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Future upstream water consumption and its impact on downstream availability in the transboundary Indus basin

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Abstract. The densely populated plains of the lower Indus basin largely depend on water resources originating in the mountains of the upper Indus basin. Although recent studies have improved our understanding of this upstream-downstream linkage and the impact of climate change, water use in the mountainous part of the Indus has been largely ignored. This study quantifies the comparative impact of upper Indus water usage on downstream water availability under future climate change and socio-economic development. Future water consumption and relative pressure on water resources vary greatly between upper Indus sub-basins and seasons. During the dry season, the share of surface water required within the upper Indus is high and increasing, and in some sub-basins future water requirements exceed availability during the critical winter months. In the lower Indus this causes spatiotemporal hotspots to emerge where seasonal water availability is reduced by over 25% compared to natural conditions. This plays an important, but previously not accounted for, compounding role in the steep decline of per capita seasonal water availability in the lower Indus in the future due to downstream population growth. Increasing consumption in the upper Indus may thus locally lead to water scarcity issues, and increasingly be a driver of downstream water stress during the dry season. The quantified perspective on the evolving upstream-downstream linkages of the transboundary Indus basin, provided in this study, highlights that long-term water management here must account for rapid socio-economic change in the upper Indus and anticipate increasing upstream-downstream water competition between riparian states.

1 Introduction

The Indus basin is shared by Pakistan, India, Afghanistan and China, and is home to over 260 million people(Wada et al., 2019). The basin is among the most depleted and water stressed in the world(Laghari et al., 2012; Wada et al., 2011). The arid plains of the lower Indus basin are densely populated and rely on the largest contiguous irrigation system in the world for their food production. Water demands for irrigation- but also increasingly for domestic and industrial purposes- considerably exceed the dry season supply of freshwater and are compensated for by the overexploitation of groundwater resources(Karimi et al., 2013; Wijngaard et al., 2018). Despite the current overuse of water resources, progress towards achieving the interlinked food-

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, and water security *Sustainable Development Goals* (SDG 2 & 6 respectively) in the Indus basin is insufficient(Rasul, 2014, 2016). Moreover, the direct- and indirect water resources required to meet these SDGs are projected to increase further under pressure from socio-economic development(Vinca et al., 2020); Smolenaars et al, 2021). Achieving and sustaining the food- and water security SDGs in the transboundary Indus basin can only succeed with basin-wide integrated adaptation efforts(Immerzeel & Bierkens, 2012; Immerzeel et al., 2020).

Over 85% of the Indus basin's annual discharge originates from the mountainous and scarcely populated upper Indus(Biemans et al., 2019). A combination of monsoon rainfall and snowmelt cause mountain water availability to surge over the Asian summer, while run-off during the dry winter is limited(Laghari et al., 2012). The vast irrigation networks and megacities of the lower Indus are therefore highly dependent on the timely provision of mountain water resources(Biemans et al., 2019; Flörke et al., 2018; Wijngaard et al., 2018). Previous modelling studies showed that climatic and socio-economic changes may intensify the existing Indus basin upstream-downstream dependencies. Climate change is projected to cause a consistent rise and seasonal shift in upper Indus run-off(Lutz et al., 2014), while population growth, economic progress and urbanization are likely to spur rapid growth of downstream water demands(Biemans et al., 2013; Wijngaard et al., 2018).

Consequently, the Indus basin has been framed as containing strong, one-dimensional upstream-downstream linkages; the mountainous upper Indus provides and the populous plains of the lower Indus consume water(Khan et al., 2020; Laghari et al., 2012; Reggiani & Rientjes, 2015; Wijngaard et al., 2018). Research investigating the future water resources of the upper Indus basin has accordingly remained largely within the bio-physical domain, exploring the effects of climate change on upstream hydrology and its role as supplier of water only (Khan et al., 2020; Lutz et al., 2014; Lutz, Immerzeel, et al., 2016; Reggiani & Rientjes, 2015). Modelling studies on the influence of anthropogenic activities on the Indus basin water system have instead largely focused on the lower Indus basin(Momblanch et al., 2019; Vinca et al., 2020; Wada et al., 2019; Yang et al., 2016), or assumed upstream water use activities to be insignificant(Biemans et al., 2019; Wijngaard et al., 2018). Only Amin et al. (2018) and Mehboob and Kim (2021) explicitly examined the development of water demands in the upper Indus basin. These studies only covered the Pakistani part of the basin and did not investigate downstream implications.

However, rapid socio-economic development is not limited only to the lower Indus basin. The upper Indus basin also contains fast emerging urban centres (Kabul, Jalalabad, Peshawar, Srinagar, see figure 1) that will place an increasing claim on water resources(Smolenaars et al, 2021). Upstream anthropogenic activities can exacerbate, or even cause, downstream hydrological droughts(Rangecroft et al., 2019; Van Loon et al., 2016), especially in basins like the Indus basin where downstream areas rely heavily on water generated by upstream sources(Zhou et al., 2019). Already now, water allocation issues in the Indus basin are exacerbating and causing considerable geopolitical tension in the water stressed Kabul sub-basin between upstream areas in Afghanistan and downstream areas in Pakistan(Atef et al., 2019). Socio-economic changes in the upper Indus will increasingly affect water availability in both the upper- and lower Indus basin, but the potential magnitude of their influence is presently unclear.

Water management and adaptation in the context of the SDGs requires a spatially explicit understanding of the interplay between future water demands and availability, and between upstream and downstream regions (Rangecroft et al., 2019; Yillia,

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2016). Additional quantified insight into the implications of changing water use activities in the upper Indus on water availability throughout the Indus basin, particularly in relation to climatic changes, is therefore needed. In this study we hypothesize that water consumption in the upper Indus can no longer be ignored and that it will be an increasingly important driver of downstream water stress in the coming century. *The aim of this paper is to quantify, both in space and time, the potential impact of upper Indus water consumption on lower Indus water availability accounting for both socio-economic development and climate change.* To do so, validated datasets on Indus hydrology and socio-economic development are combined within a water accounting analysis that conceptually simulates upstream-downstream dependencies. The research results will provide a novel quantified perspective on the comparative role of upper Indus socio-economic changes within the broader development of Indus basin upstream-downstream linkages. This insight is important for long-term water management, adaptation research and hydrological modelling at the basin and sub-basin scales.

2 Methods and Materials

To quantify the impact of upper Indus water usage on downstream water availability we applied a water accounting analysis at the sub-basin level for two scenarios over the period 1980-2080**.** For each scenario, we first quantify the development of upper Indus water usage, and then assess downstream water availability with and without upstream consumption. Water availability is operationalised as the per capita available water resources in m^3, as this accounts for the effect of population changes on the relative water resources available for socio-economic activities (Hanasaki et al., 2018). In the following sections we explain in more detail the methods and data we used for this assessment.

2.1 Spatially explicit scenario context

As the basis of our analysis we defined two quantitative and spatially explicit integrated scenarios. The socio-economic core of the scenarios was sourced from a set of regionalised and spatially downscaled *Shared Socio-economic Pathways* ('SSPs', see O'Neill et al. (2014)) specifically downscaled towards 2080 for the Indus basin by Smolenaars et al. (2021). The optimistic 'SSP1-Prosperous' (sustainable economic progress and low population growth, hereafter: SSP1) and the pessimistic 'SSP3-Downhill' (fragmented economic stagnation and high population growth, hereafter: SSP3) storylines were selected, as these provided the highest contrast and thus the broadest plausible bandwidth of results. The storylines contain spatially explicit future population projections towards 2080 at 5 arcmin (~8 km) resolution that account for population growth and urbanisation, as well as downscaled GDP projections. For the 1980-2010 reference period, we used the 5 arcmin population maps of HYDE project (Klein Goldewijk et al., 2011). Historical GDP data was obtained from IIASA(Dellink et al., 2017).

