Climate Change Impacts on Glacier Hydrology and River Discharge in the Hindu Kush–Himalayas

A Synthesis of the Scientific Basis

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Rising temperatures and changing precipitation patterns across the Hindu Kush–Himalaya (HKH) region resulting from climate change have an influence on water resource availability and food security for the downstream population. This review seeks to objectively assess the available evidence of the impacts of climate change on glacier hydrology and the wider implications upon water resources within the Indus, Ganges, and Brahmaputra basins. Glacier meltwater contribution to river flows is scale dependent and varies considerably across the east–west climatic zones of the HKH. For the Ganges and Brahmaputra this contribution is estimated to be significantly less than for the Indus to the west, with summer monsoon rains dominating flows from central and easterly areas, whereas meltwater remains a significant contributor to downstream flow of westerly basins, which receive most precipitation during winter. No corroborated trends exist in observed discharge for any basin, and such analyses are hindered by a lack of good-quality long-term data. Predicted increases in temperature will drive increased shrinkage of glaciers, leading to initial increases in meltwater produced, followed by subsequent declines with reduced glacier mass. The impacts of such changes are predicted to be minimal for the overall discharge of the Ganges and Brahmaputra, where increases in rainfall may in fact lead to increased flows but with greater variability. Within the Indus basin, reduced meltwater will have significant impacts upon available runoff; however, increased uncertainties surrounding precipitation and socioeconomic changes limit any conclusive assessment of how water availability will be affected; moreover, seasonality of runoff may be a more important factor. Scientific challenges and research recommendations are identified for the region. This review proposes the need for the scientific evidence pertaining to the region's glacier systems to be approached objectively in the future, such that a robust assessment of change can be attained.

Keywords: *Glacier; climate change; hydrology; water; Himalaya.*

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Introduction

Mountains are often referred to as the "water towers" of the world (Messerli and Ives 1997; Viviroli and Weingartner 2004) and many such high-altitude areas store much of this water as snow and/or ice. Heavily populated regions adjacent to the Himalayan mountain ranges are considered particularly vulnerable to the impacts of glacier retreat (Barnett et al 2005). Under climatic warming, increased melt can cause shrinkage in the overall glacier mass, providing short-term annual increases in meltwater contribution to downstream river flows. As the proportion of ice cover within a catchment decreases, the variability of river flows both between and within years will also increase, as catchment runoff is increasingly derived from contemporary precipitation (Rees and Collins 2006) and less from glacier meltwater stores.

In total, 10 major river systems find their sources in the mountainous Hindu Kush–Himalaya (HKH) region (Figure 1); 3 of these (Ganges, Indus, and Brahmaputra) are the focus of the present review. These mountainous regions of the Himalaya, Karakoram, and Hindu Kush that constitute the high-altitude sources of these 3 river systems will herein be referred to as the Himalayan region. This represents a discrete hydrological focus within the wider mountainous region referred to as the HKH, illustrated in Figure 1.

This paper provides an objective synthesis of the evidence surrounding observed and modeled changes to the runoff derived from snow and glacier melt, along with changing climate. Such an assessment informs upon the potential impacts of climate change on the water resources of these major river basins and identifies the most pressing knowledge gaps and associated future research priorities.

Regional characteristics

The Himalayan region is characterized by a diversity of climate that causes Himalayan glacier mass balance and river flow to vary considerably from west to east. The monsoon weakens from east to west, rarely penetrating as far as the Karakoram, so that summer precipitation declines in the same direction. The annual precipitation

