Consistent increase in High Asia's runoff due to increasing glacier melt and precipitation

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Rivers originating in the high mountains of Asia are among the most meltwater-dependent river systems on Earth, yet large human populations depend on their resources downstream[1]. Across High Asia's river basins, there is large variation in the contribution of glacier and snow melt to total runoff[2], which is poorly quantified. The lack of understanding of the hydrological regimes of High Asia's rivers is one of the main sources of uncertainty in assessing the regional hydrological impacts of climate change[3]. Here we use a large-scale, high-resolution cryospheric–hydrological model to quantify the upstream hydrological regimes of the Indus, Ganges, Brahmaputra, Salween and Mekong rivers. Subsequently, we analyse the impacts of climate change on future water availability in these basins using the latest climate model ensemble. Despite large differences in runoff composition and regimes between basins and between tributaries within basins, we project an increase in runoff at least until 2050 caused primarily by an increase in precipitation in the upper Ganges, Brahmaputra, Salween and Mekong basins and from accelerated melt in the upper Indus Basin. These findings have immediate consequences for climate change policies where a transition towards coping with intra-annual shifts in water availability is desirable.

In general, the climate in the eastern part of the Himalayas is characterized by the East-Asian and Indian monsoon systems, causing the bulk of precipitation to occur during June–September (Supplementary Fig. 4). The precipitation intensity shows a strong north–south gradient caused by orographic effects[4]. Precipitation patterns in the Hindu Kush and Karakoram ranges in the west are characterized by westerly and southwesterly flows, causing the precipitation to fall more equally distributed over the year[5] (Supplementary Fig. 4). In the Karakoram, up to two-thirds of the annual high-altitude precipitation occurs during the winter months[6,7]. In addition, basin hypsometry determines the ratio of solid and liquid precipitation within a basin. Solid precipitation can be stored long-term as perennial snow, and ice or short-term as seasonal snow before turning into runoff by melting, whereas liquid precipitation runs off directly. Each of these runoff components can be further delayed by infiltration into the soil and recharge to groundwater. The magnitude of the contribution of each of these runoff components to the total runoff determines a basin's runoff composition and to a large extent also its response to climate variability and change.

Climate change impact assessments are characterized by large uncertainties stemming from large variation in climate change projections between different general circulation models[8] (GCMs), large regional variation in climate projections and uncertainties in the associated response of the cryosphere[9,10]. In addition, the present-day hydrological regime is not well understood, constituting a major source of uncertainty in the assessment of climate change impact for hydrology in High Asia. Thus, detailed and comprehensive assessments of the future water availability in the region are only possible once the present hydrological regime is better quantified[3].

Although methods to quantify meltwater contribution exist, high-resolution modelling studies focus on small-scale watersheds[11]. High-resolution approaches that explicitly simulate ice dynamics, necessary to simulate the transient response to climate change, are even scarcer[12]. On the other hand, large-scale assessments in the region are often qualitative[2,13] or include crude assumptions and simplifications to simulate the response of the cryosphere to climate change, which cannot be resolved at low resolution[1,14–16]. In this study we close this scale gap by implementing a large-scale modelling approach at such a resolution that allows accurate simulation of key hydro-cryospheric processes. Only by using a distributed hydrological modelling approach incorporating transient changes in climate, snow cover, glacier dynamics and runoff, appropriate adaptation and mitigation strategies can be developed[17].

Here we use a fully distributed, high-resolution cryospheric–hydrological model (Supplementary Methods and Data) to assess upstream runoff composition in five major Asian river basins (Fig. 1) and we demonstrate how runoff composition and total runoff volume are expected to change until 2050 by forcing this model with an ensemble of the latest GCM outputs.

In the upper Indus Basin (UIB), stream flow is dominated by glacier melt water, contributing 40.6% of the total runoff (Fig. 1 and Supplementary Table 3). Despite its larger relative glacierized area, glacier melt contributes only 11.5% of the total runoff generated in the upper Ganges Basin (UGB). Owing to the monsoon-dominated precipitation regime in the UGB, the runoff regime is rain dominated here (Fig. 1 and Supplementary Table 3). The hydrological regime in the upper Brahmaputra Basin (UBB) is comparable to the UGB, although the relative contribution of glacier melt and snow melt in the UBB is slightly larger compared with the UGB. This can be explained by the differences in hypsometry of these basins (Supplementary Table 4), with the UBB having a larger portion of its area at higher elevations, favouring solid precipitation in this basin. Rainfall runoff is the dominant component in the upper Salween Basin (USB) and upper Mekong Basin (UMB). Notable, however, is the large contribution of seasonal snow melt in these basins, compared with the three other basins (Figs 1 and 2), because large parts of these basins are located on the Tibetan Plateau (Supplementary Table 4).