The socio-economic storylines are regional extensions of the global SSP storylines and could therefore be consistently matched with the RCP emissions framework(van Vuuren et al., 2014). To represent future climatic conditions we combined the SSP1 and SSP3 storylines with respectively the moderate RCP4.5 and extreme RCP8.5 emission scenarios. Climate change projections for these emission scenarios were obtained from eight (four per RCP) downscaled GCM projections for the wider

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South Asia region at 5 arcmin resolution(Lutz, ter Maat, et al., 2016). This resulted in two quantitative and spatially explicit future scenarios for climate, population and GDP, over the period 2011-2080 with a shared 1980-2010 historical period: SSP1-RCP4.5 and SSP3-RCP8.5 (hereafter referred to as SSP1 and SSP3).

2.2 Sub-basin delineation

Similar to other studies that quantify upstream-downstream linkages(Degefu et al., 2019; Munia et al., 2018; Munia et al., 2020), our analysis was conducted at the sub-basin level. Sub-basins (see Figure 1) were delineated using a pour point analysis in ESRI ArcGIS with a 5 arcmin drainage direction map from Hydrosheds (Lehner et al., 2006). First, the upper Indus sub-basins were established by determining the upstream area of the Indus river and its main tributaries. For each river course, the cut-off between upstream and downstream was set at major dams situated within the mountain-to-plain transition zone, which is an often used definition in Indus basin hydrology(Lutz et al., 2014; Lutz, Immerzeel, et al., 2016; Wijngaard et al., 2018). The contributing area upstream from these locations were assessed and resulted in seven sub-basins that were named after their respective main river. To facilitate the spatially explicit assessment of upper Indus water use impacts, the connectivity between the lower Indus sub-basins and the upper Indus sub-basins they receive water from needed to be established. Lower Indus sub-basins were therefore delineated at the confluences of rivers originating from the upper Indus basin. The trajectories and connecting nodes of the most important linking canals (Indus-Jhelum, Jhelum-Chenab-Ravi-Satluj and Chenab-Ravi, see figure 1) were also considered. This resulted in eighteen lower Indus sub-basins that each receive water resources from a unique combination of upper Indus sub-basins.

2.3 Analysis and data sources

2.3.1 Determining future water consumption and availability in the upper Indus

First we determined the progression of water consumption in the upper Indus basin in relation to the change in water availability under socio-economic development and climate change. For the upper Indus sub-basins, daily natural discharges were determined at the sub-basin outlets (i.e. the absolute surface water availability per sub-basin). Validated high-resolution discharge projections for the seven upper Indus sub-basins were used at daily timesteps for the reference period and for both RCPs (1980-2100) (Wijngaard et al., 2018; Wijngaard et al., 2017). These projections are generated by the distributed SPHY cryosphere–hydrology model based on the same downscaled climate forcing data that pertains to the scenarios context of this study. The SPHY model was developed specifically to simulate the glacier-dominated hydrology of High Mountain Asia and has been often been applied for the Indus basin(Biemans et al., 2019; Lutz et al., 2014; Lutz et al., 2019).
Subsequently, we decreased the daily natural discharges with daily aggregated consumptive water requirements for the domestic, industrial and agricultural sector of each sub-basin to estimate actual discharge. Consumptive water requirements were defined as the sectoral water demands, minus the return flows(Bijl et al., 2016), which represent the amount of natural water resources that are made unavailable for downstream usage. Consumptive water requirements in excess of daily surface

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water availability were assumed to be stored within the sub-basin in the closest preceding days with surplus discharge and released on the day shortages occurred. The difference between natural and actual outflow of upper Indus sub-basins therefore always equalled the consumptive requirements at the annual level, but for daily timesteps these occasionally varied. Sectoral consumption data were obtained from the following sources:

- Domestic and industrial consumptive water requirements projections for the upper Indus basin were obtained with the regression models of Bijl et al. (2016). The models simulate annual water consumption intensity per sectoral unit (capita and $US of GDP respectively) as a product of economic development (expressed in GDP per capita) increasing efficiency through time, and a pre-calibrated 'region-factor' that accounts for climatological and cultural circumstances (see Annex 1). The models were forced for each basin-country with the national-level GDP per capita projections of scenarios. As the Bijl models provided an annual consumption value, daily consumptions were assumed to be 1/365th of the annual output and thus to not vary within the projected year. The simulated daily consumption intensities were multiplied by the projected total population and GDP of the basin-share of each country, and then spatially distributed over the gridded population projections of the scenarios. Population data for both the reference and projected periods was available at 10 year timesteps. To obtain annual values the data was linearly interpolated between these timesteps. Lastly, the gridded consumption data was summed for each upper Indus sub-basin.
- To obtain water usage data for the agricultural sector the grid-based integrated crop production-hydrology *Lund–Potsdam–Jena managed Land* (LPJmL) model was used. LPJmL simulates run-offs, yields for twelve crops (irrigated and rainfed), and the interaction between them, whilst considering for climatic circumstances and anthropogenic interventions(Bondeau et al., 2007). This allows the influence of crop production on the water system to be quantitatively untangled and studied under climatic and socio-economic changes(Gerten et al., 2011; Rost et al., 2008). For this study a regional LPJmL version was used that was developed specifically to represent the monsoon-dominated double-cropping systems of South Asia at 5 arcmin resolution (see Biemans et al. (2016)). The South-Asia LPJmL version has been applied for multiple integrated assessment that include the Indus basin(Biemans et al., 2019; Wijngaard et al., 2018) and its agricultural water withdrawals have been validated for the broader South Asia region(Biemans et al., 2016; Biemans et al., 2013). The LPJmL simulations were conducted with unlimited groundwater access for irrigation, providing an estimate of the potential agricultural water usage which is unaffected by the internal LPJmL hydrology. This avoids inconsistencies with the discharge data obtained from the SPHY model. LPJmL was forced with the downscaled climate data pertaining to the scenarios and with regional land-use projections for SSP1 and SSP3 from the IMAGE framework(Stehfest et al., 2014). The land-use projections were spatially downscaled to 5 arcmin by applying the IMAGE growth-rates for rainfed and irrigated crops to 2005 land-use extents from the spatially explicit MIRCA-2000 dataset(Portmann et al., 2010), an approach that is often used for scenario based studies with LPJmL(Jägermeyr et al., 2016; Jägermeyr et al., 2017; Wijngaard et al., 2018). The daily consumptive water requirements were determined by aggregating the blue water consumption of agriculture from evapotranspiration and conveyance losses and summing these per sub-basin.

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To further interpret the consequences of climatic- and socio-economic changes on the status of water availability in the upper Indus basin the APC (Availability Per Capita) index(Hanasaki et al., 2018) was applied, which is an expanded version of the well-known Falkenmark index(Falkenmark et al., 1989). The APC index assesses the annual available water resources per capita and categorises these by the degree to which water scarcity is limiting a society:

- No water stress: >5000 m^3 per capita per year
- Low water stress: 5000-1700 m^3 per capita per year
- Moderate water stress: 1700-1000 m^3 per capita per year
- High water stress: 1000-500 m^3 per capita per year
- Extreme water stress: <500 m^3 per capita per year

Lastly, the impact of upper Indus consumption on environmental flows was studied using the *variable monthly flow* (VMF) method as applied by Pastor et al. (2019). VMF defines that a minimum of respectively 30% and 60% of mean natural flows in the dry and wet seasons must be maintained for environmental well-being. Thus, only 70% and 40% of water resources during the wet- and dry season can sustainably be consumed(Pastor et al., 2014). Minimum daily flow thresholds were determined for the mean daily flows over the historical reference period (1980-2010) and the wet and dry season definition by Laghari et al. (2012). The status of environmental flows was expressed as the days per year in which minimum flows are not met at the outlet of upper Indus sub-basins.