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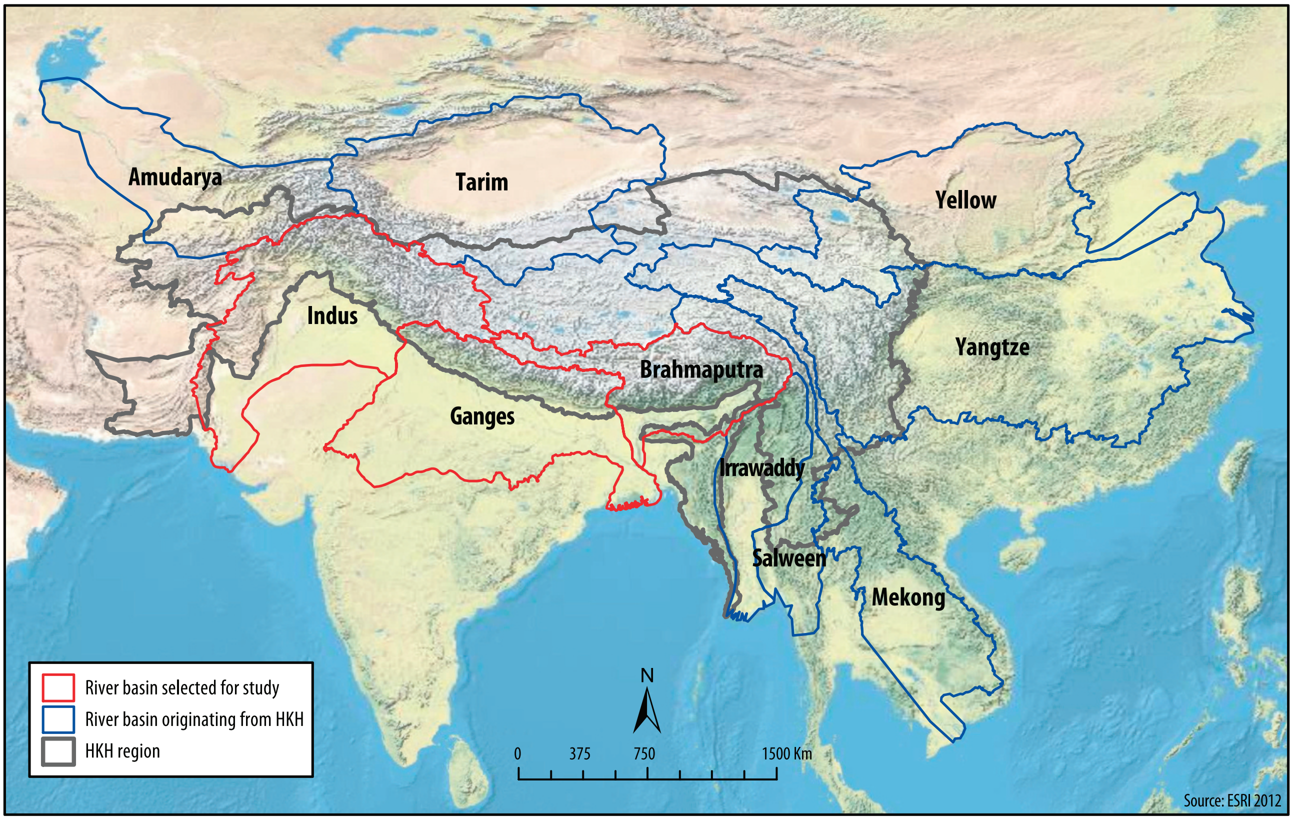
FIGURE 1 River basins formed in the high mountain HKH region, highlighting the Ganges, Indus, and Brahmaputra basins that are the focus of the present study. (Map by Hammad Gilani, courtesy of ICIMOD)



gradient ranges from over 3000 mm in the east to less than 300 mm in the more arid west (Immerzeel et al 2009). Catchments in the eastern and central Himalaya receive more than 70% of their annual rainfall in the summer monsoon period, whereas catchments to the west of the Sutlej basin receive more precipitation in winter from westerlies (Bookhagen and Burbank 2010). Glaciers, thus, experience winter accumulation and summer ablation in the west, but predominantly synchronous summer accumulation and summer melt in the east (Rees and Collins 2006).