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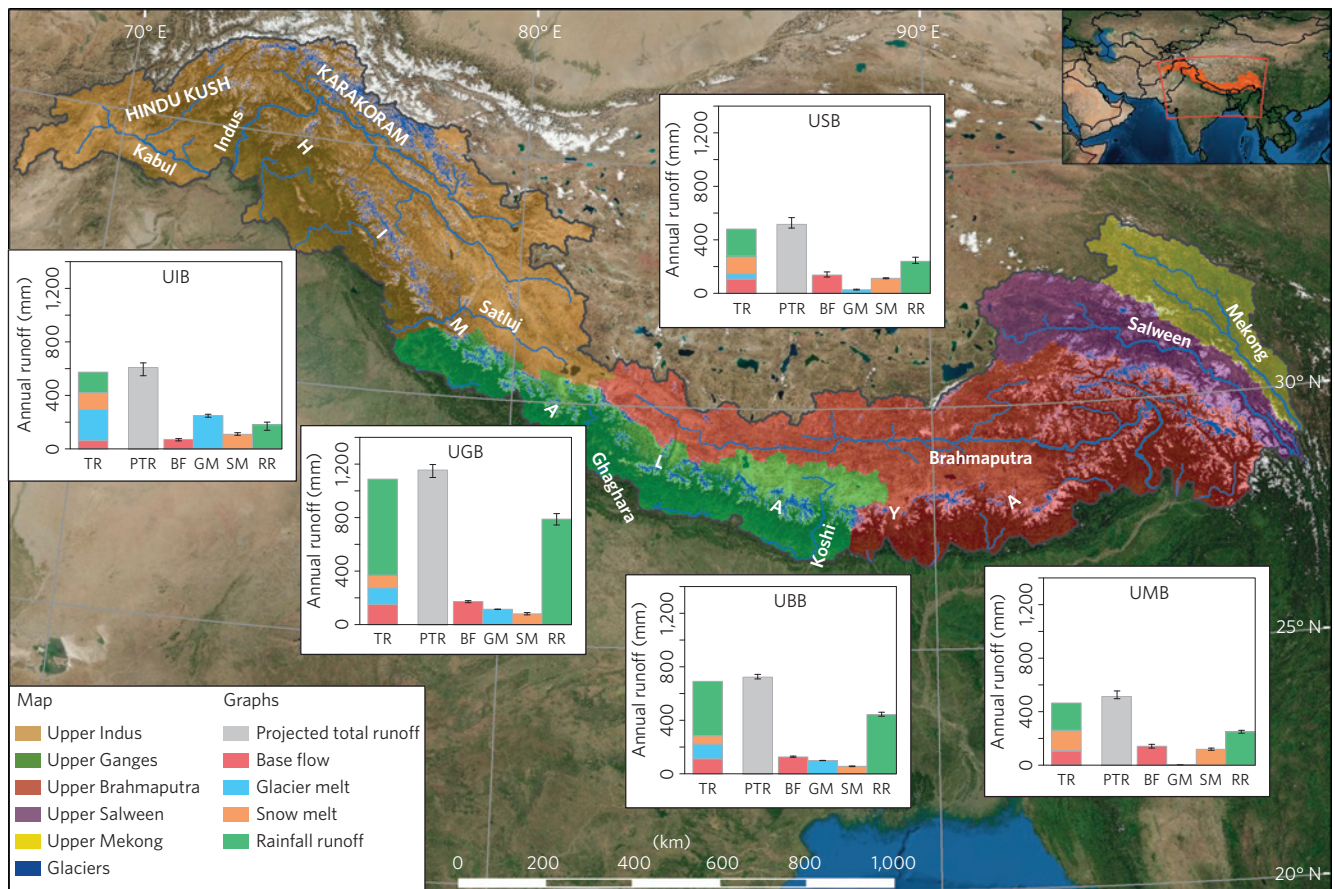
Figure 1 | The upstream basins of Indus, Ganges, Brahmaputra, Salween and Mekong. Bar plots show the average annual runoff generation (TR) for the reference period (1998–2007, REF; first column). The second column shows the mean projected annual total runoff (PTR) for the future (2041–2050 RCP4.5) when the model is forced with an ensemble of 4 GCMs. In the subsequent columns, PTR is split into four contributors (BF: baseflow, GM: glacier melt, SM: snow melt, RR: rainfall runoff). Error bars indicate the spread in model outputs for the model forced by the ensemble of 4 GCMs.