The strong seasonal character of Indus hydrology requires water resource assessments to be conducted at the seasonal level(Laghari et al., 2012). Therefore, the daily timeseries of natural and actual flows were aggregated and analysed for the two hydrological seasons suggested by Laghari et al. (2012) that correspond with the main agricultural season; the *Dry season* (Rabi cropping season, Nov-Apr) and the *Wet season* (Kharif cropping season, May-Oct). Additionally, for some analyses the seasons were disaggregated further to the four climatological seasons used in other regional water system studies(Rajbhandari et al., 2015; Wijngaard et al., 2018); *Pre-monsoon* (Mar-May), *Monsoon* (Jun-Aug), *Post-monsoon* (Sep-Nov) and *Winter* (Dec-Feb). To illustrate the progression of water consumption and availability over time, flow data was assessed as transient annual timeseries or for three assessment timesteps; the 1980-2010 historical reference period (Ref), and the future 2030-2050 (Mid) and 2060-2080 (Late) periods.

2.3.2 Quantifying downstream reductions in water availability due to upstream consumption

For the second step of our analysis we assessed the impact of the upper Indus consumption on water availability in the lower Indus. To do so, for the three assessment timesteps the average natural flow and average actual flow were determined per season and then distributed over the lower Indus sub-basins. Similar to the approach by Viviroli et al. (2020), our lower Indus water allocation algorithm assumes an equal distribution of upper Indus outflows among the downstream population of each upper Indus sub-basin. The populations of lower Indus sub-basins that are downstream from multiple upper Indus sub-basins

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were divided and assigned to the upstream sub-basins relative to the water supplied (see Figure 2). The allocation procedure used the spatially explicit population projections of the scenarios used in this study.

The total water availability of each lower Indus sub-basin was then determined by aggregating, for each timestep and season, the allocated upper Indus water resources with average water supply generated within the lower Indus sub-basin itself. Hereby, it was assumed that all water resources generated in a lower Indus sub-basin are utilized within that sub-basin. The water resources originating locally in the lower Indus sub-basins were determined with the LPJmL model. Simulations were ran with naturalized upstream inflow, natural vegetation and without anthropogenic water withdrawals, an approach that is often used to determine natural flows with LPJmL(Jägermeyr et al., 2017; Rost et al., 2008). The model was forced with the downscaled climate data that belong to the scenarios. For each of the lower Indus sub-basins, the discharges at its outlet were assessed and the inflows from outside the sub-basins were extracted (i.e. the discharges at the outlets of sub-basins directly feeding into a sub-basin), thus leaving only the water generated within the sub-basin itself.

The impact of upper Indus consumption on lower Indus water availability was then studied by comparing relative differences in total seasonal water availability between the actual and natural flow conditions for each timestep. As availability between seasons and sub-basins varied greatly, the absolute and annual based APC index was not suitable for this analysis. Water availability in the future timesteps was additionally compared to reference period availability to assess the change in lower Indus water availability through time under integrated climate change and socio-economic development. This provided insight into the comparative role of upper Indus water consumption. Similarly, per capita water availability in the lower Indus in our analysis was also affected by population growth, and by climate change through its effect on discharges. Water availability in lower Indus sub-basins was therefore additionally assessed for future timesteps with downstream population distributions and climatic conditions independently kept in reference period conditions (i.e. with population maps and discharges as they were in the 1980-2010 timestep). This allowed the isolated effects of respectively climate change and downstream population changes on future water availability in the lower Indus to also be quantified and compared to the impact of upper Indus consumption.

3 Results

3.1 Changes in upper Indus water consumption

Figure 3B shows that the reference period total water consumption in the upper Indus basin is around 6.9 km^3 yr^{-1} (compared to approximately 140 km^3 yr^{-1} in the lower Indus basin (Wijngaard et al., 2018)) Water use activities are mostly located in the Kabul, Indus and Jhelum sub-basins and are dominated by agricultural water use during the wet season. The population in the upper Indus is projected to grow by 124% and 245% towards 2080 in SSP1 and SSP3 respectively (Table 2, compared to reference period 1980-2010). The highest population growth will be in the Kabul sub-basin (188% in SSP1 and 350% in SSP3). This sub-basin contains three large cities that are projected to expand rapidly due to the strong urbanization trends. Water consumption in the upper Indus subsequently demonstrates an annual growth to 13 km^3 yr^{-1} (88%, SSP1) and 17 km^3 yr^{-1}

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(146%, SSP3) in the 2060-2080 period. Consumption increases are largely concentrated in sub-basins that already account for the majority of present water usage. The Kabul and Jhelum sub-basins are projected to face annual water use increases of respectively as much as 135% and 307% in the SSP3 late period.

The projected growth in water consumption is highest for the domestic sector (figure 3B). Population growth and economic progress are projected to increase both the number of end-users and the amount of consumed water resources per end-user. Economic growth similarly drives an increase in the industrial water use. Agricultural water use only increases slightly from present day values as expansion options in the mountainous upper Indus are limited and higher temperatures due to climate change reduce the length of the growing season of staple crops (Wijngaard et al., 2018). The relative growth in the dry season (179% in SSP1 and 296% in SSP3) is greater than in the wet season (60% in SSP1 and 102% in SSP3) and the annual average. Figure 3 shows that the seasonal disparity of water consumption in the upper Indus basin is accordingly projected to decrease by the late period in both scenarios.

3.2 Impact of climatic and socio-economic changes on upper Indus water resources

Table 2 demonstrates that the ensemble mean annual flow of the upper Indus increases by 38% and 32% respectively in the SSP1 and SSP3 scenarios for the 2060-2080 period. The increase is most pronounced in the dry season. The development of discharge does nonetheless vary greatly between the sub-basins. The Satluj and Indus sub-basins are projected to face annual flow increases of up to 54% and 51% respectively, while those of the Kabul and Jhelum sub-basins stays roughly similar over the projected period.

Despite the general increase in surface water availability, the mean annual per capita water availability in the upper Indus basin is projected to drop by 43% (SSP1) and 65% (SSP3) by the late period under pressure from rapid population growth (Table 2). The application of the APC index in Table 2 illustrates that the upper Indus basin as a whole is projected to drop from a 'no water stress' situation in the refence period to a 'low water stress' situation in the mid period of both scenarios. However, the per capita water availability change is highly heterogenous between the sub-basins. In the reference period the relatively densely populated Kabul and Jhelum sub-basins fall into the 'low water stress' category of the APC index and are projected to move into the 'high-' and 'moderate' water stress categories in the late period of the SSP3 scenario. In contrast, other sub-basins, such as Satluj, Chenab and Ravi, remain firmly in the 'no water stress' category and even face a net increase in per capita water availability in the SSP1 scenario.

Figure 4 demonstrates that during the refence period the consumed share of total annual surface water resources is negligable at about 2%. Because of the seasonal discharge patterns the consumption in the driest (winter) period of the year does exceed 10% of total discharge. Despite rapid population growth the share of total annual water resources consumed in the upper Indus basin only increases to 4.1% and 5.5% in SSP1 and SSP3 respectively in the late period (see Annex 2). However, the basin-level consumed fraction on average reaches a considerable 15% (SSP1) and 18% (SSP3) over the entire dry season and exceeds 30% during the December and January months. Corresponding to the pace of population growth, the development of relative water consumption differs between sub-basins. In the Kabul sub-basin consumptive needs during the late period in the driest months of the year exceed 80% of available surface water on average and even fully surpass it in low discharge years. In the SSP3 scenarios the consumed share during the wet season also reaches a considerable 17% to 21% (SSP1 and SSP3 respecitvely). Similarly, in the Jhelum sub-basin the average consumed share over the entire dry season reaches 18% (SSP1) and 23% (SSP3) in the late period and consumptive needs during the winter months may exceed discharges in the driest years. Sub-basins with positive discharge changes due to climate change and low population growth, such as Satluj, remain virtually unaffected in both scenarios.

The rapid increase in consumptive water needs relative to water availability during the dry season is projected to affect environmental flows in the upper Indus basin. Figure 5 illustrates that in these basins by 2080 environmetal flows are on average not met for roughly half- (Kabul) and a third of the year (Jhelum). Environmental flows appear to also gradually be affected in the Chenab and Beas sub-basins during low discharge years. Environmental flows during the monsoon season are not affected in any of the sub-basins.

