A2 and A1B scenarios using PRECIS RCM data, with a greater increase in the north than in the south, while Akhtar et al. (2008), also using PRECIS RCM data, projected an increase in annual mean temperature of 4.8 °C by the end of the century in the upper Indus Basin. Rajbhandari et al. (2014) also looked at projected temperatures to the end of the century in the Indus Basin using PRECIS RCM data, and suggested a greater increase in warming in the upper Indus than in the lower Indus, and greater warming in winter than in other seasons.

Taken together, the studies suggest that there has been an overall gradual increase in temperature in the Indus Basin, but with some differences in the reported seasonal trends. Data for the last 100 years for the Upper Indus alone also suggest that there has been a gradual increase in temperature but with periods of rise and fall.

The Ganges Basin

Many studies have shown an increasing trend in temperature in the Ganges Basin. Shrestha, Wake, Mayewski, and Dibb (1999) reported that the maximum temperature in Nepal increased at a rate of 0.06 °C/y between 1978 and 1994, with higher rates at stations located at higher altitude, and Nepal (2012) that the maximum temperature in the Koshi catchment (a sub-basin of the Ganges) increased by 0.058 °C/y over the last four decades. Similarly, Liu and Chen (2000) reported a temperature increase on the Tibetan Plateau at a rate of 0.16 °C per decade between 1955 and 1996.

Climate modelling studies project that the temperature in the basin is likely to increase further under climate change. Immerzeel et al. (2012) projected an annual increase in temperature of 0.06 °C/y between 2000 and 2100 in the Langtang catchment in Central Nepal based on five different GCMs. Similarly, Kumar et al. (2011) projected significant warming over India towards the end of the twenty-first century.

Overall, the studies indicate that there has been a consistent increase in temperature over the last 40 years in the basin, and the projection data indicate that temperature is likely to increase further under climate change.

The Brahmaputra Basin

Flügel et al. (2008) identified an increase in average annual temperature in the upper Brahmaputra River basin of 0.28 °C per decade from 1961 to 2005, and of average winter, autumn, spring and summer temperatures of 0.37, 0.35, 0.24, and 0.17 °C per decade. All trends were significant at the 95% significance level and were observed at most of the stations investigated. Immerzeel (2008) found a temperature increase of 0.6 °C per 100 years based on the Climatic Research Unit data-set for 1900–2002, with a higher increase in the spring season.

Immerzeel (2008) projected an accelerated seasonal increase in both maximum and minimum temperatures in the Brahmaputra Basin from 2000 to 2100 based on the results of six statistically downscaled GCM models. The changes were more prominent on the Tibetan Plateau than on the flood plain and the A2 storyline showed more extreme changes in temperature than the B2. By the end of the century, the average temperature of the basin is projected to increase by 3.5 and 2.3 °C for the A2 and B2 scenarios, respectively. Dobler, Yaoming, Sharma, Kienberger, and Ahrens (2011), using the COSMO-CLM RCM for the A1B, B1 and A2 scenarios, also projected an increase in temperature in all seasons, with greater increases at higher elevation, consistent with the projections by Immerzeel (2008).

Overall, the studies suggest a consistent rise in average and seasonal temperatures over the last 50 years, and the projections indicate that the temperature will continue to rise, although the magnitudes of the projected changes differ depending on the driving GCMs.

Impact of climate change on the hydrological regime

The Indus Basin

Meltwater, which is highly sensitive to temperature change, is particularly significant for flow in the Indus Basin. Glacier melt runoff provides an estimated 40% of total streamflow in the upstream areas, and discharge generated by snow and glacier melt is 151% of the total discharge naturally generated in the downstream areas (Immerzeel et al., 2010). Singh and Jain (2006) estimated that on average snow and glacier melt contribute 59% of annual flow in the Sutlej sub-basin.

Singh and Kumar (1997) projected that an increase in temperature of 2 °C would reduce the annual snow water equivalent in the Sipti catchment (10,071 km^2) by 1–7%. They calculated an overall increase in annual snow melt runoff of 4–18%, in glacier melt runoff of 33–38%, and in total streamflow of 6–12%. Similarly, Singh and Bengtsson (2004) projected a reduction in annual snow melt runoff with a 2 °C rise in temperature in the Sutlej Basin upstream of the Bhakra Dam (22,275 km^2 for the part in India). The results indicated a slight increase during the pre-monsoon period and decrease during the monsoon season. The authors further suggested that the effect on annual water availability in the Sutlej River might not be severe, but that the seasonal distribution of streamflow would be markedly affected. The meltwater from the glaciated area was projected to increase with an increase in temperature (1–3 °C) as a result of increased melt rates and a longer ablation period, whereas the meltwater from the lower part of the basin was projected to decrease as a result of reduced snowfall. However, as suggested by Rees and Collins (2006), these results must be considered with caution. In most of the models the glacier area remains static with time and rise in temperature; thus the projections do not take into account any reduction in total glacier area arising from increased melt and/or reduced accumulation, which could lead to a reduction in glacier melt in the longer term.

