An assessment of the potential impacts of climatic warming on glacier-fed river flow in the Himalaya

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Abstract A regional hydro-glaciological model has been developed to assess the potential impacts of climatic warming on glacier-fed river flows in the Indus and Ganges basins. The model, applied at a 20 km × 20 km grid resolution, considers glaciers contributing runoff to a cell as a single idealized glacier that is allowed to recede through time. Using 1961–1990 climate data as input, "baseline" flow estimates were derived for every stretch of river in either basin. A transient warming scenario of +0.06°C year^{-1} was then imposed for 100 years from an arbitrary start-date of 1991. Comparison of results at 10 sites in two representative areas suggest the impacts of such climatic warming are similar regionally, with estimates of future decadal mean flows continually increasing at 1–4% per decade, relative to baseline, at most sites considered. Flows peaked at only two of the sites several decades into the model run.

Key words regional hydro-glaciological model; climatic warming; river flow; Himalaya

INTRODUCTION

Mountain glaciers are considered sensitive indicators of climate change, and measurements taken over the last century reveal a "general shrinkage of mountain glaciers on a global scale" (Haeberli *et al.*, 1999). In the Himalayan region, there is particular concern about glacier recession because of the potential consequences downstream for the 500 million inhabitants of the Indus, Ganges and Brahmaputra basins, as river flows are first expected to increase but then decline. It has been said that Himalayan glaciers will vanish within 40 years, leading to drastic reductions in river flow and widespread water shortages (Pearce, 1999; WWF, 2005).

There have been few studies of the impact of climatic warming on glacier-fed river flows in the Himalaya (e.g. Singh & Kumar, 1997*a*; Singh & Bengtsson, 2005; Sharma *et al.*, 2000). Most have involved the application of models in specific catchments where instantaneous step-changes in temperature were imposed for simulation periods of less than a decade, with glacier dimensions time-invariant. Climatic warming is, however, progressive and glacier volume and area change continually. The intensive data requirements of many of the models, together with their inability to consider transient conditions, preclude their application at a broad, regional-scale over longer timescales. A simple temperature-index-based hydro-glaciological model was therefore developed with a view to assessing, in a region where data measurements are sparse, how gradual changes in climate will affect glacier-fed river flows. The model, applied at a 20 km × 20 km grid-resolution, considers glaciers contributing to runoff in a cell as a single generic glacier whose dimensions are allowed to vary through time. Designed for glaciers in recession, the model generates estimates of long-term variation in river flows, as glacier thickness and area deplete.

The model was applied separately to the entire Indus and Ganges river basins, first with standard-period (1961–1990), or "baseline", climate data, and, then, with a transient climatic warming scenario of +0.06°C year^{-1} for a period of 100 years from an arbitrary start-date of 1991, with precipitation maintained at baseline levels. Estimates of future decadal mean flow were derived by routing the runoff generated in each 400 km^2 grid-cell through a digital elevation model (DEM). These were combined with similarly derived baseline flow estimates to provide estimates of future proportional changes in mean flow for every stretch of river in either basin. Results from 10 sites in two representative areas in the upper reaches of the two basins were analysed to show how the impacts of climatic warming on glacier-fed river flows might vary regionally.

THE HYDRO-GLACIOLOGICAL MODEL

The regional hydro-glaciological model developed in this study was a conceptual, physically-based semi-distributed model, in which the relevant river basin was subdivided into grid-cells at a

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20 km × 20 km resolution. Runoff is calculated for each cell independently. The model comprises: a rainfall–runoff model, operating in the ice-free portion of the cell; a glacier-melt model for estimating melt from glaciers; and a snowpack module, to represent the accumulation and melting of snow.