3.3 Future downstream water availability under socio-economic- and climate change

The influence of upper-Indus consumption on the per capita water availability in the lower Indus basin (see Annex 5) varies greatly between the seasons. Analogous to the periods of the year in which the consumed share in the upper Indus is highest, Figure 6 illustrates that its impact on downstream water availability is most pronounced in the winter season. During the reference period some sub-basins are already shown to be slightly affected in the order of 8% to 12%, but in the late period the available water may reduce by more than a quarter in some sub-basins on average. However, the impact during the post-monsoon season demonstrates the most considerable rise. Several sub-basins shift from being largely unaffected during the reference period to facing mean water availability reductions of 14% (SSP1) and 20% (SSP3) in the late period. The influence on water availability during the monsoon season doubles in most basins, but nevertheless does not exceed 6%. Throughout all seasons the impact of upper Indus consumption is strongest in the sub-basins that receive their water from the Kabul and Jhelum upper Indus sub-basins. Additionally, sub-basins with limited local per capita water availability (e.g. due to high population densities or extremely arid conditions) will be more affected, as their relative dependency on mountain water resources is higher. The regional urbanization trend and subsequent spatial concentration of population magnifies this effect in several sub-basins containing large cities. The pattern of basins most affected by upstream consumption is similar between the scenarios, but the degree of impact is higher in the SSP3 scenario.

The impact of upper Indus consumption on lower Indus water availability is not an isolated process, but intertwined with climate changes and with socio-economic changes in the lower Indus itself. Table 2 and Figure 4 demonstrated that climate change causes an increase in discharge from the upper Indus basin and for the lower Indus a slight increase in precipitation is also projected(Lutz et al., 2019). The isolated impact of climate change (Figure 7) likewise increases late period per capita water availability in most lower Indus sub-basins by 20% to 50% compared to reference period climatic conditions. In the areas downstream from the Beas and Satluj upstream sub-basins this increase may even exceed 50%. The increase in downstream water availability from climate change outweighs the decrease due to upper Indus water use, except in the sub-basins directly downstream from the Kabul and Jhelum sub-basins during the dry season in SSP1. Figure 7 moreover demonstrates that lower Indus population growth from an average of 168 million inhabitants over the reference period to 267 million in the SSP1 late period (see Annex 3) cause a 20% to 50% decrease in per capita water availability of most sub-basins. Rapid population growth to 443 million inhabitants in the SSP3 scenario drives an almost universal decrease of over 60%. Accordingly, the combined impact of climate change and socio-economic development in the upper Indus largely results in a net increase in the absolute water available to lower Indus sub-basins. However, population growth in the lower Indus basin also requires these resources to be shared among more recipients. The absolute dependency of the lower Indus basin on water resources originating in the upper Indus basin thereby increases. The integrated effect of these processes drives the mean per capita water availability for the majority of lower Indus sub-basins in the SSP1 late period to reduce by 10% to 40% compared to reference period availability, with only the sub-basins downstream from the Beas sub-basin showing slight increase (see Figure 7). In SSP3 the integrated drivers cause a general reduction between 40% to 60%. The double sided negative effects of socio-economic development on lower Indus water availability thus outpace the positive effect of climate change.

4 Discussion

In this study we quantified the development of water consumption in the upper Indus basin and its effect on water availability in the lower Indus basin. The water accounting analysis that was applied to obtain these results by design is a simplified conceptual representation of the complex Indus basin water system, as this allowed the broader patterns of upstream-downstream dependencies to be assessed. The methodological approach influences the quantifications presented in this study and their implications.

Primarily, upper Indus consumption was assumed to be fulfilled exclusively with surface water resources generated seasonally within the sub-basins. In reality, there may be spatial mismatches or quality related preference that cause part of upper Indus water demands to be fulfilled with unsustainable groundwater extractions. Groundwater reservoirs may moreover perform a modulating role between seasons, with excess surface water resources infiltrating in wet periods to be used in times when water is scarce. Around the city of Kabul groundwater levels have however dropped considerably over the last decades(Mack et al., 2013). Similarly, on the lower Indus plains, groundwater resources are an important supplementary source for urban and agricultural water demand(Basharat et al., 2015; Biemans et al., 2019; Wijngaard et al., 2018), but are also depleting rapidly(Richey et al., 2015; Salam et al., 2020). The impact of upper Indus basin water consumption on water availability in the lower Indus in the dry season will be reduced while these resources are still available. This does however imply that groundwater dependency, and thereby overextractions, are likely to aggravate. Due to a lack of spatial coverage in observational data, the availability and long-term durability of groundwater resources in the upper Indus basin remain uncertain(Cheema et al., 2014; Qureshi et al., 2010; Salam et al., 2020). More research into the status and development of groundwater here is required so that it may be considered in future research steps.

Water quality issues can similarly play an important role in upstream-downstream relations(Wolf, 2007). Return flows from domestic, industrial and agricultural water usage upstream may be polluted and reduce the downstream availability of water that is of usable quality(Yoon et al., 2015). However, water stress and availability in our analysis are operationalized using indicators for water quantity. The water stress experienced in the lower Indus due to expanding upstream activities may hence be higher than the reduction in availability projected in this study, if pollution prevention measures are not taken. Follow-up research could expand the water accounting analysis applied in this research with water quality indicators for a more holistic assessment of future upstream-downstream linkages.

Lastly, our analysis assumes upstream outflows are distributed equally over all downstream inhabitants. Water use activities in the lower Indus sub-basins are thereby not considered. However, inhabitants closer to upper Indus sub-basins may consume more upstream water than their equitable allocated share and reduce water availability further downstream. Other lower Indus sub-basins with surplus local water resources may positively affect water availability in other sub-basins. The results of this study thus provide quantified insight into general trend of lower Indus water availability and the times and areas most likely to be affected by changing upper Indus water use activities, instead of a fully disaggregated quantification of future water available within the lower Indus basin. High-resolution spatial information on the development of water resources is however required to support data-driven adaptation and policy making towards the SDGs(Laghari et al., 2012; Rangecroft et al., 2019; Yillia, 2016). Further spatial disaggregation with fully distributed models and analyses of implications for adaptation measures are important follow-up steps for robust adaptation planning. Follow-up research could additionally perform a similar water accounting analysis to quantify hydrological interactions between sub-basins within the lower Indus. The relation between the irrigation-dominated plains of the Indus midstream and the hyper-arid delta could be of particular interest(Laghari et al., 2012). The quantifications presented here do nonetheless provide valuable initial insight into the increasing relevance of water use activities in the upper Indus for the basin's upstream-downstream linkages. Consistent with other studies(Vinca et al., 2020; Wijngaard et al., 2018), per capita water availability in the lower Indus was shown to decrease over the projected period under integrated climatic and socio-economic changes, while the dependency on upstream water resources increases. Within this development, the aggregated reduction in average annual lower Indus water availability, that can be contributed to expanding water consumption in the upper Indus, remains negligible between 4% and 5%. However, our results also demonstrate that, when spatio-temporally disaggregated, hotspots seasons and sub-basins emerge in the lower Indus where the reduction in water availability due to upstream consumption exceeds 25%. Most affected hereby are the densely populated and rapidly urbanizing central Indus plains, downstream of the Jhelum and Kabul sub-basins, during the dry winter season. This suggests that growing upstream consumption will considerably contribute to increasing water stress in the lower Indus in the period of the year in which pressure on water resources is already highest (Wijngaard et al., 2018).

This study furthermore provides novel insight into the future water balance of upper Indus sub-basins. Strong population growth was demonstrated to cause the Jhelum and Kabul sub-basins to become water stressed themselves by the second half of the century. During the low-flow winter season consumptive water requirements here will consistently claim the majority of available surface water. The actual water demands required to satisfy consumptive requirements are manifold higher(Bijl et

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al., 2018) and can likely structurally not be met. This indicates that adaptation is essential to mitigate water scarcity issues and achieve water security SDGs in these upstream sub-basins as well. During the wettest period of the year over 90% of surface water remains available. A valuable adaptation avenue suggested by Amin et al. (2018) may therefore lay with modulating seasonal difference with storage dams specifically for upper Indus water provision.