Akhtar et al. (2008) analyzed the projected impact of climate change in the Hunza, Gilgit and Astore sub-basins using the PRECIS regional climate model with the SRES A2 scenario. The future scenario (2071–2100) was simulated for three stages of glacier coverage – 100%, 50% and 0% – using the HBV-Met model. The discharge values increased for the 100% and 50% glacier scenarios, and decreased drastically (by up to 94%) for the 0% glacier scenario. The HBV-Met model shows glacier melt as a major source of the river. Similarly, Immerzeel et al. (2010) studied the impact of climate change on the upstream area of the Indus Basin for 2046–2065 under the A1B scenario in five different GCMs and including the best-guess glacier scenario based on glacier mass-balance calculations. The mean upstream water supply was projected to decrease by 8.4%, with the reduction in melt runoff partly compensated for by increased upstream rainfall (+25%). In both studies, the decrease in glacier area led to a decrease in water supply from upstream areas. In a recent study by Immerzeel, Pellicciotti, and Bierkens (2013), climate projections based on the RCP emission scenarios in a dynamic glacier model were used to analyze the potential changes in glacier dynamics in the Baltoro sub-basin (upper Indus); the results showed glacier area reduced by 33% and glacier volume by 50% in 2100 (for RCP 8.5), with a peak in total glacier melt in 2044 under RCP 4.5 or 2065 under RCP 8.5, followed by a decline.

Lutz et al. (2014) investigated the impact of climate change on the hydrological regime in a large spatial domain covering the Indus, Ganges and Brahmaputra Basins using the SPHY model (a fully distributed cryospheric hydrological model) with the output from eight different GCMs which represent variations in future climate ranging from dry and cold to wet and warm. Most of the climate-model data suggested that annual runoff will increase by 7–12% by 2050, primarily due to accelerated melt in the upper Indus Basin together with an increase in precipitation. Laghari et al. (2012) also suggested that water availability might increase in the short term, but will decrease in the long term. However, the projected future hydrology depends on the precipitation projections, which have a large uncertainty and large variation between annually averaged and seasonal projections among the GCMs. Furthermore, the conceptualization of the hydrological models brings another level of uncertainty. For example, the HBV model used by Akhtar et al. (2008) is a semi-lumped model (sub-basin scale), whereas Immerzeel et al. (2013) and Lutz et al. (2014) used a high-resolution fully distributed glacio-hydrological model. The latter can simulate cryospheric processes very well, including glacier dynamics in the context of climate change.

The Ganges Basin

A number of authors have estimated the contribution of snow and glacier melt to streamflow in the Ganges Basin and selected catchment. Immerzeel et al. (2010) estimated that snow and glacier melt contributes 10% to streamflow overall in the Ganges. Siderius et al. (2013), using four different hydrological models (LPjmL, JULES, SWAT and VIC), estimated the snow melt contribution at 1–5% (at Farakka), with the difference attributed to the different model structure (elevation bands, input data) and snow melt approach, as well as exclusion of glacier melt. Similarly, Alford and Armstrong (2010) estimated the glacier melt contribution to total streamflow in various individual catchments in Nepal at between 2% and 30%, with an average of 10%; while Nepal, Krause, Flügel, Fink, and Fischer (2014b) estimated the snow and glacier melt contribution in the Dudh Koshi catchment at 34% (17% from glacier area and 17% from non-glacier area), with similar values estimated for glacier melt contribution by Alford and Armstrong (2010). Panday, Williams, Frey, & Brown (2014) estimated a snow melt contribution to streamflow of 30% in the Tamor catchment. In general, the glacier melt contribution is high in upstream areas due to the relatively small catchments and higher melt runoff, and low in the lower-elevation areas, where runoff from rainfall is much higher.

