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Importance of snow and glacier meltwater for agriculture on the Indo-Gangetic Plain

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Densely populated floodplains downstream of Asia's mountain ranges depend heavily on mountain water resources, in particular for irrigation. An intensive and complex multi-cropping irrigated agricultural system has developed here to optimize the use of these mountain water resources in conjunction with monsoonal rainfall. Snow and glacier melt thereby modulate the seasonal pattern of river flows and, together with groundwater, provide water when rainfall is scarce. Climate change is expected to weaken this modulating effect, with potentially strong effects on food production in one of the world's breadbaskets. Here we quantify the space-, time- and crop-specific dependence of agriculture in the Indo-Gangetic Plains on mountain water resources, using a coupled state-of-the-art, high-resolution, cryosphere–hydrology–crop model. We show that dependence varies strongly in space and time and is highest in the Indus basin, where in the pre-monsoon season up to 60% of the total irrigation withdrawals originate from mountain snow and glacier melt, and that it contributes an additional 11% to total crop production. Although dependence in the floodplains of the Ganges is comparatively lower, meltwater is still essential during the dry season, in particular for crops such as sugar cane. The dependency on meltwater in the Brahmaputra is negligible. In total, 129 million farmers in the Indus and Ganges substantially depend on snow and glacier melt for their livelihoods. Snow and glacier melt provides enough water to grow food crops to sustain a balanced diet for 38 million people. These findings provide important information for agricultural and climate change adaptation policies in a climate change hot spot where shifts in water availability and demand are projected as a result of climate change and socio-economic growth.

Providing food for more than 9 billion people with limited water resources in a changing climate will be one of the defining challenges of the twenty-first century[1]. With population growth, water scarcity is no longer confined to dry regions; even in the floodplains of some of the largest rivers in the world—the Indus, Ganges and Brahmaputra (IGB)—water is scarce on a per capita basis and during critical low-flow periods[2]. Here population has rapidly expanded, co-evolving with improvements in agricultural productivity and water supply, by means of reservoirs[3] and canals and the energy-driven expansion of groundwater use[4,5]. These have equipped the plains of the IGB region with the world's largest connected irrigated agricultural area, an intensive rice–wheat multiple-cropping system, making it a breadbasket on which almost one billion people rely[6].

It is also one of the global climate change hot spots, where a stronger than global average climate signal intersects with large numbers of vulnerable and poor people[7,8], and where prevalence of hunger and malnutrition is still amongst the highest in the world[9,10].

Food production in the IGB is intricately linked to the timely supply of water resources. A constant supply of water for downstream irrigation results from the unique interplay between seasonal snowmelt in spring and autumn, peak glacier melt in the Asian summer months and rainfall concentrated in the monsoon season, with slowly recharging groundwater resources supplementing shortfalls in supply throughout the year[11]. Not only does the specific timing of meltwater resources modulate the seasonal pattern of monsoon rainfall and river flows, it also buffers interannual differences with glacier melt increasing when monsoon rainfall and snow cover are low[12,13], making the mountains Asia's 'water towers'[14].

With climate change, the modulating effect provided by snow and glacier melt might strengthen at first, due to increased melt, before eventually weakening[15–17]. Up to two-thirds of the present-day ice mass stored in Hindu Kush–Himalayan glaciers is projected to be lost by the end of the century under current greenhouse gases emission scenarios[18]. Even if the ambitious Paris Agreement of a 1.5 °C limit to global warming becomes reality, the ice volume will still be reduced by one-third[18]. To add to increased stress, dwindling groundwater levels, mainly in the northwest of the IGB[19,20], will limit its continued use and the buffer role it currently provides[21].

Strong socio-economic development characterized by massive urbanization processes, demographic growth and fast technological and industrial development will further increase water demand, and probably lead to a further increase in the water gap during the twenty-first century[22]. These changes are considered a serious threat to crop productivity and food production[23], with potentially detrimental effects on food security[24]. To anticipate change, and to adapt management accordingly, a thorough understanding of the dependency of agricultural production on different sources of water supply is essential.

While recent research has advanced understanding of cryosphere hydrological processes and the timing of source-specific water supply contributions in the mountains[15,25,26], the linkage with time- and space-specific demand has yet to be clarified. Existing large-scale models lack a proper representation of essential demand characteristics such as multiple-cropping and

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conjunctive use[27], and the distribution of water through canals, inhibiting their capacity to translate upstream changes into downstream impacts[28].