Glaciers occupy an estimated area of 60,000 km^2 within the HKH (Bajracharya and Shrestha 2011) and approximately 44,200 km^2 within the geographical region covered in this review. There has been much discussion recently about the state and fate of glaciers in high mountain Asia (HMA) (Scherler et al 2011; Bolch et al 2012; Gardelle et al 2012; Jacob et al 2012; Kääb et al 2012). Recent reviews of all available field and remote sensing studies that quantify changes in glacier extent and mass balance in the Himalayas and the Karakoram (Miller et al 2011; Bolch et al 2012) indicate that glaciers have generally been losing mass, except in the Karakoram mountain range where there are indications of mass gain. In another study (Jacob et al 2012), data from the Gravity Recovery and Climate Experiment (GRACE) satellite mission were used to assess changes in ice volume. They estimate that during the period 2003–2007 the ice mass loss over HMA was 4 ± 20 Gt y^{-1}, roughly a factor of 10 fewer than estimated by Bolch et al (2012). A recent study (Kääb et al 2012) based on Ice, Cloud and Land Elevation Satellite (ICESat) laser altimetry provides yet another estimate of 12.8 ± 3.5 Gt y^{-1} ice mass loss, with large variation in the HMA between locations. Determining regional change from such remote observations and over short time spans has evident limitations and neglects the regional variability that can occur, such as regional anomalies found in the Karakoram (Hewitt 2011).

Changes in catchment glacio-hydrological responses/systems

For each of the 3 major catchments of the Ganges, Brahmaputra, and Indus, both the observed and model-based evidence are considered in turn to provide a systematic overview of the variability in glacio-hydrological response. This review focuses primarily upon glacier melt contributions to river flow, as lack of information on snowmelt limits subregional assessment.

Ganges Basin

Analysis of existing hydrological and glacier data with models developed for Nepalese catchments by Alford and Armstrong (2010) indicates variable glacier melt contributions to stream flow between basins, ranging from 2 to 20%, with an average of around 10%, representing 4% of the mean annual estimated outflow of Nepalese rivers. Immerzeel et al (2010) similarly find that snow and glacier melt amounts to 8.7% (snow = 5.5%, glacier = 3.3%) of the overall discharge of the Ganges River naturally generated in downstream areas. The monsoon in the humid east generates the vast majority of the river flow even at high elevations and therefore total discharge is primarily affected by monsoon rainfall (Alford and Armstrong 2010). Findings from the much smaller Din Gad catchment in the Garwhal Himalaya (Thayyen et al 2007) indicate that interannual variability in runoff is primarily driven by precipitation, but meltwater plays an important seasonal role in sustaining flows during dry periods. Applying a snowmelt model to the runoff from Dokriani Glacier, it was found by Singh et al (2006) that the contributions of rainfall and glacier melt to runoff are 13% and 87%, respectively. Recent evidence (Andermann et al 2012) also discusses the impact of transient groundwater on river flows from Nepal, finding that the volume of water through these stores is approximately 6 times higher than the glacier melt contribution.

According to Shrestha and Shrestha (2004), river flow data from large glacier-fed rivers in Nepal show annual discharge of the Karnali (1962–2000) and Sapta Koshi (1977–1995) rivers declining, whereas annual discharges from the Narayani (1963–1994) are increasing. Studying climatic and hydrological trends across the Kosi Basin of Nepal, Sharma et al (2000a) find an overall decrease in total annual discharge over the period 1947 to 1993, a pattern that was found to be more significant during low-flow periods. A similar analysis of the Bagmati River in Nepal (Sharma and Shakya 2006) finds only a decreasing trend in monsoon flows, whereas flood frequency and duration were shown to have increased over the observed period (1965–2000); the majority of this flow is attributed to a decrease in monsoon precipitation and little change in other seasons. Gautam et al (2010), however, applied hydroclimatic assessments of a small snow-fed watershed in the vicinity of Kathmandu, Nepal, finding that annual average maximum and minimum flows are increasing, validated by gauged data.

There is considerable difficulty in detecting signals of a changing climate on actual glacier meltwater contribution to river discharge because of the complexity of physical processes operating within the melt zone and access constraints limiting in situ measurements of discharge. Hydrometric data from the Garwhal Himalaya (Thayyen et al 2007) indicate decreases in glacier runoff during the 1990s, but that changing precipitation characteristics have a more significant effect on headwater runoff than a receding glacier, with contributions ranging between 2.3 and 7.5%.