The impact of climate change on various aspects of the hydrological regime has been investigated by a number of authors. Nepal et al. (2014b) estimated that the contribution of snow melt to river flow in the Dudh Koshi catchment would decrease by 31% with a 2 °C rise in temperature, and by 60% with a 4 °C rise, changing the river from 'snow-dominated' to 'rain-dominated'. Wiltshire (2014) suggested that under a warming climate, the volume of glaciers in the eastern Himalayas (Nepal and Bhutan) will decline over the twenty-first century, despite increasing precipitation, as a result of less precipitation falling as snow as well as increased ablation. Application of the Water Balance Model in the Tamor catchment suggested an annual decrease in runoff of up to 8% for a 5 °C temperature increase (Sharma et al., 2000); however, the study did not take glacier melt into account. All these studies suggest that a rise in temperature will affect the snow melt pattern and annual runoff.

A study by Immerzeel et al. (2010) for 2046–2065 under the A1B scenario projected a decrease of 17.6% in mean upstream water supply in the Ganges Basin, with the reduction in melt runoff partly compensated for by increased upstream rainfall (+8%). Immerzeel et al. (2013) suggested that under projected climate change, the glacier area in the Langtang catchment will be reduced by 54% by the end of the century and the ice volume by 60%. Initially, net glacier melt runoff will increase, with a peak in 2045 and 2048 for RCP 4.5 and RCP 8.5, respectively, after which it will decrease. However, water availability is not likely to decline during this century as the reduction in runoff will be offset by an increase in precipitation. Lutz et al. (2014), in their investigation of the whole IGB region (see the section on the Indus), investigated the projected monthly runoff in the Koshi River basin (in eastern Nepal). They found that the runoff is likely to increase up to 2050, primarily due to an increase in precipitation in upstream areas, with the maximum increase during the pre-monsoon period, but the hydrograph remains unchanged. These studies indicate that the future reduction due to melt runoff will be offset by increased precipitation.

There are also indications of intra-annual change. Mirza et al. (2003) studied the implications of climate change for river discharge and floods in Bangladesh based on climate change scenarios from four GCMs, and concluded that the peak discharge in the Ganges River would increase substantially, leading to significant changes in extent and depth of inundation.

The Brahmaputra Basin

Immerzeel et al. (2010) estimated that the discharge generated by snow and glacier melt in the Brahmaputra Basin is 27% of the total discharge naturally generated in the downstream areas of the Brahmaputra Basin. Climate change is expected to have a significant effect on the hydrology and water resources of this basin (Immerzeel et al., 2010; Mirza, 2002). The study by Immerzeel et al. (2010) for 2046–2065 under the A1B scenario projected a decrease of 19.6% in mean upstream water supply, with the reduction in melt runoff partly compensated for by increased upstream rainfall (+25%). Prasch (2010) indicated that water availability will decrease on average, with the magnitude of the trend varying according to the chosen IPCC SRES scenario. The main reason for the decrease in streamflow was the forced input data (regional CLM climate model driven by GCM ECHAM 5 for the A2, A1B and B1 scenarios) and the increase in evapotranspiration. The model also predicted that the percentage of snowfall in precipitation will continue to decrease. Prasch, Marke, Strasser, and Mauser (2011) suggested that glacier ice melt will accelerate from 2011 to 2040 due to the increase in air temperature and longer melting periods, and that as the amount of glacier ice is reduced, ice melt will decrease. Lutz et al. (2014), in their investigation of the whole IGB region (see above), projected an increase in total runoff in the upper Brahmaputra Basin up to 2050, primarily due to an increase in precipitation and accelerated melt runoff, with the increase occurring throughout the year.

A number of authors have looked at intra-annual variation and the impact on flooding. Mirza (2002) projected a substantial increase in mean peak discharge in the Brahmaputra River (although less than in the Ganges), based on climate change scenarios from four GCMs, which could lead to more frequent flooding of different magnitudes. Ghosh and Dutta (2012) estimated an increase in both peak discharge and flood-wave duration under PRECIS (A2 scenario) projected climate change scenarios in both the pre-monsoon and monsoon seasons. The increment in peak flow in the monsoon season is likely to be greater for moderate events and smaller for extreme events with higher return periods. Gain, Immerzeel, Sperna Weiland, and Bierkens (2011) indicated that there will be a strong increase in peak flows, both in size and frequency, although dry-season conditions are likely to increase.