Here we introduce a coupled state-of-the-art, high-resolution, cryosphere–hydrology–crop model and we assess the spatial and intra-annual variation in glacier and snowmelt water contribution to streamflow for the entire IGB. Subsequently, we quantify the dependence of downstream agricultural production on snow and glacier melt from the mountains, and the numbers of people who depend on these water towers for their livelihood and for food. We take into account time-specific representation of crop development and crop water use. This experimental design also illustrates a worst case climate scenario, where a strong decrease in ice and snow reserves leads to a predominantly monsoon-driven run-off pattern. These insights are important in regard to proper anticipation and timely adaptation by agriculture to the expected changes in water availability and other climate change impacts.

Contribution of mountain water to downstream irrigation

Snow and glacier melt contributions to river discharge vary from headwaters to oceans, and from west to east along the Himalayan arc (Fig. 1). Of the three major South Asian rivers, at the location where the rivers leave the mountains and enter the plains, the contribution of snow and glacier melt is largest in the upper Indus, as discussed in greater depth in ref. [15]. Here we show that, close to the outlet into the Arabian Sea, Indus discharge still consists of 60–70% of water originating from mountain snow and glacier melt due to the low contribution of rainfall to run-off in the arid climate of the plains (Fig. 1) (see Supplementary Fig. 1 for data on climate). In the Ganges and Brahmaputra Basins, larger contributions of monsoon rainfall to run-off mean that the relative importance of glacier and snowmelt in streamflow declines rapidly when propagating downstream, to less than 10 and 20% of mean annual discharge, respectively. Snow and glacier melt run-off, however, have a strong seasonality and vary over the course of the year (Fig. 1b–d). Although the volumetric contribution of meltwater to streamflow peaks in the middle of the summer (July/August; Fig. 1b–d), its relative contribution to streamflow is largest in May and June when temperatures are already high but there is still little rainfall-induced run-off (see Fig. 1e–g and Supplementary Fig. 1).

Large volumes of water leaving the mountains will, however, never reach the sea. Based on our explicit simulation of water supply to individual irrigation command areas in the IGB, the green-shaded areas in Fig. 1 show that meltwater contributions to irrigation water supply are considerable over large command areas fed by the canal systems, but with very high spatial variability. In the Indus Basin, meltwater forms a major contribution to all canal-fed irrigated areas. In the Ganges Basin, meltwater contributes substantially to irrigation water supply in the intensely cropped northwestern part of the basin. Elsewhere in the Ganges basin, most of the irrigation water supply originates from run-off generated by precipitation in the plains itself. In the Brahmaputra Basin meltwater plays a minor role in downstream agriculture, as large irrigation systems are absent here and high precipitation levels suffice to sustain predominantly rain-fed agriculture.

Rice and cotton are major users of water

Water scarcity in these monsoon-dominated regions of South Asia, where about 70% of precipitation falls between June and September, is largely caused by a mismatch over time and space between water demand and supply. Spatial variation in irrigation water demand depends on the type of crop and how much of that demand can be met by local precipitation, whereas the onset and duration of crop growing seasons determine the temporal variation in demand (Supplementary Fig. 2).

Water applications (that is, withdrawals minus losses during conveyance) to rice, cotton and wheat, the largest consumers of water in the Indus (Supplementary Fig. 2), each have their own time scale (Fig. 2). Cotton is typically sown in the summer months of April and May[29], whereas rice is generally transplanted a few weeks later during the first monsoon rains in June or July (in what is locally called the kharif season). Wheat grows mainly during winter (the rabi season) in all basins. In the Ganges, most water is applied to wheat during the rabi season, followed by rice grown mainly during the kharif season and sugar cane, which grows all year round. In the Brahmaputra, the irrigation water goes mainly to rice (Supplementary Fig. 2), typically grown two to three times per year[30] (Fig. 2, left-hand panels).

The three basins also differ with respect to the sources used to withdraw this irrigation water throughout the year. In the Indus Basin, meltwater contribution to withdrawal varies between 20% in the rabi season to >60% just before the monsoon in June, whereas the absolute meltwater withdrawals peak in August (Fig. 2, right-hand panels). The annual average contribution of meltwater to the estimated 516 BCM of total irrigation water withdrawn is 37% in the plains of the Indus. In the Ganges Plains, meltwater is used only between March and June, with a maximum of around 20% during the month of May, but it contributes only 4% to the total estimated mean annual irrigation water withdrawal of 294 BCM. The Brahmaputra Plains, with an estimated annual irrigation withdrawal of only 14 BCM, do not show a major use of meltwater over the year.