The Kabul and Jhelum are however transboundary sub-basins. Upstream areas and water use activities are located largely in respectively Afghanistan and India, while the densely inhabited downstream plains they supply with water are part of Pakistan. Increasing upstream water use, and hydrological interventions to facilitate this use such as storage dams, may therefore intensify upstream-downstream water competition and aggravate existing hydro-political tensions between the riparian states(Atef et al., 2019; Gupta & Ebrahim, 2017). These issues may further exacerbate as downstream demands are also likely to increase with substantial projected population growth, particularly in the SSP3-RCP8.5 scenario (Wijngaard et al., 2018). Storage dams are additionally likely to cause ecosystem damage. The results of this study therefore support the claims of previous studies(Miner et al., 2009; Qamar et al., 2019; Wada et al., 2019) that the Indus Water Treaty may need to be revisited and include the Kabul basin to ensure equitable and sustainable water allocation across basin countries under changing socio-economic and climatic conditions.

The patterns revealed in this study highlight that ensuing modelling studies of the Indus basin water system and adaptation strategies towards water and food security SDGs must explicitly account for changing upper Indus water usage and its effects on upstream-downstream dependencies. The gridded water consumption projections for the upper Indus basin developed here form an important baseline for such assessments. The identified hotspots moreover provide targets of special consideration for long-term water management, adaptation policy making and future hydrological modelling studies.

5 Conclusion

Growing water usage in the upper Indus basin is a significant factor in the evolving upstream-downstream linkages of the Indus basin. The combined consumption of upper Indus sub-basins is projected to increase from 6.9 $km^3\ yr^{-1}$ presently to 13-17$km^3\ yr^{-1}$ by 2060-2080. This causes considerable pressure on surface water resources in the dry season. The Kabul and Jhelum sub-basins in particular are demonstrated to become increasingly water stressed due to rapid population growth, despite an increase in surface water availability through climate change. Water requirements during the critical winter months here may structurally exceed 50% (Jhelum) and 90% (Kabul) of surface water availability in the future and increasingly impede environmental flows from being met. Scarcely populated upstream sub-basins, such as Satluj and Ravi, instead see the effects of climate change come out ahead and face an overall increase in future water availability.

The large differences in relative upper Indus water consumption between seasons and sub-basins result in spatiotemporal impact hotspots in the lower Indus where surface water availability is reduced by over 25% compared to natural flow conditions. This amplifies a greater decrease in future downstream per capita water availability due to population growth. The negative impact of these two socio-economic drivers outweighs the positive effects of climate change on water availability,

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especially under the rapid population growth of the SSP3-RCP8.5 scenario. Growing upper Indus water consumption particularly plays a substantial role in the decreasing trend of dry season water availability of the densely populated central plains of the lower Indus basin. Expanding water usage in the upper Indus may thus lead to *in situ* water scarcity issues in several upstream sub-basins and intensify the already considerable water stress faced downstream during the dry season.

The quantified outlook on the development of upstream-downstream linkages under various drivers provided in this study holds several insights for long-term water management and adaptation planning in the hydro-politically complex Indus basin. Foremost, adaptation strategies towards achieving the interlinked water and food security SDGs are required not just in lower Indus plains of Pakistan, but also for the Kabul and Jhelum sub-basins of the upper Indus that belong largely to Afghanistan and India. This implies that adaptation policy making must explicitly consider for the future evolution of upstream-downstream dependencies and its transboundary implications for water demand and availability. Disaggregated modelling assessment of the future Indus basin water system in support of the development of such adaptation strategies therefore need to include socio-economic changes in the upper Indus as well. Subsequent research may focus on further untangling Indus upstream-downstream linkages by disaggregating hydrological dependencies within the lower Indus as well, and by evaluating implications by-and-for adaptation strategies.

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Author contributions

WS and HB conceptualised and designed the methodological approach of this study. WS collected the data, performed the data analysis and wrote the original draft paper. MJ and SD were responsible for regional validation and interpretation of model outputs. SD, AL, WI, FL, MJ and HB reviewed and edited the final draft. FL, HB and WW supervised the procedure.

Competing interests

The author declare no competing interests.

Code/Data availability

All code and data are available from the authors upon request.

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Figure 1: Elevation map of the Indus basin with delineation of upper- (numbered) and lower Indus sub-basins.

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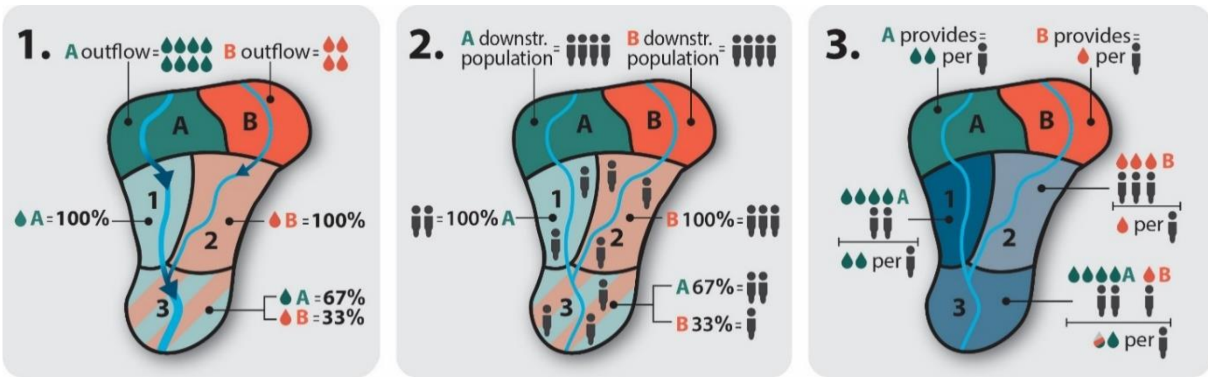

Figure 2: Conceptual representation of the allocation of upstream sub-basin water resources to downstream sub-basins. First, (1) the relative contribution of each upstream sub-basin to the total upstream inflow of each downstream sub-basin is determined. Next, (2) the population of each downstream sub-basin is determined and assigned to the upstream sub-basins by their relative flow contribution. Lastly, (3) upstream outflows are divided by their total assigned downstream populations to obtain the per capita upstream water availability they provide to the downstream sub-basins. The upstream per capita water availability per downstream sub-basin is the mean per capita availability provided by all contributing upstream basins, weighted by their assigned populations. The total per capita water availability of a downstream sub-basin is determined by aggregating the local downstream per capita water availability and the upstream per capita water availability.