At the outlets of the UIB, the contribution of glacier melt in the Indus River is much larger compared with the Kabul and Satluj rivers (Supplementary Fig. 6). The snow-dominated Kabul River's flow peaks during the spring months, while the glacier-melt-dominated Indus River's flow peaks during summer, when glacier melt is at its maximum. The discharge in the Satluj River peaks during the summer months as well, but this is explained by a monsoon-dominated rainfall regime in this basin (Fig. 2), rather than by glacier melt. Hence, the Satluj discharge peak is directly related to the peak in rainfall during the monsoon, which is also the case for the UGB, UBB, USB and UMB (Supplementary Fig. 6). In the UBB, glacier melt is important for the most eastern tributaries (Fig. 3), enhancing the flow peak at the upstream basin outlet during the summer months (Supplementary Fig. 6). The Salween and Mekong discharges peak during the monsoon months, where flow composition is dominated by snow melt during the first months and dominated by rainfall runoff during the last months of the monsoon season (Supplementary Fig. 6). The contribution of baseflow to the total flow varies from 11% in the UIB to 23% in the UMB (Fig. 1).

To estimate the impacts of climate change for the future hydrological regimes in the five basins, we force the model with the latest ensemble of climate models. Although GCMs agree that, between the reference period (1998–2007) and 2050, temperatures will increase in the region by ∼1–2.2 °C and, with roughly the same magnitude throughout the year, precipitation projections are uncertain. Averaged over the five basins, changes in precipitation of −3.5 to +9.5% are projected for the same period. This uncertainty range is even larger for individual basins and for specific seasons

(Supplementary Fig. 7). On the whole, an increase in precipitation is projected for each basin except for the UIB, where projections of precipitation change show opposite signs.

For the river basins with significant contribution of glacier melt to total flow, the future evolution of the glacier cover is crucial. Observed glacier changes are not uniform in the region[6,9,18,19]. Although glaciers are losing mass in most parts of the Himalayas, stability or even mass gain is observed in the Pamir and Karakoram ranges. As the 1 km model resolution does not allow for explicit inclusion of ice flow, we use a parameterization of basin-scale glacier changes[20] calibrated to regional mass-balance trends[21] to simulate future glacier changes. As a result of increasing air temperatures, a decrease in glacier extent is projected for all basins for all ensemble members despite the projected precipitation increase in most ensemble members (Supplementary Table 6). Our basin-scale estimates of future glacier changes are in good agreement with previous large-scale work[22].

For all basins, the amount of glacier melt water contributing to the total flow does not change much at least until 2050 because the decrease in glacier area is compensated by an increase in melt rate (Fig. 1 and Supplementary Fig. 5 and Table 7). For the UIB, increasing glacier melt water is projected by all ensemble members in both representative concentration pathways (RCPs).