Although irrigation in the mountains is essential for local food security, the levels of water withdrawals and food production are minor compared to downstream numbers. We estimate annual average irrigation withdrawals of 10 BCM (2% of total basin withdrawal), 1.6 BCM (0.5%) and 0.4 BCM (3%) in the Indus, Ganges and Brahmaputra mountains, respectively.

Meltwater buffers pre-monsoon drought

A closer look into the crop-specific link between water use per crop and sources of withdrawal reveals a temporal variation in meltwater use for different crops (Fig. 3). For cotton and rice in the Indus Basin, the first half of the growing season is when the relative meltwater contribution is highest. The crucial modulating effect of meltwater becomes especially apparent during summer in the Indus, when snow and glaciers provide water to crops before the monsoon rains arrive. In the Ganges Basin, sugar cane, grown predominantly in the northwestern areas of the Basin, relies substantially on meltwater. Although small in size, this region is a very important food-producing region with the highest yields in India[31].

Crop-specific dependence on meltwater

Using a hydrological model with the ability to simulate daily crop growth and carbon assimilation for the 12 major global crop classes allows estimation not only of the contribution of meltwater to irrigation, but also of the effect of this meltwater contribution on crop yields. This effect is more than just a simple linear relationship based on the average annual meltwater contribution to total irrigation; the extent to which crop yields rely on the availability of snow and glacier meltwater is also dependent on the crop stages in which meltwater is used.

To estimate the meltwater contribution to crop yields and total agricultural production, we performed a series of model runs in which we isolated the different sources of water supply and compared resulting yields (see Supplementary information).

In the most southerly irrigated areas of the Indus, close to the outlet, irrigated cotton and rice production is almost entirely sustained by meltwater due to the very dry climate and almost total dependency on water originating from the mountains. Wheat yields