Despite continued glacier shrinkage as a result of increased temperatures, the impacts of this increased melting on downstream flows is potentially negligible (Jain 2008), and discharge in higher reaches basin dependent. Sharma et al (2000b)—applying a distributed hydrological model to the Tamor Basin in eastern Nepal under a hypothetical scenario of unchanged land use and precipitation pattern—showed a 5°C temperature rise could result in a 9% decrease in average annual runoff. In the Langtang Khola basin in Nepal (Fukushima et al 1991; Braun et al 1993) increased summer discharge of between 50–100% was shown for a 2°C temperature increase. A more wide-scale study by Mizra (1997) found that there is inevitable variability between subbasins, but that increases in the mean annual runoff are expected in all subbasins considered.

Projected increases of 5% in mean annual runoff by 2070–2100 for the Ganges were found by Arora and Boer (2001), but the approach assessed only changes to the meteorological variables, not considering changes to the cryosphere. Immerzeel et al (2010) projected runoff changes in 2050 for the entire upstream area with an elevation higher than 2000 masl, and in the most likely scenario a decrease in mean runoff of 17.6% was projected, a combined result of a decrease in precipitation and glacier melt. However, in small high-altitude catchments a contrasting pattern was projected (Immerzeel et al 2012). Modeling of catchments along the profile of the Ganges by Rees et al (2004) revealed that changes in proportions of glacier cover in upstream areas would have an impact upon flows in headwater catchments, with increases in mean flow during the first decades followed by subsequent decreases, while downstream the impacts were barely noticeable. Such conclusions are corroborated by other studies (Jain 2008).

Indus Basin

The Indus river regime is affected by a range of stratified climatic zones, from high-altitude catchments with large areas covered by glaciers controlling runoff via seasonal temperature input, to mid-altitude catchments with summer flow dominated by preceding winter precipitation, to foothill areas predominantly controlled by rainfall both in winter and in the monsoon season (Archer 2003). Snow and glacier melt is considered the primary driver of the hydrological regime (Mukhopadhyay and Dutta 2010). Modeling of the Upper Indus by Immerzeel et al (2010) indicated that some 34% of total stream flow in this area is generated by snowmelt, 26% from glacier melt, and such findings are corroborated by Bookhagen and Burbank (2010)—both indicating regimes that are hugely sensitive to temperature changes. Using the normalized melt index to quantify meltwater importance, Immerzeel et al (2010) indicated that Indus flow generated from snow and glacier melt is 151% greater than flow generated in downstream areas. However, observed data can suggest variable patterns, with Winiger et al (2005) suggesting that some 70% of annual runoff entering the plains is derived from seasonal monsoon rains in the lower parts, and Singh and Bengtsson (2005) finding that the relative average annual contribution of snow and glacier melt on the River Chenab at Akhnoor is 49%. Observed data are thus contrary to more popular concepts of snow and glacier melt being the primary driver of downstream river flows.

Bhutiyani et al (2008) find a statistically significant decrease in the observed average annual and summer monsoon discharge data from the River Sutlej in the western Himalaya over the period 1922–2004. Similar trends in decreasing discharge and sediment loads have been observed by Tahir et al (2011). Khattak et al (2011) find positive runoff trends during winter and spring, with negative trends during summer, explained by winter warming, which produces earlier melt and reduced rainfall during summer. All such assessments are complicated by the extensive storage and irrigation network in place upstream of areas for which gauged data are available.

Impacts of declining glacier mass on river discharge as a result of climate change will be more substantial in the Indus basin because of the high proportion of discharge derived from meltwater (Rees and Collins 2006). Assessing the sensitivity of the Sutlej River basin to climate change, Singh and Bengtsson (2004) found that 2 main features exist in a warmer climate: first, that melt contributions from lower parts are reduced because of decreased snow cover and a shorter melting season; second, that in upper glacierized areas there is increased melt because of an extended ablation period. Seasonal stream flow indicates a reduction in all seasons except spring, and overall this was found to result in a decrease of 4–6% in average annual runoff. Singh and Bengtsson (2004) suggested that temperature increases of 1–3°C would reduce snow melt by 11–23% in the Sutlej basin, but also indicated an increase in glacier melt by 16–50%.