Discussion and conclusions

Historical and projected trends in precipitation and temperature

Taken together, the different studies indicate that there has been no consistent or statistically significant trend in precipitation overall in the upper Indus, Ganges or Brahmaputra Basins over the past 50–100 years, although localized and seasonal trends have been observed. In the Indus Basin, some stations have showed a significant increase in annual precipitation, an overall trend towards increased winter rainfall, and some indication of increased summer rainfall north of the Himalayan divide (where total rainfall is low), while in the Brahmaputra Basin there is some indication of a small overall increase. The projections indicate an overall increase in annual precipitation in all three basins under climate change scenarios, with some seasonal variation. In the Ganges and Brahmaputra Basins, monsoon precipitation is projected to increase but pre-monsoon precipitation to decrease; in the Brahmaputra Basin, post-monsoon precipitation is also projected to increase, with a shift in timing of peak monsoon precipitation.

Most authors have reported a gradual rise in temperatures over the past 40–100 years in all three basins, with some seasonal differences, although results in the upper Indus Basin were not statistically significant. Projections indicate that the temperature in all three basins is likely to increase further under climate change scenarios, with greater warming in winter in the Indus Basin.

Impact of climate change on the hydrological regime

The major findings on the projected impacts of climate change on the hydrology of the three basins and individual catchments are summarized in Table 2. Overall, in all three basins, the projections indicate a reduction in snow (and thus snow melt) and an increase in glacier melt to approximately mid-century, followed by a decrease. Although there are likely to be increased amounts of meltwater available for the next few decades, the amount might decrease abruptly thereafter as glacier storage is reduced. The exact timing remains uncertain. However, there is still considerable uncertainty in the predictions, due both to lack of sufficient baseline information on glaciers and understanding of glacier dynamics, and to uncertainties in the precipitation projections.

There are variations in glacier response and water availability in the three basins as a result of the differences in geography and influence of monsoon and non-monsoon precipitation. In the Indus Basin, changes in snow and glacier melt are projected to have a

Table 2. Projected impacts of climate change on the hydrology of the IGB basins.

River basin/catchment	Impact	Publication
Indus River basin		
Upper Indus***	Annual runoff might increase by 7–12% by 2050 due to accelerated melt with increase in precipitation	Lutz et al. (2014)
Spiti**	Decrease in annual snow water equivalent with increase in temperature	Singh and Kumar (1997)
Sutlej**	Reduction in snowfall in lower-elevation areas due to rise in temperature, and decrease in annual snow melt runoff with increase in temperature	Singh and Bengtsson (2004)
Hunza, Gilgit and Astore**	‘No glacier’ scenario might decrease discharge drastically	Akhtar et al. (2008)
Baltoro**	Glacier area reduced by 33% and glacier volume by 50% by 2100; glacier melt might peak in 2044 or 2065 and then decline	Immerzeel et al. (2013)
Ganges River basin		
Ganges*	Increase in peak flow	Mirza et al. (2003)
Ganges***	Upstream water supply might decrease by up to 17%	Immerzeel et al. (2010)
Ganges***	Runoff is likely to increase	Lutz et al. (2014)
Tamor **	Decrease in annual runoff	Sharma et al. (2000)
Langtang **	Continuous decrease in glacier area; runoff will increase to mid-century and then decrease, but reduction will be compensated by increase in precipitation	Immerzeel et al. (2013)
Koshi***	Runoff is likely to increase; hydrograph remains constant	Lutz et al. (2014)
Dudh Kosi**	Snow melt contribution will decrease substantially under 2 °C or 4 °C rise in temperature	Nepal et al. (2014b)
Eastern Himalaya***	Reduced glacier volume resulting from decreased snowfall and increased ablation	Wiltshire (2014)
Brahmaputra River basin		
Brahmaputra***	Upstream water supply may decrease by 20%	Immerzeel et al. (2010)
Brahmaputra***	Water availability may decrease on average due to increase in evapotranspiration, magnitude varies with scenario; snowfall will decrease	Prasch (2010)
Brahmaputra***	Glacier ice-melt will accelerate up to 2040 and decrease thereafter	Prasch et al. (2011)
Brahmaputra***	Substantial increase in mean peak discharge based on GCMs	Monirul Qader Mirza (2002)
Brahmaputra***	Increase in peak discharge and flood-wave duration under A2 scenario	Ghosh & Dutta (2012)
Brahmaputra***	Increase in total runoff up to 2050 due to increase in precipitation and accelerated melt runoff	Lutz et al. (2014)
Lower Brahmaputra***	Strong increase in flood peak	Gain et al. (2011)

*Micro scale: $<100\,km^2$; **meso scale: $100–10{,}000\,km^2$;***macro scale: $>10{,}000\,km^2$.

marked impact on water availability as melt runoff provides a high proportion of total streamflow, especially in upstream areas. Although there may be little change, or a small increase, in annual streamflow, there could be marked changes in seasonal distribution, with less water available in summer. The possibility of seasonal shifts in availability is particularly important for irrigation and agriculture. In the Ganges Basin, overall water availability is likely to be maintained up to mid-century as the reduction in runoff will be offset by an increase in precipitation, whereas in the Brahmaputra River basin, the projections indicate a reduction in upstream water supply. In both the Ganges and Brahmaputra Basins, differences in seasonal distribution, including increased summer (monsoon) flow, and peak runoff could result in an increased risk of flooding.