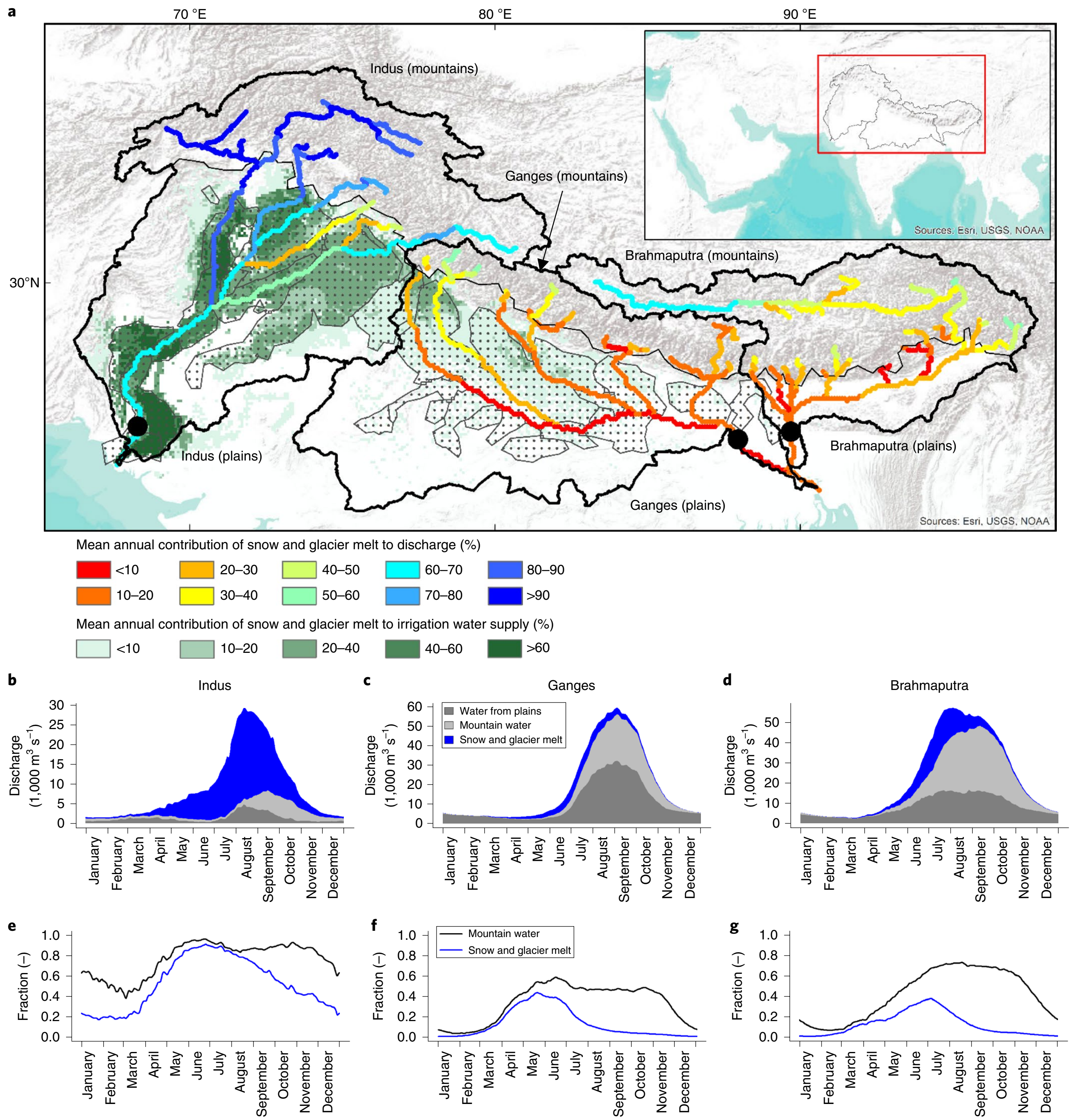

Fig. 1 | The contribution of snow and glacier melt to downstream discharge and irrigation supply (1981–2010). a, The spatially explicit, mean annual contributions of snow and glacier melt to the discharge and irrigation water supply. The dotted polygons represent the command areas of the large-scale irrigation canal systems through which water from the main river is diverted and distributed. The filled black circles show locations for which the annual cycle of discharge is quantified below (the source of the map refers to the background only). **b**–**g**, The daily mean contribution of total mountain water (both the rainfall run-off and snow and glacier melt originating from mountain areas), and of snow and glacier melt only, to the total downstream discharge close to river outlets: absolute (**b**–**d**) and relative (**e**–**g**).

rely less on meltwater, but largely on groundwater withdrawals, because this crop grows predominantly during winter when meltwater availability is limited. Sugar cane is grown throughout the year and therefore uses more meltwater in the Ganges than other crops (Fig. 4).

In terms of total crop production, 9% of the ~46 million tons of wheat that is harvested each year in the Indus Basin can be attributed to glacier and snowmelt. Similarly, 15% of the annual 19 million tons of rice production, 28% of the 4 million tons of cotton and 17% of the 53 million tons of sugar cane produced in the Indus can be attributed to this meltwater. In the Ganges Basin, 3% of cotton production and 7% of sugar cane production can be attributed to meltwater (Supplementary Table 2). Crop production from meltwater in the Brahmaputra is negligible. Note that these