Rainfall–runoff model

Each grid-cell was subdivided into 20 equal-height elevation bands, and the distribution of cell area between bands was allocated according to the Generalized Pareto Distribution, in which the shape and scale parameters were defined by the mean, minimum and maximum elevation of each 20-km cell, as described by the HYDRO1k DEM (USGS, 2001). The model runs at a daily time step, and requires, as input to each cell, daily values of precipitation, potential evaporation and temperature. These were derived by disaggregation of the 1961–1990 standard-period 0.5° global mean monthly climatology from Climatic Research Unit (CRU; New *et al.*, 2000). The input data were further adjusted for elevation within cells using lapse rates. Precipitation increased linearly (P_{lapse}) by 50 mm 100 m^{-1} year^{-1} within a specified elevation range of 2500–5000 m ($zadj_{min}$, $zadj_{max}$) in the Indus, and by 90 mm 100 m^{-1} year^{-1} from 1500–4000 m in the Ganges. Outside these ranges, precipitation remained constant. An air temperature lapse rate (T_{lapse}) of –6°C km^{-1} was applied in each band. Precipitation in a band was considered to fall as snow when the air temperature of the band ($T_{snow\text{-}rain}$) was ≤ +2°C. Daily runoff generated was aggregated at runtime to provide estimates of annual and seasonal runoff for each cell.

The rainfall–runoff calculations are based on the Probability Distribution Model (PDM) (Moore, 1985). Runoff from both rainfall and snowmelt in each band were routed through two parallel storage reservoirs, representing rapid runoff and baseflow. Daily runoff from a band was calculated as the sum of the water released from both stores each day, and cell runoff as the sum of the area-weighted runoff from all bands.

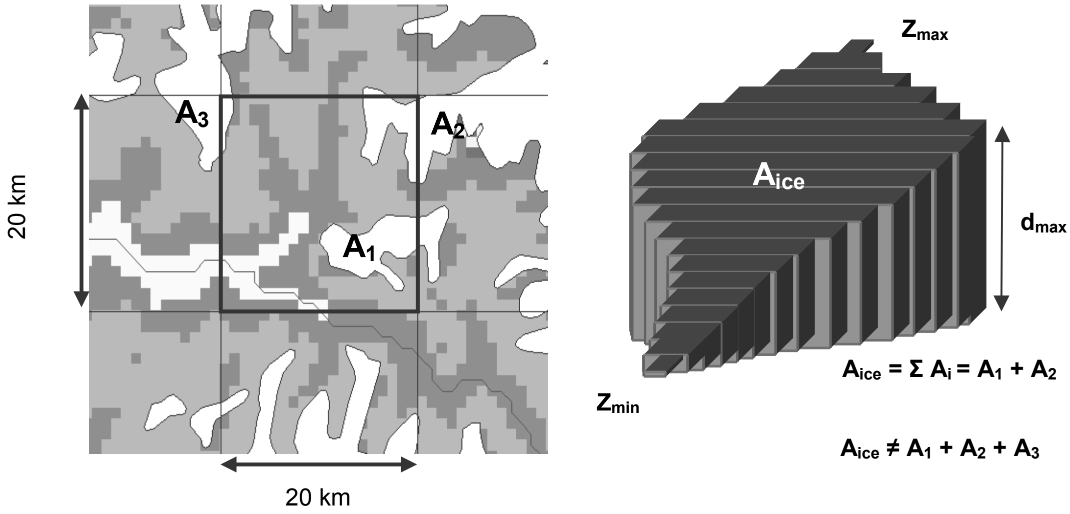
Snowpack module

Accumulation and melting of snow in an elevation band was represented in the snowpack module by a dry- and wet-store in series (Bell & Moore, 1999). New snowfall was added to the dry-store. Melt from the dry- enters the wet-store when daily air temperature for a band exceeds 0°C (T_{melt}), at a rate of 4 mm C^{-1} day^{-1}, the degree-day factor for snow (DDF_{snow}). Rain on snow contributes directly to the wet-store. Daily release from the wet-store is proportional to the water depth in the store.