The projections of climate parameters (such as precipitation and temperature) under various scenarios of change, and of the potential impacts on the hydrological regime, which are calculated using these parameters as forcing data must be viewed with some caution as they are based on results drawn from various GCMs, and the performance of the GCMs in the Hindu Kush Himalayan region is still low. Many authors have concluded that the coarse spatial resolution of the models is a major limitation for impact assessment and suggested that the projection of future changes in extreme events in the mountainous terrain is particularly limited (Akhtar et al., 2008; Kay, Davies, Bell, & Jones, 2008). As the various scenarios show different magnitudes of change in the climate parameters, the variability in projected future hydrology is also high.

Impact on water availability

Overall, although total annual water availability may increase, at least in the short-to-medium term, the increase in hydrological extremes and shifts in seasonal peaks may to some extent counteract the benefits. For example, an increase in rainfall in the monsoon season does not necessarily increase water availability, as most of the rainfall cannot be stored in the saturated ground and becomes runoff, which may in turn contribute to increased flooding, as suggested by Nepal et al. (2014b) based on a study in the Dudh Koshi catchment in eastern Nepal.

Future outlook

The review indicates that knowledge about the impact of climate change on cryospheric processes and related melt runoff has improved over time. Previously, studies were dominated by incremental scenarios (changes in precipitation and temperature in response to certain factors) with the glacier area maintained as intact over time. With the introduction of improved GCMs and RCMs, it has become possible to apply dynamic downscaling to the model outputs. At the same time, glacier dynamics have been incorporated into the models, allowing changes in glacier area and volume under different climatic conditions to be included.

Despite this progress, the assessment of climate change impact on water resources is still subject to great uncertainty. One of the major uncertainties is the climate projection, which has a marked influence on the simulated runoff in the context of future hydrology. In addition, the application of hydrological models involves uncertainty at various levels as the models are simplified conceptualizations of a real-world system. Therefore, the results of assessments of the impact of climate change on water availability should be taken as indicative rather than absolute.

In communicating results on the impact of climate change on water resources to policy and decision makers, the uncertainties associated with the results should also be made clear. This will add value while designing adaptation strategies for different ecological zones and associated with various climate scenarios. The projections of impact on hydrology and water availability have considerable implications for policy, with clear indications of trends that will need to be addressed in future planning. The potential challenges vary from basin to basin, and within basins between upstream and downstream areas and among different catchments. In the Indus, reduction in the amount and changes in timing of meltwater could have a major impact on water availability for agriculture, and there is a strong need to develop adaptation options and improve water productivity. In the Brahmaputra and to a lesser extent the Ganges, changes in seasonal and peak flow could have a devastating impact on the highly flood-prone plains of Bangladesh, with implications for flood control, agriculture and infrastructure. Long-term changes in water availability have implications for hydropower planning, while seasonal shifts indicate the urgent need to develop appropriate adaptation options.

In future, the focus should be on improving the knowledge base so that the uncertainty can be reduced. The needs range from more detailed long-term observations of climate variables in high mountain areas, especially precipitation data that can be used to improve regional climate models and the climate projection; through improved baseline and time-series data on the extent and changes in glacier cover; to improved understanding of glacier dynamics and research into permafrost melt.

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References

Agarwal, A., Babel, M. S., & Maskey, S. (2014). Analysis of future precipitation in the Koshi river basin, Nepal. *Journal of Hydrology*, *513*, 422–434. doi:10.1016/j.jhydrol.2014.03.047

Akhtar, M., Ahmad, N., & Booij, M. J. (2008). The impact of climate change on the water resources of Hindukush-Karakorum-Himalaya region under different glacier coverage scenarios. *Journal of Hydrology*, *355*, 148–163.

Alford, D., & Armstrong, R. (2010). The role of glaciers in stream flow from the Nepal Himalaya. *The Cryosphere Discussions*, *4*, 469–494. doi:10.5194/tcd-4-469-2010

Ali, K. F., & De Boer, D. H. (2007). Spatial patterns and variation of suspended sediment yield in the Upper Indus River basin, Northern Pakistan. *Journal of Hydrology*, *334*, 368–387.