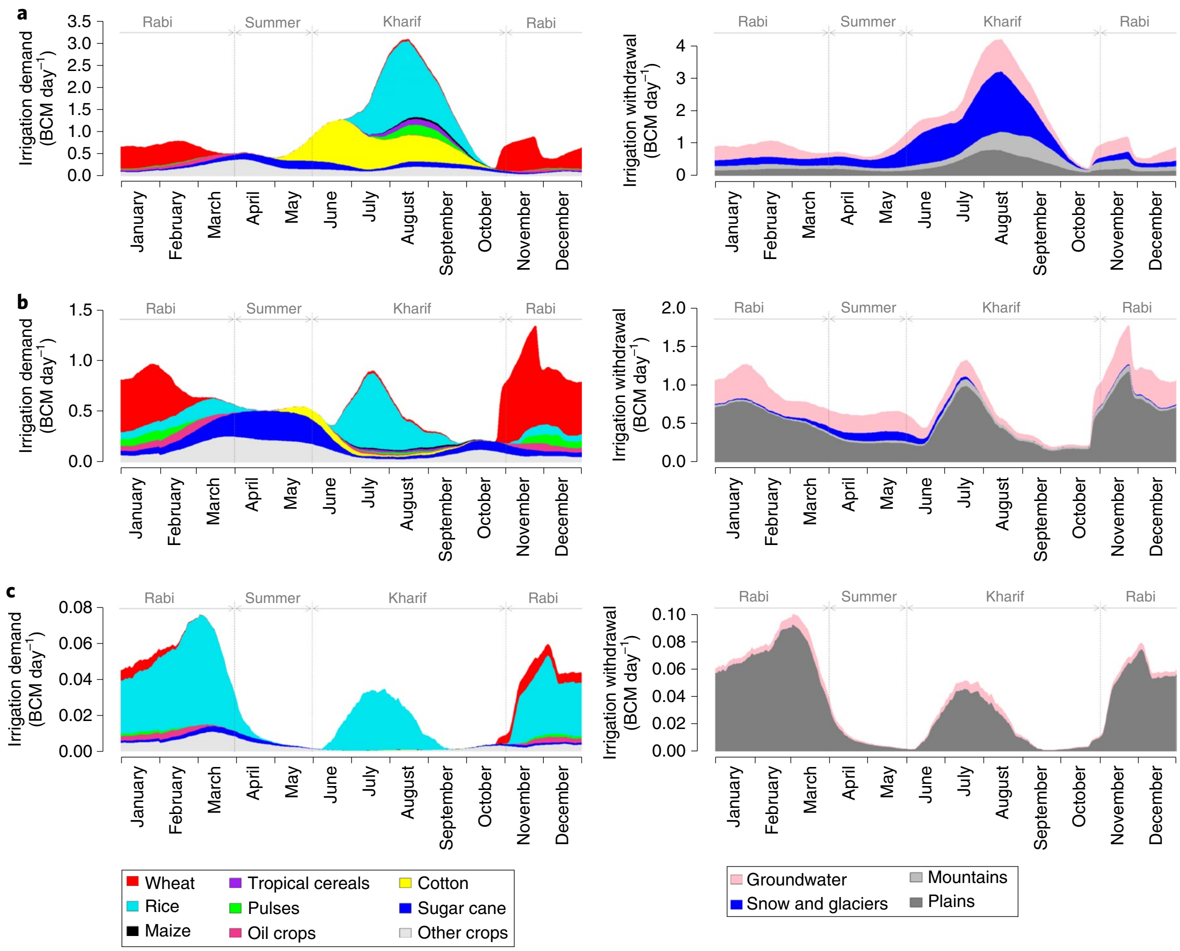

Fig. 2 | The mean annual cycle of irrigation water applied per crop versus the annual cycle of irrigation withdrawal per origin of source in the IGB. **a**–**c**, Irrigation demand (left) and withdrawal (right) in the Indus (**a**), Ganges (**b**) and Brahmaputra (**c**). Withdrawals are slightly higher than demands due to losses during conveyance of the water from the source to the field. The water sources termed 'mountains' and 'plains' refer to withdrawals from the surface water originating from the mountain areas (but excluding the melt component) and the downstream areas, respectively. BCM, billion cubic metres.

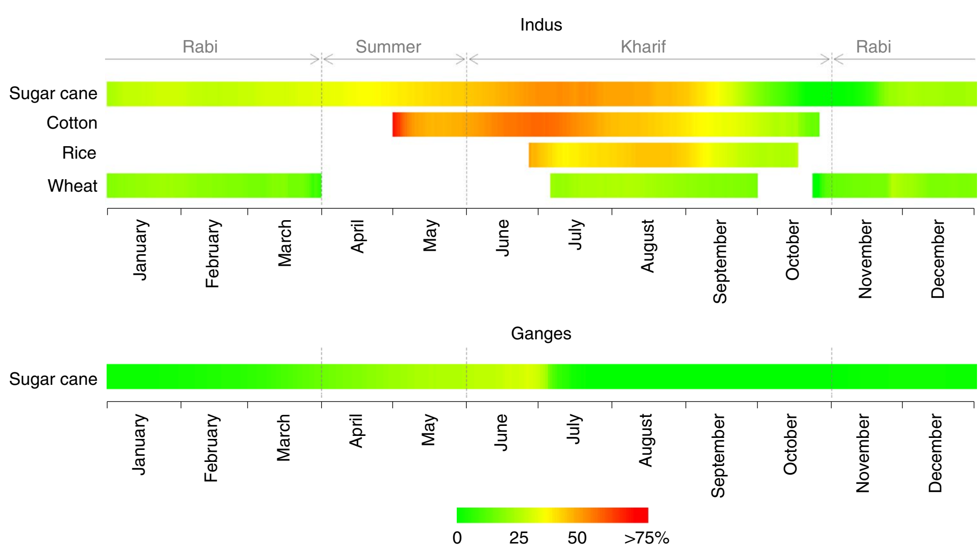

Fig. 3 | The calendar for irrigated crops, with temporal mean annual relative contribution of meltwater, in the Indus and Ganges. Only crops with a large area and large meltwater contribution at Basin level are shown.