Glacier-melt model

The model assumes that the meltwater contribution from a glacier can be adequately estimated by representing the glacier generically, as having an idealized shape and depth. In this study, glaciers contributing runoff to a 20-km cell (i.e. those with the terminus falling within a cell) were considered as a single "generic" glacier. The total surface area of contributing glaciers, obtained from the Digital Chart of the World (DCW) (ESRI, 1993), defines the initial surface area of the generic glacier (Fig. 1). Each generic glacier was given a simple shape and depth profile, described by 20 contiguous rectangular prisms, or "ice-bands". The horizontal elevations of the top surfaces of the ice bands were arranged at regular intervals between the minimum and maximum elevations of the generic glacier, which were determined as the minimum and maximum elevations, respectively, of all contributing glaciers. A wedge-shaped depth profile was assumed for the *thalweg* of each generic glacier, with a nominal minimum depth of 25 m set at both extremes and a maximum thickness halfway up the glacier. The maximum thickness varied according to the glacier's area, up to a maximum of 250 m (Liu & Ding, 1986). The area of each ice-band was defined according to a pre-defined shape profile that was considered typical of alpine valley glaciers.

Uniquely, the glacier-melt component allows the surface area of the generic glacier to reduce according to the prescribed geometry as the receding ice thins. The snowpack module was applied to ice-bands whenever daily precipitation fell as snow or if snow remained in a band. Ice-melt occurred in a band only when ice was exposed (i.e. when the snowpack dry- and wet-store were



(a) (b)

Fig.1 Defining a generic glacier: (a) identify contributing glaciers from DCW (polygons) and HYDRO1k (shaded); (b) conceptual representation of the glacier

both empty) and the air temperature at that elevation was >0°C. Ice-melt was calculated using a degree-day factor for ice (DDF_{ice}) of 12 mm °C^{-1} day^{-1}. Total discharge from the glacier was the sum of the runoff generated from all ice-bands. Once ice-depth depleted to zero the rainfall–runoff model was activated to calculate generate runoff in a band. At the end of each calendar year, accumulated snow was redistributed uniformly as ice over the remaining ice-bands.

MODEL APPLICATION

Baseline flows and model calibration

The model was applied in both basins at the daily time-step for a 10-year period using the CRU 1961–1990 climatology. The daily runoff output (mm) was aggregated at run-time to give estimates of standard-period average annual runoff for each cell. The runoff grids were then converted to river flows (m^3 s^{-1}) in GIS: the grids were first re-sampled to a 1-km resolution and overlaid onto the HYDRO1k flow-direction grid to derive a flow-accumulation grid; the accumulated average annual runoff of every 1-km cell was then converted to provide a grid of baseline mean flow in each basin.

Key model parameters were calibrated by an iterative process of comparing modelled baseline flows, derived from a variety of sensible parameter settings, with discharge measurements for 40 gauging stations in either basin (from Archer, 2003, and DHM, 1998). The aim of the calibration was not to achieve absolute accuracy for any particular catchment but simply to ensure that reasonably realistic estimates of flow were generated by the model. The final chosen parameter values, as stated in the previous section, were consistent with published data (e.g. Singh & Kumar, 1997*b*) and gave mean bias errors for modelled average annual runoff of +6% in the Upper Indus (no. 11, bias range: –47% to +93%, standard deviation: 38%) and –2% in the Upper Ganges (no. 29, bias range: –41% to +87%, standard deviation: 29%).

Climatic warming scenario

Next, the model was applied in both basins for 100 years from an arbitrary start-date of 1991 with a transient climatic warming scenario of +0.06°C year^{-1} applied, but maintaining standard period precipitation. This scenario is realistic against reported values of +0.06 to +0.12°C year^{-1} in Nepal (Shrestha *et al.*, 1999). Daily runoff outputs were aggregated at run-time to provide estimates of average decadal runoff for each 20-km cell in the respective basins. These too were converted to provide ten 1-km grids of decadal mean flow. A comparison of how flows vary from decade to decade, relative to baseline, could thus be made by overlaying the decadal flow grids onto the baseline flow grid. Resulting grids express future changes as a percentage (%) of baseline.