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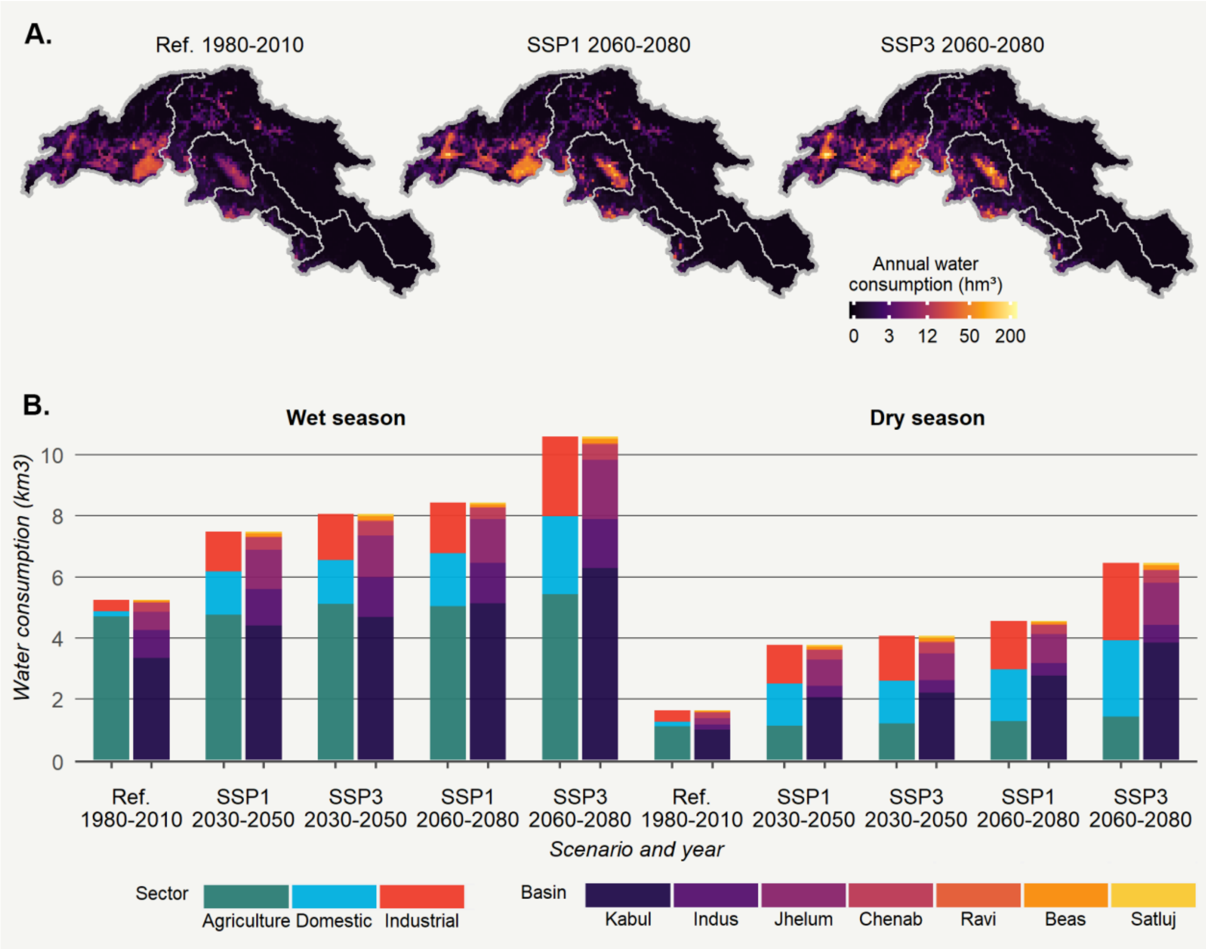

Figure 3: Spatially (A.), seasonally and sectoral (B.) disaggregated water consumption in the sub-basins of the upper Indus basin. Agricultural water use is based on the ensemble mean.

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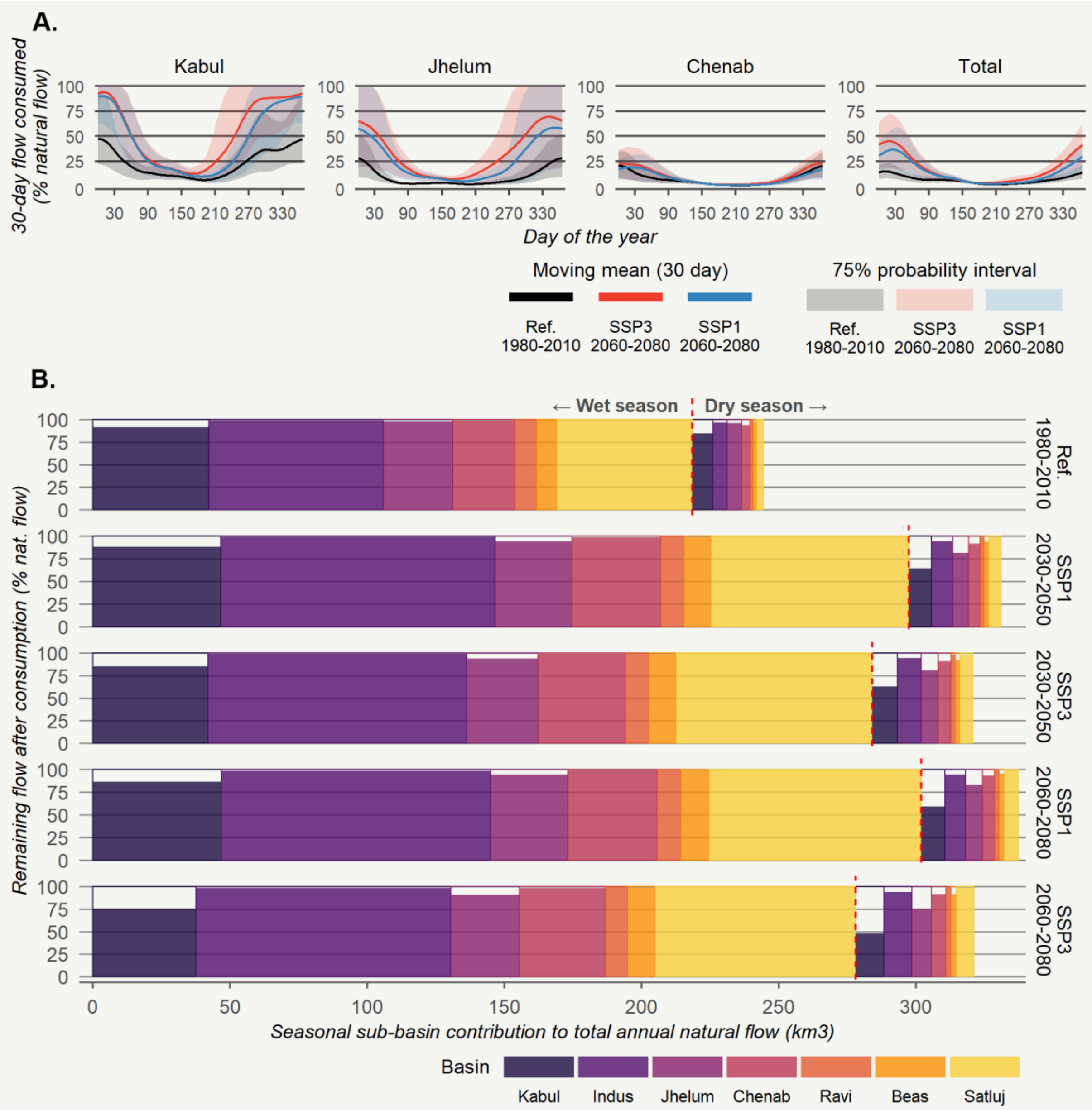

575 **Figure 4: Daily share of natural flow consumed in upper Indus sub-basins during the reference period and the projected late time periods (top). Development of ensemble mean absolute upper Indus outflow under climate change and the impact of consumption (bottom).**