Archer, D., & Fowler, H. (2004). Spatial and temporal variations in precipitation in the Upper Indus Basin, global teleconnections and hydrological implications. *Hydrology and Earth System Sciences*, *8*, 47–61. doi:10.5194/hess-8-47-2004

Barnett, T. P., Adam, J. C., & Lettenmaier, D. P. (2005). Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature*, *438*, 303–309. doi:10.1038/nature04141

Barry, R. G. (2008). *Mountain weather and climate*. UK: Cambridge University Press.

Bhutiyani, M. R., Kale, V. S., & Pawar, N. J. (2007). Long-term trends in maximum, minimum and mean annual air temperatures across the Northwestern Himalaya during the twentieth century. *Climatic Change*, *85*, 159–177.

Bolch, T., Kulkarni, A., Kääb, A., Huggel, C., Paul, F. Cogley, J. G., … Stoffel, M. (2012). The state and fate of Himalayan glaciers. *Science*, *336*(6079), 310–314.

Chaudhry, Q. Z., & Rasul, G. (2007). Development of a mesoscale convective system over the foothills of Himalaya into a severe storm. Mountains witnesses of Global Changes. Volume 10.

Dobler, A., Yaoming, M., Sharma, N., Kienberger, S., & Ahrens, B. (2011). Regional climate projections in two alpine river basins: Upper Danube and Upper Brahmaputra. *Advances in Science and Research*, *7*, 11–20. doi:10.5194/asr-7-11-2011

Eriksson, M., Jianchu, X., Shrestha, A. B., Vaidya, R. A., Nepal, S., & Sandström, K. (2009). *The changing Himalayas impact of climate change on water resources and livelihoods in the greater Himalaya*. Kathmandu: International Centre for Integrated Mountain Development (ICIMOD).

FAO, Aquastat. (2011a). Indus River basin. Retrieved from http://www.fao.org/nr/water/aquastat/basins/indus/index.stm

FAO, Aquastat. (2011b). Ganges-Brahmaputra-Meghna Basin. Retrieved from http://www.fao.org/nr/water/aquastat/basins/gbm/index.stm

Flügel, W.-A., Pechstedt, J., Bongartz, K., Bartosch, A., Eriksson, M., & Clark, M. (2008). Analysis of climate change trend and possible impacts in the Upper Brahmaputra River Basin – the BRAHMATWINN Project. 13th IWRA World Water Congress 2008, Montpelier, France.

Forsythe, N., Fowler, H. J., Blenkinsop, S., Burton, A., Kilsby, C. G., Archer, D. R., & … Hashmi, M. Z. (2014). Application of a stochastic weather generator to assess climate change impacts in a semi-arid climate: The Upper Indus Basin. *Journal of Hydrology*, *517*, 1019–1034. doi:10.1016/j.jhydrol.2014.06.031

Fowler, H. J., & Archer, D. R. (2006). Conflicting signals of climatic change in the Upper Indus Basin. *Journal of Climate*, *19*, 4276–4293. doi:10.1175/JCLI3860.1

Gain, A. K., Immerzeel, W. W., Sperna Weiland, F. C., & Bierkens, M. F. P. (2011). Impact of climate change on the stream flow of the lower Brahmaputra: Trends in high and low flows based on discharge-weighted ensemble modelling. *Hydrology and Earth System Sciences*, *15*, 1537–1545. doi:10.5194/hess-15-1537-2011

Ghosh, S., & Dutta, S. (2012). Impact of climate change on flood characteristics in Brahmaputra basin using a macro-scale distributed hydrological model. *Journal of Earth System Science*, *121*, 637–657. doi:10.1007/s12040-012-0181-y

Goswami, D. C. (1985). Brahmaputra river, Assam, India: Physiography, basin denudation, and channel aggradation. *Water Resources Research*, *21*, 959–978. doi:10.1029/WR021i007p00959

Immerzeel, W. (2008). Historical trends and future predictions of climate variability in the Brahmaputra basin. *International Journal of Climatology*, *28*, 243–254. doi:10.1002/joc.1528

Immerzeel, W. W., Beek, L. P. H., Konz, M., Shrestha, A. B., & Bierkens, M. F. P. (2012). Hydrological response to climate change in a glacierized catchment in the Himalayas. *Climatic Change*, *110*, 721–736.