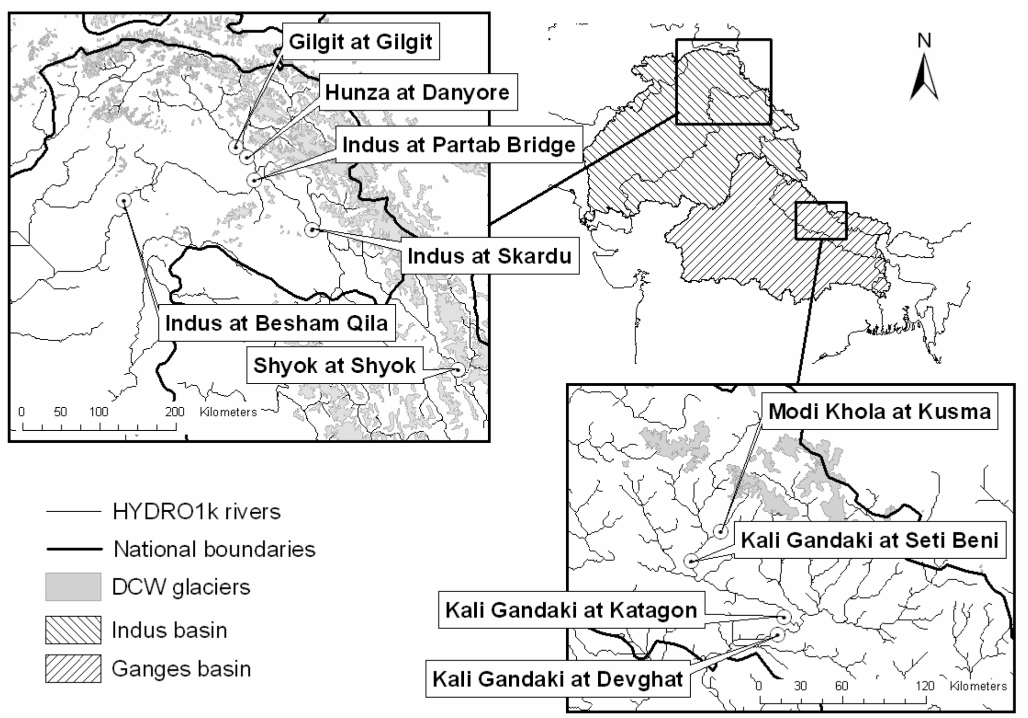


Fig. 2 Kali Gandaki and Upper Indus focal areas.