The future amount of snow melt in the UIB decreases slightly for all ensemble members in both RCPs, as the increasing temperatures and limited change in precipitation result in a shift towards more liquid precipitation (Fig. 1 and Supplementary Fig. 5 and 7). Overall, for three out of four ensemble members in RCP4.5, the annual
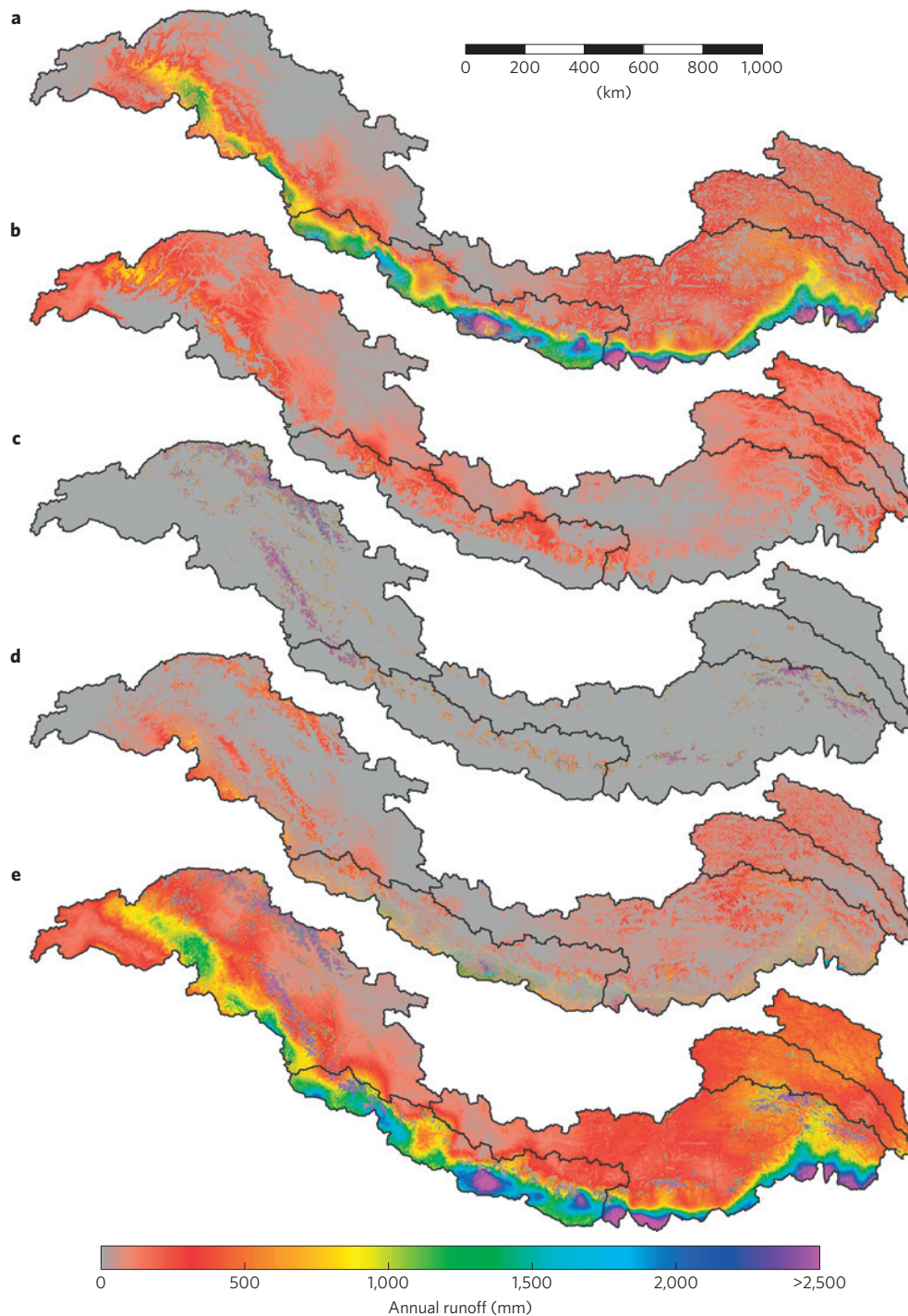
Figure 2 | Annual runoff generated during the reference period (1998–2007) at 1 × 1 km model resolution. a–d, The runoff generated by each component: rainfall runoff (**a**), snow melt (**b**), glacier melt (**c**), baseflow (**d**). **e**, The total runoff, being the sum of the four components.

runoff generated in the UIB increases by 7–12% in 2041–2050 with respect to the reference period. Only for the dry and warm scenario a decrease (−5%) in runoff is projected (Fig. 1) primarily resulting from a precipitation decrease (Supplementary Fig. 7). For RCP8.5 three ensemble members project a 2–8% increase in runoff whereas the dry and warm scenario projects a −5% decrease in runoff (Supplementary Fig. 5). The projected changes in the average annual hydrographs of the Kabul, Indus and Satluj rivers reveal how different the responses to climate change are between rivers with different stream flow composition (Fig. 4 and Supplementary Fig. 8). For example, the flow in the Indus River

is dominated by temperature-driven glacier melt during summer, and the uncertainty in future flow is therefore relatively small as a result of small uncertainty in future temperature changes. The Kabul River, on the other hand, has a much larger rainfall-runoff and snow component, leading to a larger uncertainty in future flow as a result of large uncertainties in future precipitation (Fig. 4 and Supplementary Fig. 7).