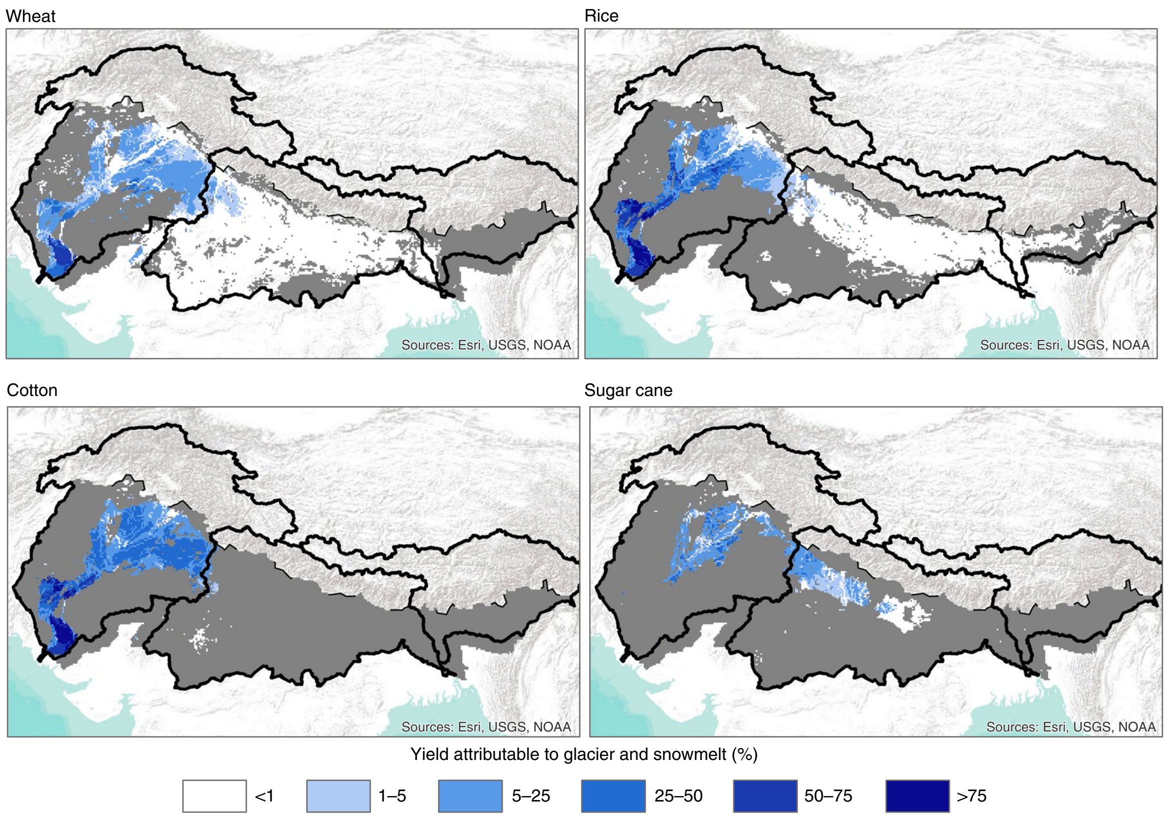

Fig. 4 | The percentage of production attributable to upstream glacier and snowmelt for major crops. Regions with no or very small areas cultivated with respective crops are shaded grey (the source of the map refers to the background only).

numbers reflect Basin averages, but the relevance of meltwater to production is much higher at specific locations (Fig. 4).

People's dependence on meltwater

The total (urban and rural) population living in the IGB is around 900 million. To interpret the human dimension of this meltwater-dependent production, we translate it to the number of people dependent on meltwater for either their food or their livelihood. Assuming that a balanced diet, of which 80% consists of vegetal products, requires 2,400 kcal day^{-1} from food crops (as in refs. [32,33]), the additional amount of food produced with meltwater in the plains is equivalent to the total caloric intake of 38 million people (Supplementary Table 2). When focusing only on the production of staple crops, the average rice consumption of 52 million people and wheat consumption of 64 million people[34] can be attributed to meltwater. A third indicator, the total downstream rural population that is substantially dependent on upstream meltwater for their livelihood (defined as the rural population[35] living in areas where meltwater contribution to irrigation water supply is >10%), is estimated at 129 million. This is in addition to the 48 million farmers who live in the Indus, Ganges and Brahmaputra mountains, many of whom depend directly on local glacier and snowmelt.

Implications

Our findings constitute an important step forward in understanding the links between water demand and supply in the Indo-Gangetic Plains: an issue of key policy relevance because of the tens of millions of people who are directly dependent on irrigation water. We show that meltwater modulates the seasonality and variability of the monsoon, but it is a misconception that snow and glacier melt is of critical importance to agricultural production everywhere. Our study highlights the differential impact temporally and among the three basins.