Immerzeel, W. W., Pellicciotti, F., & Bierkens, M. F. P. (2013). Rising river flows throughout the twenty-first century in two Himalayan glacierized watersheds. *Nature Geoscience*, *6*, 742–745. doi:10.1038/ngeo1896

Immerzeel, W. W., van Beek, L. P. H., & Bierkens, M. F. P. (2010). Climate change will affect the Asian water towers. *Science*, *328*, 1382–1385. doi:10.1126/science.1183188

IPCC. (2007). Climate change 2007: Impacts, adaptation and vulnerability: Working group II contribution to the fourth assessment report of the IPCC intergovernmental panel on climate change. In M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden, & C. E. Hanson (Eds.), *Assessment* (p. 976). Cambridge, UK: Cambridge University Press.

Islam, S., Rehman, N., Sheikh, M. M., & Khan, A. M. (2009). *Assessment of future changes in temperature related extreme indices over Pakistan using regional climate model PRECIS* Research Report GCISC-RR-05. Islamabad: Global Change Impact Study Centre.

IUCN, IWMI, Ramsar Convention, WRI. (2003). Water Resources Atlas. Retrieved from http://multimedia.wri.org/watersheds_2003/index.html

Kay, A. L., Davies, H. N., Bell, V. A., & Jones, R. G. (2008). Comparison of uncertainty sources for climate change impacts: Flood frequency in England. *Change*, *92*, 41–63. doi:10.1007/s10584-008-9471-4

Kääb, A., Berthier, E., Nuth, C., Gardelle, J., & Arnaud, Y. (2012). Contrasting patterns of early twenty-first-century glacier mass change in the Himalayas. *Nature*, *488*, 495–498.

Kazmi, D. H., Li, J., Rasul, G., Tong, J., Ali, G., Cheema, S. B., … Fischer, T. (2014). Statistical downscaling and future scenario generation of temperatures for Pakistan Region. *Theoretical and Applied Climatology*, doi:10.1007/s00704-014-1176-1.

Khattak, M. S., Babel, M. S., & Sharif, M. (2011). Hydro-meteorological trends in the Upper Indus River basin in Pakistan. *Climate Research*, *46*, 103–119. doi:10.3354/cr00957

Kumar, K. K., Patwardhan, S. K., Kulkarni, A., Kamala, K., Rao, K. K., & Jones, R. (2011). Simulated projections for summer monsoon climate over India by a high-resolution regional climate model (PRECIS). *Current Science*, *101*, 312–326.

Kundzewicz, Z. W., Mata, L. J., Arnell, N. W., Döll, P., Kabat, P., Jiménez, B., & … Scott, M. J. (2007). *Climate change 2007 – the physical science basis, science*. Cambridge: Cambridge University Press.

Laghari, A. N., Vanham, D., & Rauch, W. (2012). The Indus basin in the framework of current and future water resources management. *Hydrology and Earth System Sciences*, *16*, 1063–1083. doi:10.5194/hess-16-1063-2012

Liu, X., & Chen, B. (2000). Climatic warming in the Tibetan Plateau during recent decades. *International Journal of Climatology*, *20*, 1729–1742. doi:10.1002/1097-0088(20001130)20:14<1729:AID-JOC556>3.0.CO;2-Y

Lutz, A. F., Immerzeel, W. W., Shrestha, A. B., & Bierkens, M. F. P. (2014). Consistent increase in High Asia's runoff due to increasing glacier melt and precipitation. *Nature Climate Change*, *4*, 587–592. doi:10.1038/nclimate2237

Mirza, M.M.Q. (2002). Global warming and changes in the probability of occurrence of floods in Bangladesh and implications. *Global Environmental Change*, *12*, 127–138. doi:10.1016/S0959-3780(02)00002-X

Mirza, M. M. Q., Warrick, R. A., & Ericksen, N. J. (2003). The implications of climate change on floods of the ganges, Brahmaputra and Meghna rivers in Bangladesh. *Climatic Change*, *57*, 287–318. doi:10.1023/A:1022825915791

Molden, D. J., Vaidya, R. A., Shrestha, A. B., Rasul, G., & Shrestha, M. S. (2014). Water infrastructure for the Hindu Kush Himalayas. *International Journal of Water Resources Development*, *30*, 60–77. doi:10.1080/07900627.2013.859044

Nepal, S. (2012). *Evaluating Upstream-downstream Linkages of Hydrological Dynamics in the Himalayan Region*. PhD. Thesis. Friedrich Schiller University of Jena, Jena.