Hydrological modeling of the upper Indus basin using the snowmelt runoff model by Immerzeel et al (2009) found that regional warming is affecting the discharge in the basin because of accelerated melting of glaciers. Under Special Report on Emission Scenarios (SRES) A2 scenario for 2071–2999, using Providing REgional Climates for Impacts Studies (PRECIS) regional simulation output, with an assumed 50% decrease in glacier area, total glacier runoff was shown to reduce by 22%; however, this was offset by increases in rainfall by 53%, resulting in total runoff increases of 7%. Late-spring and summer flows are expected to decrease significantly by around 2050 and in subsequent decades (Immerzeel et al 2010). Detailed modeling of climate change impacts in the upper Indus basin (Akhtar et al 2008) indicates that discharge under an SRES A2 scenario for 2071–2100 will increase for models assuming 50–100% glacier coverage, but reduce substantially under 0% coverage. Rees et al (2004) show clear differences in the modeled impacts of temperature increases in the west compared with more easterly areas, with flows in the Indus increasing by 14–90% compared to mean baseline flows in the first decade simulated, subsequently followed by decreasing flows until the 10th decade, when flows reach between −30% and −90% of baseline flows.

Brahmaputra Basin

An average monthly hydrograph of daily discharge data from the Bahadurabad gauging station in Bangladesh, for the period 1956–1993, indicates that generally discharge relates to rainfall, with a 1-month lag time, and that there is no visible spring contribution from glacier and snowmelt (Immerzeel 2008). The same study concludes that glacier melt is not a significant component of downstream discharge in the Brahmaputra. Such findings are validated by a more recent study indicating that meltwater from snow and glaciers amounts to 21% of the total discharge generated in downstream areas, and that less than 19% of this meltwater is generated from glaciers (Immerzeel et al 2010). The lack of observed data, however, at higher reaches in particular, limits validation of the hydrological responses discussed.

Comparatively less research into the impacts of climate change on the glacier hydrology and discharge exists for the Brahmaputra basin compared to the Indus or Ganges. Rees et al (2004) found that, in the headwaters, there was a general decrease in decadal mean flows for all temperature scenarios, mainly a result of decreasing snow cover. The predicted decreases accord well with the recent findings of Immerzeel et al (2010), who mention a 19.6% decrease in flow from the upper Brahmaputra basin for the period 2046–2065. A detailed analysis of changes to downstream river flows, using discharge-weighted ensemble inputs from 12 global climate models (GCMs), was conducted by Gain et al (2011). For both scenarios (A1B and A2) average flow and low flow are projected to increase in size, and peak flows are expected to have large increases. Despite the fact that there is considerable uncertainty in predicting changes to the South Asian monsoon, all GCMs were found to indicate an increase in discharge in the lower Brahmaputra River owing to a projected increase in precipitation downstream.

Scientific challenges and recommendations

The studies reviewed in this paper and the science related to assessing climate change impact on water resources are subject to a cascade of uncertainty that is currently insufficiently quantified, and scientific focus should be on reducing these uncertainties. All these uncertainties together result in a rather wide bandwidth regarding the potential impact of climate change on the region's water resources. The HKH is a complex region and a number of specific recommendations to reduce the uncertainty in water resources impact studies can be made and prioritized as follows:

- Improve the poorly defined distribution of precipitation data in high-altitude catchments;
- Quantify the spatial variation in glacial and snowmelt;
- Monitor and derive detailed patterns of current and future stream flow;
- Include a range of contemporary downscaled climate models across different emission scenarios in hydrological impact models;
- Improve glacio-hydrological model quality;
- Develop research into permafrost melt contributions to downstream runoff.

These recommendations are but a few of the scientific research priorities required to better understand how the region's hydrology is changing and what the impacts are on water availability, among others. However, such research must also consider the utility of such science and how to communicate and engage with stakeholders, especially to ensure sustainable scientific research programs. Viviroli et al (2011) provide more comprehensive recommendations for research required to inform policy and water management in the HKH and many other high-mountain environments around the world.