For the rainfall-runoff-dominated UGB, the future hydrology largely depends on the precipitation projections. These projections have very large uncertainties, and large variation between the annually averaged and seasonal projections (Supplementary Fig. 7).
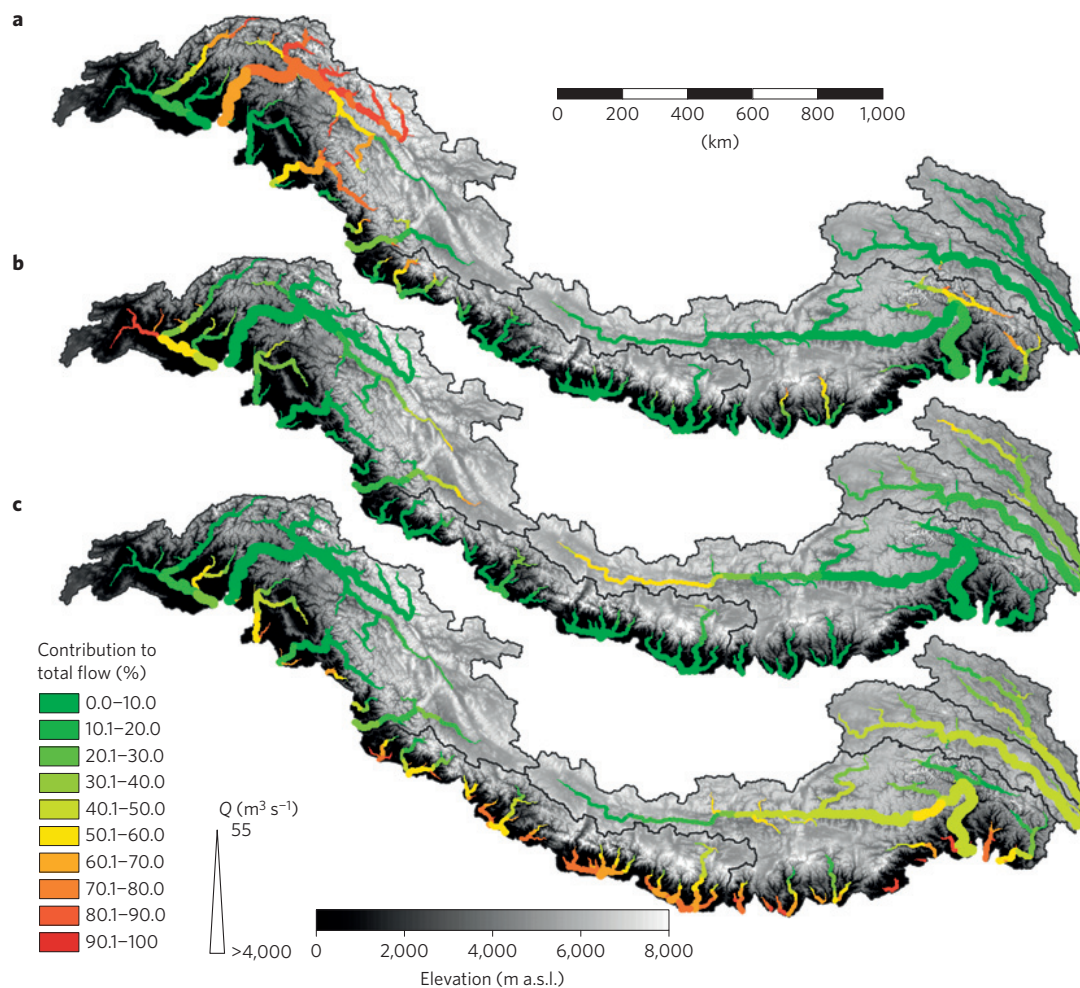
Figure 3 | Contribution to total flow by flow components in major streams. a–c, Contribution to total flow by glacier melt (**a**), snow melt (**b**) and rainfall runoff (**c**) for major streams during the reference period (1998–2007). Line thickness indicates the average discharge (Q) during the reference period.