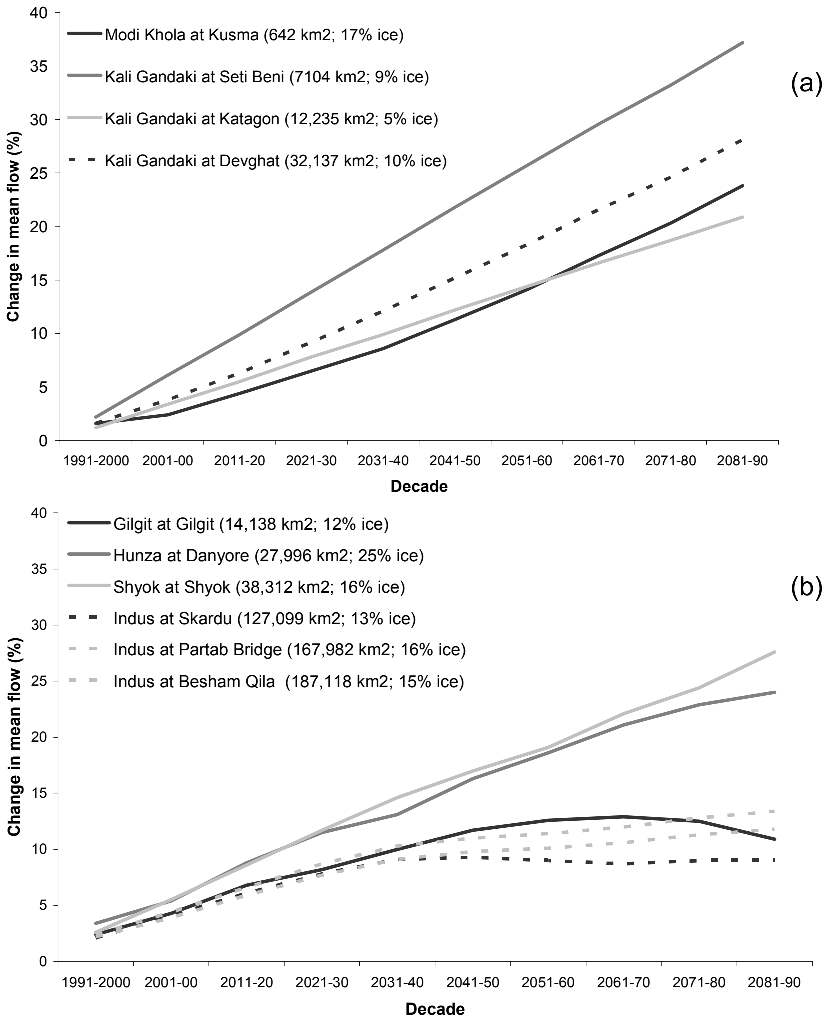


Fig. 3 Changes in decadal mean flows, relative to baseline, in the (a) Kali Gandaki and (b) Upper Indus basins.

RESULTS ANALYSIS

To assess the regional impact of glacier retreat on future river flows, changes in decadal mean flows were studied at 10 separate locations in two representative focal areas: the Upper Indus; and the Kali Gandaki River in the Upper Ganges in Nepal (Fig. 2). Under climatic warming, river flows in glacier-fed catchments are expected to show initial increases, as the area of exposed ice increases with rising temperature, followed, ultimately, by a reduction, once ice area begins to diminish. Model results from the two focal areas (Fig. 3) show decadal mean flows continually increasing at most sites at rates of around 1–4% per decade, relative to baseline, over the 100-year model run. Flows appear to peak at two of the sites in the Upper Indus only: for the Gilgit River at Gilgit, at about +13% of baseline in decade 2061–1970, and for the Indus River at Skardu, at +9.3% of baseline in decade 2041–1960. The results suggest that, under this particular warming scenario and for all but two of the selected catchments, headwater glaciers are exposed at a rate which exceeds that of ice area loss (due to recession) at their termini for the entire period, such behaviour being sustained by a sufficient volume of ice at high elevation. Different rates of flow increases reflect local variations in precipitation, the proportion of glacial ice within catchments, and the distribution of the ice with elevation. For the Indus at Skardu and the Gilgit at Gilgit, peak flows denote the moment the rate of ice loss from headwater glacier termini exceeds the rate at which ice is being exposed at higher elevations; flows reduce thereafter as ice area declines.

CONCLUSIONS

Developing an understanding of how glacier-fed rivers respond to climatic warming is difficult in the Himalaya because little is known of the hydrology and glaciology of the region and records of mountain climatic variables and runoff are sparse and short. To overcome this problem a simple temperature-index based macro-scale hydro-glaciological model was developed with parameter values consistent with the literature. Comparison between the observations and baseline model output show reasonably realistic estimates of mean flow being obtained, suggesting that the model provides an adequate basis for assessing the potential impacts of climatic warming. However, there is scope for improving the model, such as, through the use of more representative input data, better characterization of ice with elevation, and improved interpretation of glacier dynamics. Sensitivity analyses for the major parameters would also improve confidence in the forecasts, and may also have effect the timings and scales of river responses. Despite this, the results were plausible and indicated that the impacts of climatic warming on glacier-fed river flows are broadly similar across the region, with the feared widespread water shortages appearing unlikely for many decades.

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