Nepal, S., Flügel, W.-A., & Shrestha, A. B. (2014a). Upstream-downstream linkages of hydrological processes in the Himalayan region. *Ecological Processes*, *3*(19), 1–16.

Nepal, S., Krause, P., Flügel, W.-A., Fink, M., & Fischer, C. (2014b). Understanding the hydrological system dynamics of a glaciated alpine catchment in the Himalayan region using the J2000 hydrological model. *Hydrological Processes*, *28*, 1329–1344. doi:10.1002/hyp.9627

Panday, P. K., Williams, C. A., Frey, K. E., & Brown, M. E., (2014). Application and evaluation of a snowmelt runoff model in the Tamor River basin, Eastern Himalaya using a Markov Chain Monte Carlo (MCMC) data assimilation approach. *Hydrological Processes*, *28*(21), 5337–53.

Pervez, M. S., & Henebry, G. M. (2014). Projections of the Ganges–Brahmaputra precipitation—Downscaled from GCM predictors. *Journal of Hydrology*, *517*, 120–134. doi:10.1016/j.jhydrol.2014.05.016

Prasch, M., (2010). Distributed process oriented modelling of the future impact of glacier melt water on runoff in the Lhasa River Basin in Tibet. PhD thesis. Faculty of Geosciences, University of Munich (LMU).

Prasch, M., Marke, T., Strasser, U., & Mauser, W. (2011). Large scale integrated hydrological modelling of the impact of climate change on the water balance with DANUBIA. *Advances in Science and Research*, *7*, 61–70. doi:10.5194/asr-7-61-2011

Rajbhandari, R., Shrestha, A. B., Kulkarni, A., Patwardhan, S. K., & Bajracharya, S. R. (2014). Projected changes in climate over the Indus river basin using high resolution regional climate model (PRECIS). *Climate Dynamics*, *44*, 339–357. doi:10.1007/s00382-014-2183-8

Rees, H. G., & Collins, D. N. (2006). Regional differences in response of flow in glacier-fed Himalayan rivers to climatic warming. *Hydrological Processes*, *20*, 2157–2169. doi:10.1002/hyp.6209

Sharma, K. P., Vorosmarty, C. J., & Moore, III, B. (2000). Sensitivity of the Himalayan hydrology to land-use and climatic changes. *Climatic Change*, *47*, 117–139. doi:10.1023/A:1005668724203

Shrestha, A. B., (2008). Resource Manual on Flash Flood Risk Management. Module 2: Non-structural Measures. Vol. (includes CD insert), ICIMOD, 91 pp.

Shrestha, A. B., Wake, C. P., Mayewski, P. A., & Dibb, J. E. (1999). Maximum temperature trends in the Himalaya and its vicinity: An analysis based on temperature records from Nepal for the period 1971–94. *Journal of Climate*, *12*, 2775–2786. doi:10.1175/1520-0442(1999)012<2775:MTTITH>2.0.CO;2

Shrestha, A. B., Wake, C. P., Dibb, J. E., Mayewski, P. A, (2000). Precipitation fluctuations in the Nepal Himalaya and its vicinity and relationship with some large-scale climatology parameters. *International Journal of Climatology*, *20*, 317–327.

Siderius, C., Biemans, H., Wiltshire, A., Rao, S., Franssen, W. H. P., Kumar, P., & … Collins, D. N. (2013). Snowmelt contributions to discharge of the Ganges. *Science of the Total Environment*, S93–101, 468–469.

Singh, P., & Bengtsson, L. (2004). Hydrological sensitivity of a large Himalayan basin to climate change. *Hydrological Processes*, *18*, 2363–2385. doi:10.1002/hyp.1468

Singh, P., & Kumar, N. (1997). Impact assessment of climate change on the hydrological response of a snow and glacier melt runoff dominated Himalayan river. *Journal of Hydrology*, *193*, 316–350.

Singh, P., & Jain, S. K., (2006). Snow and glacier melt in the Satluj river at Bhakra Dam in the western Himalayan region. *Journal of Hydrology*, *326*, 199–214 doi:10.1080/02626660209492910.

Singh, P., Kumar, V., Thomas, T., & Arora, M. (2008). Changes in rainfall and relative humidity in river basins in northwest and central India. *Hydrological Processes*, *22*, 2982–2992. doi:10.1002/hyp.6871

Wiltshire, A. J. (2014). Climate change implications for the glaciers of the Hindu Kush, Karakoram and Himalayan region. *The Cryosphere*, *8*, 941–958. doi:10.5194/tc-8-941-2014