Overall, all ensemble members in both RCPs project precipitation increases for the UGB during the monsoon, leading to increases in total annual runoff up to 10% for RCP4.5 and 27% for RCP8.5 respectively. The absolute amounts of glacier melt and snow melt do not change much, but their relative contributions decrease owing to the increased rainfall runoff. As a consequence, increased flows are observed during the discharge peak in the monsoon season, with large uncertainty in the magnitude of flow increase (Fig. 4 and Supplementary Fig. 8).

For the UBB, the uncertainty in the precipitation projections is small compared with the other basins, especially for RCP4.5 (Supplementary Fig. 7). An increase in precipitation up to 12% for RCP4.5 and up to 18% for RCP8.5 is projected, which in combination with rising temperatures leads to 3–8% increase in annual runoff for RCP4.5 and 1–13% increase for RCP8.5. This is also reflected in the Brahmaputra outlet's average annual hydrograph for 2041–2050 (Fig. 4 and Supplementary Fig. 8) where year-round increases in flow are projected due to the consistent increase in precipitation. Notably, the projected increase in precipitation during the monsoon months is small compared with the neighbouring UGB and USB, explaining the smaller increase in runoff during the monsoon season.

Given the similarities of the hydrological regimes and climate change projections in the USB and UMB, their hydrological responses are similar. Projected precipitation increases are fairly constant for all seasons and the uncertainty in precipitation projections is slightly larger for the USB compared with the UMB

(Supplementary Fig. 7). An associated increase in runoff is expected for all ensemble members (Fig. 1 and Supplementary Fig. 5). At the outlet of the upstream basins, increased flows are expected for August–May related to increased precipitation and a shift in snow melt peak to earlier spring, whereas decreasing flows are expected in June and July, related to the same shift (Fig. 4 and Supplementary Fig. 8). Furthermore, the snow melt peak decreases in magnitude as the ratio of liquid and solid precipitation shifts in favour of liquid precipitation in response to increased temperatures.

The relative contribution of baseflow remains unchanged for the future scenarios and therefore baseflow changes proportionally to the change in total runoff.

Previous work indicated future increases in runoff in two contrasting smaller catchments in the UIB and UGB (ref. 12). Here we use a new high-resolution cryospheric–hydrological modelling approach to show that these findings also hold at large scale, despite the large differences in hydrological regimes between basins and between rivers and tributaries within basins. In contrast to the UGB, UBB, USB and UMB, where the main driver of runoff increase is the projected increase in precipitation, the main driver in the UIB is accelerated melt. The contradictory precipitation projections for this basin make water availability in the UIB highly uncertain in the long run, requiring further research. As a consistent increase in runoff is expected for these five basins at least until 2050, a change of focus to coping with extreme events and intra-annual shifts in water availability is desirable. Changes in the frequency of extreme events, which are not addressed in this study, may increase
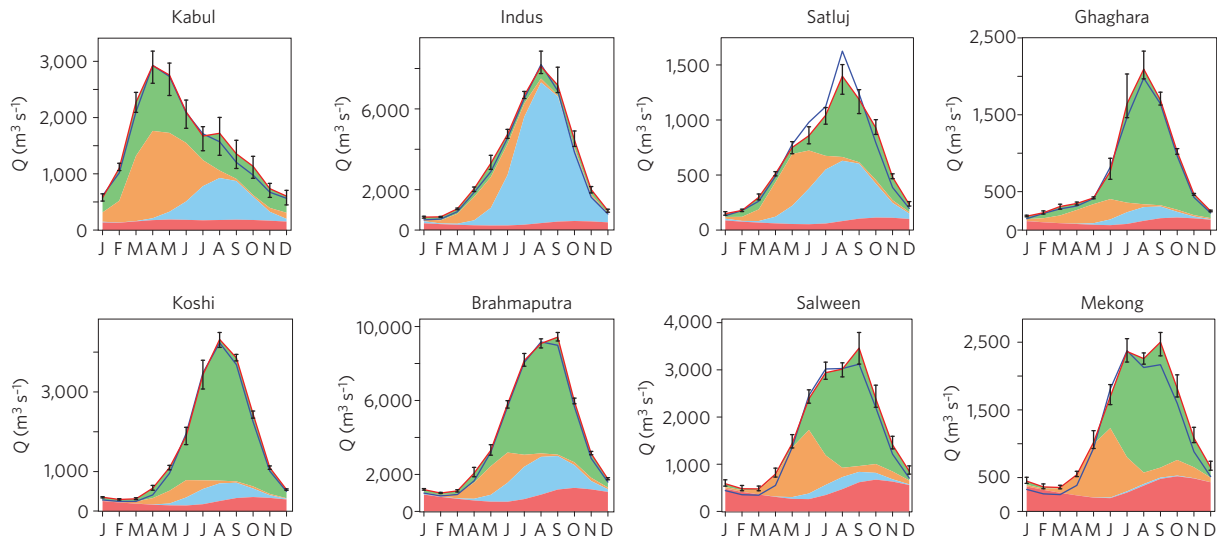
Figure 4 | Average annual hydrographs for the future period (2041–2050, RCP4.5) at major rivers' outlets from the upstream domain (locations are indicated in Supplementary Fig. 1). Plots show the mean projected discharge (Q) when forced with the 4-GCM ensemble (red line) and the discharge for the reference period (1998–2007, blue line). For the future period the stream flow composition is indicated for four components: baseflow (red), glacier melt (blue), snow melt (orange), rainfall runoff (green). The error bars indicate the spread in projections for the future period when forced with the ensemble of 4 GCMs.