Our experimental design allowed us to assess the dependency of current food production on meltwater, thereby also illustrating a worst case climate scenario in which the modulating effects of stored ice and snow are absent. Climate change-induced shifts in the quantity, timing and composition of upstream water supply[36] may change the modulating effect of meltwater to a large degree. Although climate change scenarios show that the volume of glacier meltwater production is largely secured this century[16,18], with dwindling glaciers contributing even above-average meltwater in the near future, its peak discharge is expected to shift by up to one month earlier. Moreover, perennial snowmelt plays an equally important role in the meltwater supply and is likely to further perturb the modulating effect over shorter time scales[37].

At the same time, however, other climate change effects leading to warming and changes in monsoon timing and intensity[38] will also affect irrigation water demands and supply.

While an increase in groundwater use might offset some of the loss or shift in meltwater and monsoon precipitation, particularly in regions where a high dependency on meltwater already coincides with unsustainable groundwater use (Supplementary Fig. 6), groundwater alone will not be a reliable buffer.

Man-made reservoirs can partly compensate for the loss of modulating capacity of the natural reservoir of snow and glaciers, when snowmelt patterns change and glaciers recede, but at the same time their operational management is complicated by changes in low-flow periods or shifts in downstream demand. Our model included the most important existing reservoirs, but many more are either planned or under construction. Especially for those sites where snow and glacier melt constitute a considerable component of flow, a thorough robustness check should be conducted. Similarly, the success of India's proposed massive River Interlinking Project, intended to bring water from surplus regions to those with deficits[39], will be dependent on a proper understanding of the sources of, and seasonality in, flows and water supply. To evaluate food security strategies that anticipate the changing water resources in South Asia, it is crucial to study them in an integrated manner, including the effects of changes in monsoon, groundwater depletion, the role of reservoirs, melting glaciers and snowpacks, the impact of socio-economic developments and consideration of upstream–downstream linkages.

A better understanding of the match, or mismatch, between supply and demand over time has relevance beyond agriculture and food production. Other sectors rely to an equal extent on the correct timing of water availability, whether it is having enough water for energy (both hydropower producing and cooling in the case of thermal power[40]), for drinking water for South Asia's expanding urban population, for industry[22,41] or for sustaining aquatic ecosystems[42]. Not only quantity matters: water quality and pollution mitigation in rivers is an increasing policy concern in the region (as illustrated by India's 'Clean Ganga' ambition), and is strongly dependent on a minimal but guaranteed supply of low flows to dilute any contaminants.

Finally, as water-sharing treaties tend to focus on low flows, trans-boundary cooperation within these international basins[43] will be affected by any change in the contribution of meltwater. Currently, disputed upstream hydropower development in India is testing the robustness of the Indus Water Treaty[44], which allocated rights of usage of the three western tributaries to Pakistan but with some provision for customary rights to India. To distinguish man-made impact on flows from climate-related will be vital for successful conflict resolution. Developing a governance architecture that can anticipate and deal with changes will be critical to building resilience.

Methods

We used a coupled cryosphere–hydrology–crop model to analyse the spatial and temporal links between water supply generated upstream and water demand for agriculture in the downstream plains.

Mountain hydrology and snow and glacier melt. The hydrology in the upstream mountainous parts of the IGB basins was simulated using the physically based, fully distributed spatial processes in hydrology (SPHY) cryospheric-hydrological model[45]. This model is state of the art for the simulation of cryospheric-hydrological processes at large river basin scale in Asia, and has been applied in the IGB basins in previous work[15,22,36]. SPHY has been specifically developed for application at large river basin scale under data-scarce conditions.

The model runs at 5 × 5 km spatial resolution and a daily time step. Daily discharge is simulated by: (1) calculating total run-off for each grid cell as the sum of four different components: glacier run-off, snow run-off, rainfall run-off (that is, the sum surface run-off and lateral flow) and base flow, and (2) routing the total run-off and its components downstream, using a simplified routing scheme that requires a digital elevation model and a recession coefficient (see also Supplementary information). Further details on the set-up used in this study are described in ref. [22].

For the upstream domain, the SPHY model was calibrated against Moderate Resolution Imaging Spectrometer snow cover, geodetic glacier mass balance data and observed discharge at six gauging stations spread over the three basins, representing the most upstream catchments and more downstream parts of the SPHY model domain, respectively[22].

SPHY-simulated daily discharges of 27 subcatchments of the upper IGB were fed into the downstream Lund–Potsdam–Jena-managed land model (LPJmL) at the corresponding inlet points (as in ref. [22]). This coupling of SPHY and LPJmL allows for analysis of where and when water that is generated upstream is important for downstream water users, in particular for irrigation.