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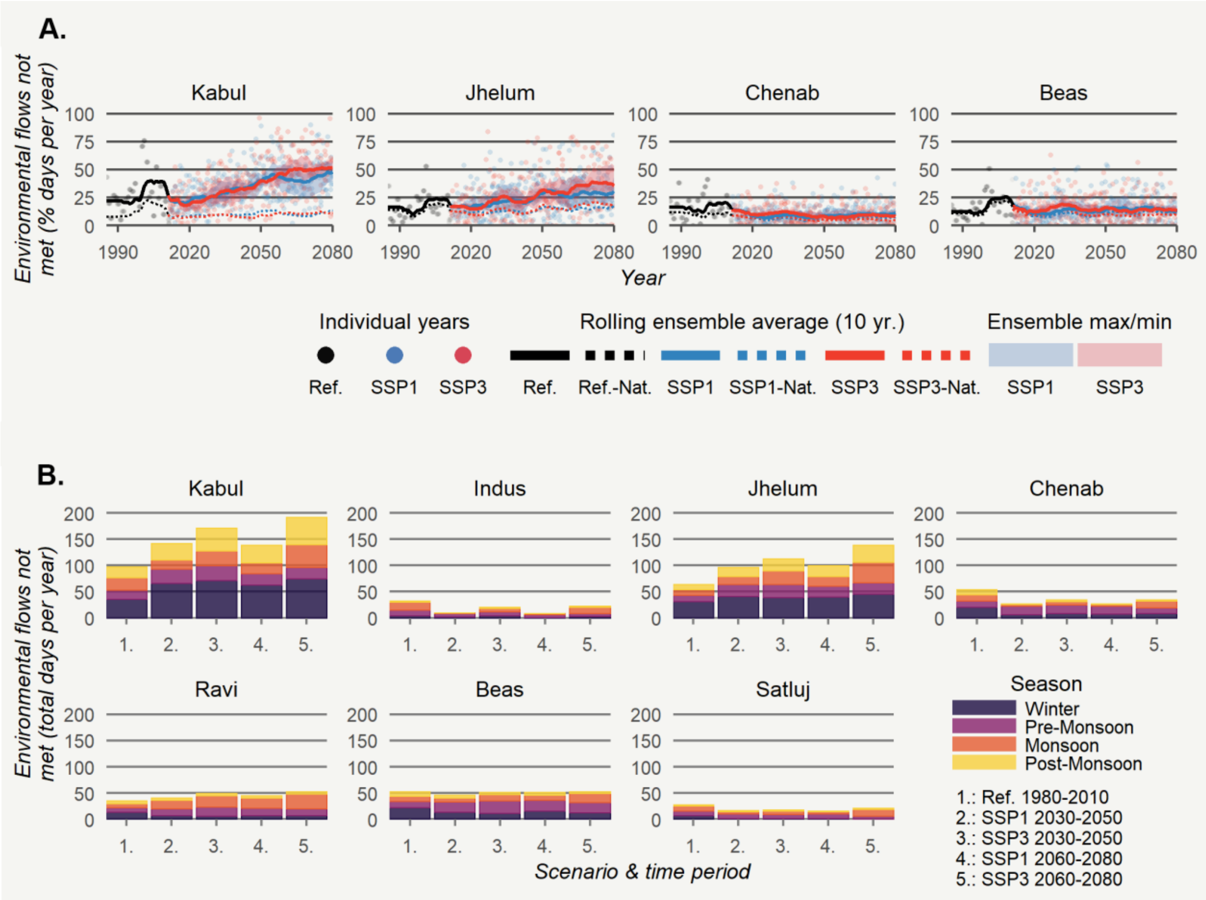

580 **Figure 5: Impact of upper Indus consumption on environmental flows at the outlet of the upper Indus sub basins over the assessment period (A.) and per season (B.).**

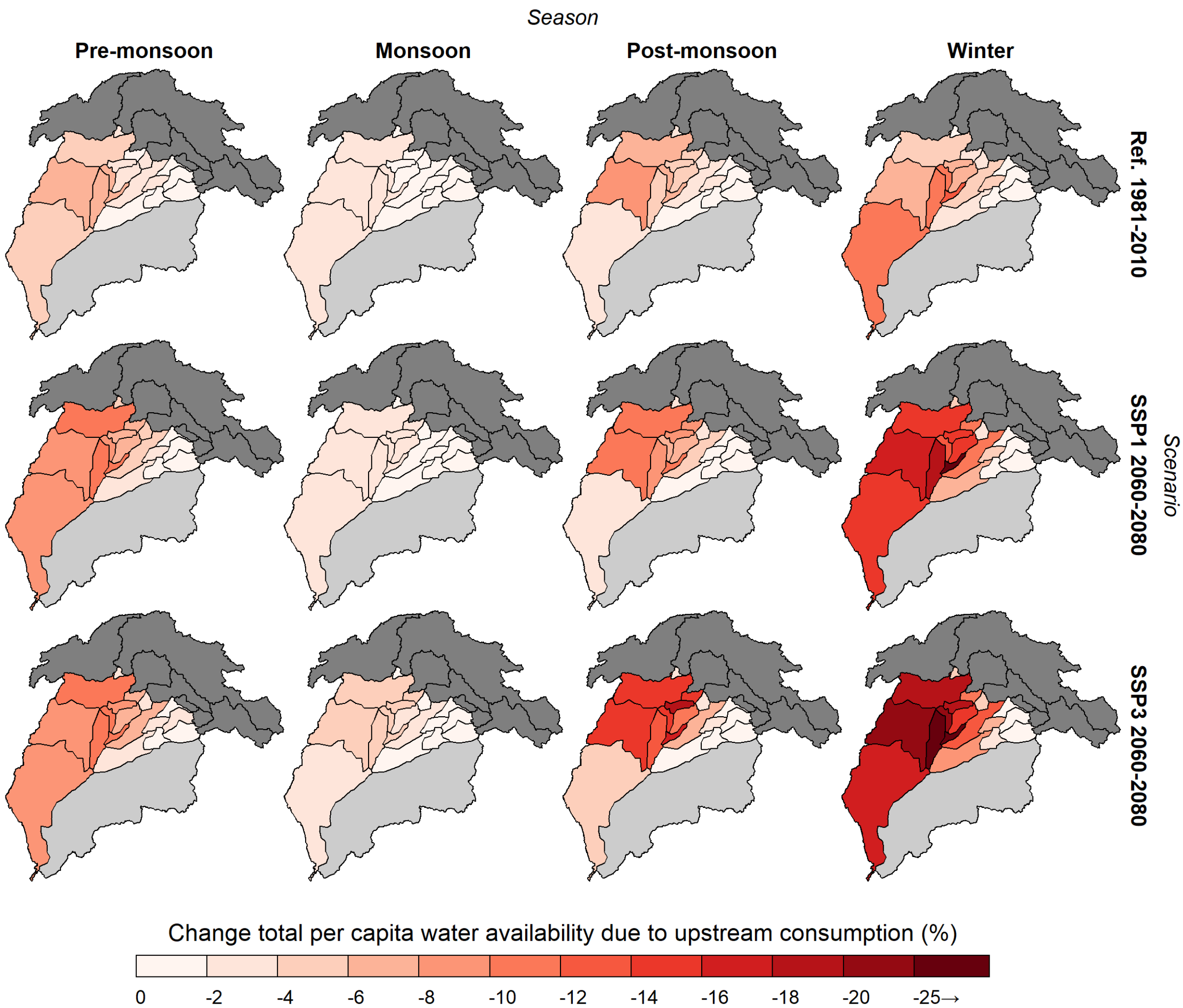

Figure 6: Seasonal mean impact of upper Indus water consumption on the water availability per capita of the lower Indus sub basins for all years and ensemble members. The dark grey area herein represents the upper Indus sub-basins. The light grey area is not downstream of any of the upper Indus sub-basins and is therefore omitted.