natural hazards, while intra-annual shifts in water availability can have major consequences for regional food security when flow peaks and growing seasons are not coinciding.

Methods

We use a fully distributed, high-resolution (1×1 km, daily time step) cryospheric–hydrological model designed specifically for application at the large river basin scale. The model includes all major hydrological as well as cryospheric processes, allowing the quantification of the contribution of glacier melt, snow melt, direct rainfall runoff and baseflow to the total flow. To determine the contribution of each of the four components to the total runoff within a grid cell, the grid cell surface is divided into fractions. The ice cover is obtained from an updated version of the Randolph Glacier Inventory[23] provided by ICIMOD, and is described as a fractional glacier cover ranging from 0 (no ice cover) to 1 (complete ice cover) to account for sub-grid variability in glacier coverage. Glacier melt is simulated using a degree-day modelling approach with different melt factors for debris-free glaciers and debris-covered glaciers. Debris-covered and debris-free glaciers are distinguished by slope and elevation thresholds. For the remaining fraction of the grid cell the model maintains a dynamic snow storage, where snow melt is simulated using a degree-day modelling approach. Refreezing of melt water within the snow storage is also explicitly included. Below the snow storage and in areas without glaciers or snow, a variable soil water storage is maintained to derive the amount of rainfall runoff and infiltration to groundwater. The soil is split into a root zone layer and a subsoil layer with quantitative soil properties, estimated using pedotransfer functions[24] and soil type[25]. Calculated soil water fluxes include evapotranspiration, surface runoff, lateral drainage, water exchange between the rootzone and subsoil through percolation and capillary rise. The groundwater is recharged from the subsoil and releases water as baseflow. Future glacier changes are simulated applying a recently developed parameterization for glacier changes at the large river basin scale[20]. The model is initially set up for a ten-year reference period (1998–2007) using large-scale meteorological forcing data sets[26,27] and calibrated to observed stream flow. For the future projections, we use the delta change approach[28], to force the model with the latest climate model ensemble generated for the fifth assessment report of the Intergovernmental Panel on Climate Change by the fifth phase of the Climate Model Intercomparison Project[29]. We do this for two RCPs: RCP4.5 and RCP8.5. For each RCP, four GCMs are selected covering the 10–90 percentile-space in the range of projections for temperature change as well as precipitation change (Supplementary Table 5). Details on the methodology and data sets used can be found in the Supplementary Information.

Data produced in this study can be requested from the corresponding author.

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Author contributions

All authors contributed significantly to this work. The study was conceived by W.W.I., A.B.S and A.F.L. A.F.L. and W.W.I. designed and implemented the cryospheric–hydrological model and conducted the analysis. A.F.L. prepared the manuscript. W.W.I., A.B.S. and M.F.P.B. contributed to the writing.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to A.L.

Competing financial interests

The authors declare no competing financial interests.