Downstream hydrology, irrigation water demand and supply. To simulate downstream water availability, agricultural water demand and crop production, we use an adjusted version of LPJmL[46]. LPJmL simulates a coupled hydrology and carbon cycle, which makes it a tool suitable for study of the interactions between water availability and food production[32].

LPJmL simulates daily water balance at a 5 × 5-min grid scale with a daily time step, with run-off routed through the river system at a constant flow velocity of $1\,\mathrm{m\,s^{-1}}$. The effect of large reservoirs on streamflow and water supply for irrigation is simulated by a simple generic reservoir operation scheme[3]. The version of LPJmL used in this study simulates a double-cropping system, distinguishing between monsoon-season crops (the kharif season) and winter-season crops (rabi season)[27] (Supplementary Fig. 1). The supply of irrigation in both seasons is dependent on land use (that is, whether the crop is irrigated), the soil water deficit and the availability of irrigation water. The daily irrigation demand for an irrigated crop in a cell is calculated as the minimum amount of water needed to fill the soil to field capacity and the amount needed to fulfil the atmospheric evaporative demand. Subsequently, the withdrawal demand is calculated by accounting for losses during conveyance, distribution and application of water, depending on the type of irrigation system installed (surface, sprinkler or drip) and the soil type of the irrigated cell[47].

Water is first supplied from surface water, rivers and reservoirs and distributed through an extensive irrigation canal system. If the irrigation demand cannot be fulfilled by the available surface water, water is withdrawn from groundwater locally leading to depletion when withdrawal exceeds recharge.

The simulated discharge of the coupled SPHY–LPJmL model, including the effects of human impacts such as reservoir operations and water withdrawals, was validated to observed discharge at three locations close to the outlets of the three river basins. See the section 'Model performance' in Supplementary information for details.

Crop yields. Rain-fed and irrigated growth for 12 crops (including wheat, rice, cotton and sugar cane; Supplementary Fig. 1) was simulated based on daily assimilation of carbon. In case of water stress to plants allocation of carbon to the storage organs is decreased, leading to reduced yields. Crops are harvested when either maturity or the maximum number of growing days is reached[48,49]. LPJmL yields for the most important food crops were calibrated against subnational (for India and Pakistan) agricultural statistics, as in previous studies[27] (Supplementary Fig. 3).

Modelling protocol. The coupled model is forced with the recently developed reference climate dataset for the IGB river basins[50], which includes an additional correction for the underestimation of high-altitude precipitation using glacier mass balance data as a proxy to estimate actual precipitation amounts[51,52]. SPHY is forced with daily precipitation and mean, maximum and minimum air temperature, whereas LPJmL is forced with daily precipitation, mean air temperature and long- and short-wave radiation.

To distinguish irrigation water supply from water from the mountains, and subsequently also from snow and glacier melt, a series of model simulations was performed:

(1) A run where only surface water can be used for irrigation, assuming there is no water supply from upstream. Only the 'downstream'-generated surface water can be used for irrigation.
(2) A run where downstream and upstream surface water from base flow and rainfall run-off can be used for irrigation.
(3) A run where all downstream and upstream surface water, including snow and glacier melt, can be used for irrigation.
(4) A run with irrigation supply from surface water and groundwater, assuming that groundwater is applied only when surface water is not available. In this simulation groundwater supply is not restricted, but will lead to depletion when groundwater withdrawal is greater than groundwater recharge.

Differences in simulated water withdrawals and crop yields were used to quantify the spatial, temporal and crop-specific dependence of irrigation water withdrawal and crop production on water originating from snow and glacier melt. More specifically, the difference between runs 2 and 3 defines the volumes of water and crop yields attributable to meltwater, whereas run 4 is used to calculate the total withdrawals and yields when all water sources are applied.

For a more detailed description of the model structure, input data and the validation of model performance we refer the reader to the Supplementary information.

Data availability

All SPHY and LPJmL output data generated in this study (discharge, irrigation water use by crops and crop yields), as well as the data that support the findings of this study are available from the corresponding author on reasonable request.

Code availability

The source codes of SPHY and the adjusted LPJmL version used in this study can be obtained from the corresponding author on reasonable request.

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Author contributions

H.B., C.S., A.F.L. and W.W.I. designed the study. H.B. developed the downstream model with help from C.S. and W.v.B. R.R.W. and A.F.L. developed and ran the upstream model. H.B., A.F.L. and T.H. analysed the data and prepared the Figures. H.B. wrote the article with major contributions from C.S., A.F.L., W.I., S.N., B.A., P.W. and A.B.S.

Competing interests

The authors declare no competing interests.

Additional information

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