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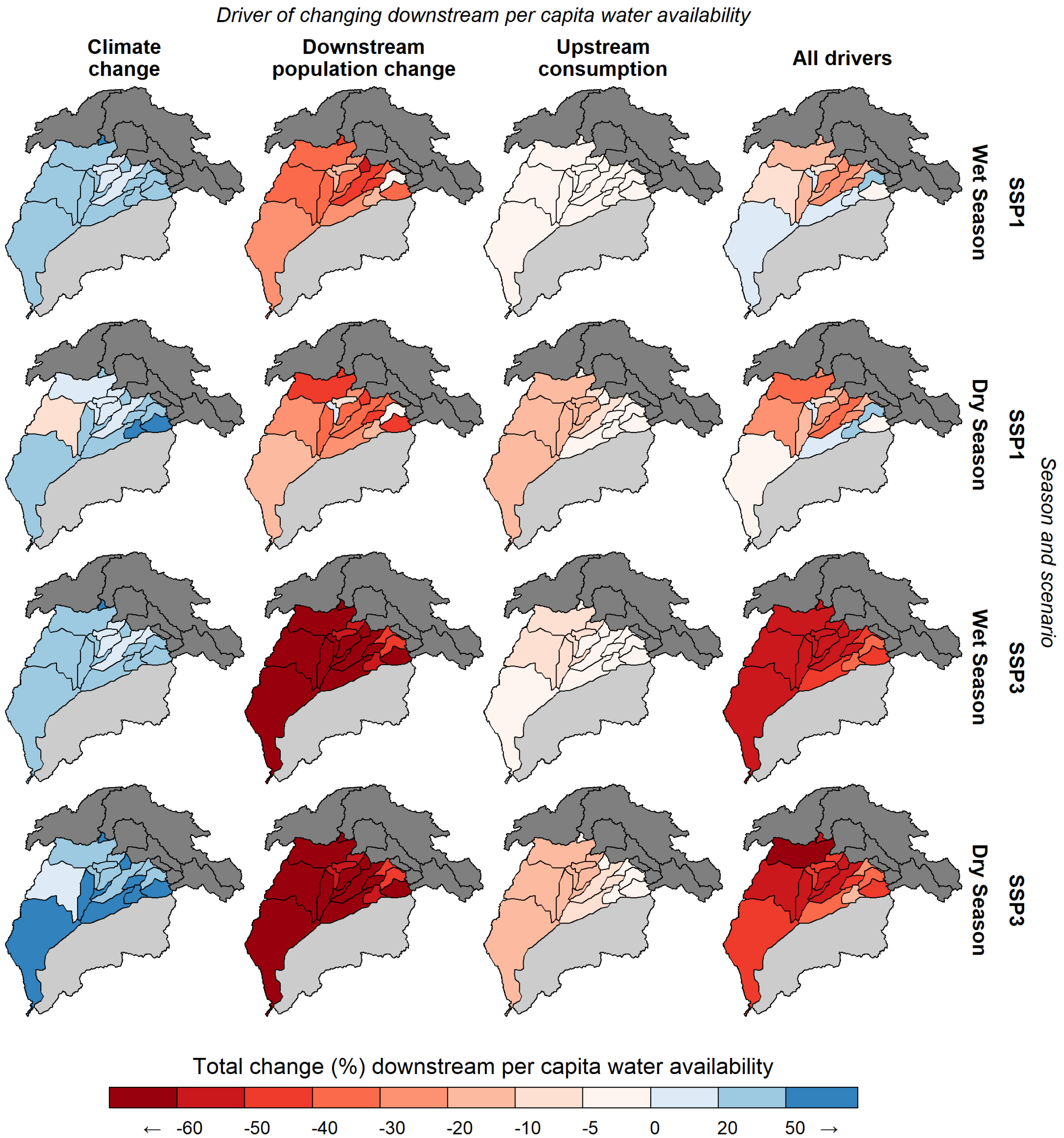

590 **Figure 7: Isolated impact of climate change, downstream population change and upstream consumption on seasonal lower Indus water availability in the late period (i.e. compared to late period situation without the effect of the respective driver). Additionally the change in late period water availability with all drivers considered, compared to reference period water availability.**

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Table 1: Input datasets used for water accounting analysis

Input dataset	Resolution (time/space)	Source
Discharge		
Upper Indus	Daily 1980-2100/ Sub-basin outlets	Wijngaard et al. (2017)
Lower Indus	Daily 1980-2080/ 5 arcmin	Simulated by this study, model and calibration from Bondeau et al. (2007) & Biemans et al. (2016)
Consumption		
Domestic	Annual 1980-2080/ National level	Simulated by this study, model and calibration from Bijl et al. (2016)
Industrial	Annual 1980-2080/ National level	Simulated by this study, model and calibration from Bijl et al. (2016)
Agricultural	Monthly 1980-2080/ 5 arcmin	Simulated by this study, model and calibration from Bondeau et al. (2007) & Biemans et al. (2016)
Scenarios		
Population projections	Annual 1980-2080/ 5 arcmin	Smolenaars et al., (2021) for future (2015-2080) & Klein Goldewijk et al. (2011) for historical (1980-2015)
GDP projections	Annual 1980-2080/ National level	Future (2015-2080) Smolenaars et al., 2021 & historical (1980-2015) Dellink et al. (2017)
Climate data	Daily 1980-2100/ 5 arcmin	Lutz, ter Maat, et al. (2016)

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Table 2: Development of population, water consumption, natural flow and water availability (ensemble means) for the upper Indus sub-basins.

Sub-basin	Population (millions)					Natural flow (km3)									
	Ref.	*Mid.*		*Late.*		*Ref.*		*Mid.*				*Late.*			
	-	*SSP1*	*SSP3*	*SSP1*	*SSP3*	-		*SSP1*		*SSP3*		*SSP1*		*SSP3*	
						Dry	*Wet*	*Dry*	*Wet*	*Dry*	*Wet*	*Dry*	*Wet*	*Dry*	*Wet*
Kabul	16	40	47	46	74	7.5	42	8.3	47	9.2	42	8.7	47	10	37.7
Upper Indus	4.5	6.9	8.1	6.2	9.4	5.2	63	7.8	100	8.7	94	7.4	98	10	93
Jhelum	7.9	16.9	17.1	16.6	23.1	5.3	25	5.9	28	6.2	26	6.4	28	7.2	25
Chenab	2.6	3.9	4.4	3.0	4.7	3.0	23	4.1	32	4.6	32	4.3	33	5.2	31
Ravi	0.33	0.26	0.41	0.11	0.31	1.1	7.9	1.5	8.4	1.6	8.4	1.6	8.6	1.8	8.2
Beas	0.95	1.4	1.7	1.4	2.0	1.3	7.6	1.7	10	1.7	9.9	1.9	10	1.9	10
Satluj	0.68	0.82	1.1	0.58	1.2	2.5	49	4.4	72	4.7	71	5.2	77	6.4	73
Total	**33**	**70**	**80**	**74**	**114**	**26**	**218**	**34**	**297**	**37**	**284**	**35**	**302**	**43**	**278**

Sub-Basin	Water consumption (km3)					Water availability (m3/cap/year)				
	Ref.	*Mid.*		*Late.*		*Ref.*	*Mid.*		*Late.*	
	-	*SSP1*	*SSP3*	*SSP1*	*SSP3*	-	*SSP1*	*SSP3*	*SSP1*	*SSP3*
Kabul	4.3	6.5	6.9	7.9	10.1	3090	1380	1090	1210	640
Upper Indus	1.1	1.6	1.7	1.7	2.2	15160	15620	12680	17000	10960
Jhelum	0.81	2.1	2.3	2.4	3.3	3840	2010	1880	2070	1390
Chenab	0.48	0.74	0.83	0.67	0.91	10000	9260	8320	12430	7700
Ravi	0.034	0.046	0.065	0.033	0.058	27270	38080	24390	92730	32260
Beas	0.090	0.19	0.23	0.18	0.29	9370	8360	6820	8500	5950
Satluj	0.054	0.11	0.15	0.092	0.17	75740	93170	68820	141720	66170
Total	**6.9**	**11.3**	**12.2**	**13.0**	**17.0**	**7380**	**4720**	**4010**	**4560**	**2790**

Sub-Basin	Water availability- only pop. change (m3/cap/year)					Water availability – only climate change (m3/cap/year)				
	Ref.	*Mid.*		*Late.*		*Ref.*	*Mid.*		*Late.*	
	-	*SSP1*	*SSP3*	*SSP1*	*SSP3*	-	*SSP1*	*SSP3*	*SSP1*	*SSP3*
Kabul	3090	1240	1050	1080	670	3090	3460	3200	3480	2980
Upper Indus	15160	9880	8420	11000	7260	15160	23960	22820	23420	22890
Jhelum	3840	1790	1770	1830	1310	3840	4290	4080	4350	4080
Chenab	10000	6670	5910	8670	5530	10000	13880	14080	14350	13920
Ravi	27270	34620	21950	81820	29030	27270	30000	30300	30910	30300
Beas	9370	6360	5240	6360	4450	9370	12320	12210	12530	12530
Satluj	75740	62800	46820	88790	42920	75740	112350	111320	120880	116760
Total	**7380**	**3470**	**3050**	**3290**	**2120**	**7380**	**10050**	**9710**	**10230**	**9720**

Water stress level:

None	Low	Moderate	High	Absolute