Discussion and conclusions

The evidence clearly indicates that glacier shrinkage and the relative contribution of glacier melt to the region's river discharge are lower than reported in the Fourth Assessment Report (Intergovernmental Panel on Climate Change [IPCC] 2007). However, there are clearly corroborated impacts of continued glacier shrinkage on the water resources of these various basins, but the impacts must be framed within an appropriate spatial and temporal reference. The available evidence comes from observed gauge data, remote sensing, and hydrological modeling studies and does not provide equal coverage between the catchments. The most striking features resulting from this synthesis are:

- There is corroborated evidence that, in the short term, a reduction in glacier mass from increased temperatures will lead to an increase of meltwater into the receiving river, but with prolonged glacier shrinkage there will be a correlated reduction in contribution over time.
- From the minimal evidence on river discharge trends that exists, there does not seem to be a corroborated change in the discharge from the Upper Indus basin; moreover, variable patterns linked to the monsoon rainfall are noted in the Ganges, and there is little observed evidence for the Brahmaputra from which to make such assessments.
- Glaciers to the east feeding the Ganges and Brahmaputra do not provide a significant contribution to downstream total annual discharge. This is primarily because of the fact that monsoon rains coincide with the warmest temperatures at higher altitudes, with the contribution from glacier meltwater at such time insignificant compared to the volume of runoff generated by rainfall. The relative contribution to flow does, however, increase nearer to the glacier source and during spring and dry periods, while also varying considerably between subbasins.
- Models suggest that glaciers to the west provide a significant contribution to annual discharge in the lower reaches of the Indus, because of weaker monsoon rains and greater aridity at lower altitudes, whereas the limited observed data can indicate otherwise. River basins in the western parts of the region are highly sensitive to climate change because the basins are drier and less influenced by monsoon rainfall. The relatively higher dependence on meltwater is due to the large glacierized fraction and persistent snow cover in the large expanses at higher altitudes, providing meltwater stores during the warmer seasons that do not receive the same level of summer monsoon rains as towards the east.
- Predicted—but uncertain—increases in rainfall as a result of climate change will likely drive higher annual discharge in the river Ganges, whereas reductions to glacier mass will have negligible effects on the total annual discharge of the Ganges. Thus, it is unlikely that the Ganges will become a seasonal river and that the impact of reduced meltwater from glaciers on annual average downstream flows will likely be negligible, contrary to more alarmist claims.

- Increased glacier melt as a result of climate change will provide short-term increases in the contribution to discharge of the Indus River, but is likely to lead to decreases in the future, as potential meltwater stores will diminish. There is, however, uncertainty in how these decreases will be offset by changing rainfall. The seasonality of the runoff from glacier and snowmelt may be a more important factor, with evidence indicating that a change in timing due to increasing temperatures or decreased winter precipitation could have significant downstream impacts in spring.
- Increased snow and ice melt in the headwaters of the Brahmaputra are expected to lead to long-term decreasing discharge, but will be offset by increased rainfall in lower reaches—leading to an overall increase in the downstream annual and mean peak discharge.

Overall we conclude that the evidence from the Himalayan region indicates that the HKH is undergoing changes in the cryosphere as a result of climate change, but the patterns of change, and their impacts, are by no means uniform across the region. Glacier melt contribution is scale dependent and will vary considerably between basins in high mountain areas of the Himalaya, and meltwater contribution to river discharge varies considerably across the diversity of hydroclimatic conditions and scales considered that exist across the Himalayan headwater regions.

Fundamentally, it is the lack of observed data on glacier melt, precipitation, and river discharge in upper reaches that limits rigorous analysis of change. Uncertainty in the predictive ability of GCMs and the response of glaciers to temperature increases further limits the confidence that can be ascribed to modeling of future change. Climate models consistently project an increase in temperature over the coming decades, whereas for precipitation the models show less agreement, but the general direction of change is that precipitation will increase consistently with an acceleration of the hydrological cycle.

Whether a basin will face an increase or a decrease in water availability depends mostly on the magnitude and direction of the change in precipitation and the scale being considered. These may well be much stronger determinants than the presence of glaciers and require detailed assessment of scenarios being generated for the fifth assessment report of the IPCC.

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