

Response to Reviewer

Interactive Comment on “Climate change vs. Socio-economic development: Understanding the future South-Asian water gap” by René R. Wijngaard et al.

We greatly acknowledge the reviewer for his/her remarks and suggestions, which improved the quality of the manuscript significantly. We have carefully considered the suggestions of the reviewer and we provide a point-by-point response to the reviewer's comments. For clarity, the reviewer's comments are given in italics and the responses are given in plain text. References that do not refer to those in the main manuscript are listed below. The manuscript will be modified accordingly to the responses that are given to the comments.

The research in the article under review is an attempt to predict the combined impact of climate change and socio-economic changes on water scarcity in the downstream portions of 3 rivers originating in the Himalayas: the Indus, the Ganga and the Brahmaputra. It seeks to improve upon earlier predictive modelling by using a larger ensemble of climate predictions, separate hydrological models for upstream (hill) and downstream (plains/delta) regions, and more careful simulation of agricultural water use in the downstream region through using recently developed models that simulate distribution through canal systems and timing of water demand in multiple cropping systems. It also draws upon recently published Shared Socioeconomic Pathways (SSP) developed by the climate change community that describe alternative socio-economic development scenarios.

The technical side of the research has been done quite competently for the most part and the writing is also mostly clear and well organized. My concerns with the paper mostly are at the macro-level, viz., as to what (value) assumptions it makes in framing the research, and what contribution it makes to our understanding of the likely outcomes of multiple-stressors operating in the study region. Also a couple of concerns about the modelling.

Thank you. We have tried to address all concerns and our detailed response is provided below.

1. *Water uses considered: The authors only take into consideration water use in agriculture, industry and the domestic sectors. In doing so, they leave out in-stream environmental (and fishing) needs, as well as minimum ecosystem flows that need to go out to the ocean. This framing creates the impression that it is ‘okay’ to consume all the surface flow, which is problematic. Given the higher temporal and spatial resolution that the models have incorporated, the authors can easily provide for these other uses also. Which uses to cater to is of course a value-loaded decision, but no more than the decisions already made. The authors could allow for variation in societal values by showing the trade-offs between (e.g.) meeting minimum ecosystem flow standards (that might affect agricultural production) and prioritising agricultural needs (thereby violating minimum flows).*

We indeed only consider water use in the agricultural, domestic, and industrial sectors. We consider water use in these sectors, because these sectors are the largest water consumers in South Asia (FAO, 2016). Although there is a version of LPJmL that does allocate water requirements of aquatic ecosystems and its trade-off with food production (Jägermeyr et al., 2017), we decided not to impose any restrictions to withdrawals in this study, because we believe that the water requirements by ecosystems are not considered in this region (yet). Since the Indus, Ganges, and Brahmaputra river basins are facing rapid and continuous population growth, food demand will increase and a higher agricultural production is required. Therefore, agricultural needs will probably be prioritized at the cost of environmental flows. To investigate which impact (future) blue water consumption has on environmental flow transgressions we have however added an extra subsection “Environmental Flows” to the Results section. The outcomes in this subsection show that the transgression of future environmental flows will likely be limited with sustained environmental flows requirements (EFRs) during the monsoon season and unmet EFRs during the low flow season in the Indus and Ganges river basins. Further we discuss environmental flows and the use of EFRs in the Introduction section and will add an extra subsection “Analysis of

Environmental Flows" to the Methods section to describe the methodology behind the derivation of EFRs.

2. *Definition of water scarcity: The manner in which water scarcity is defined (with respect to the above 3 uses) is in terms of a 'blue water gap' (gap between supply and demand of blue water) which then manifests itself as over-extraction of groundwater. But over-extraction has inter-temporal effects, so it seems that this is a definition of 'unsustainability'. On the other hand, the manner in which groundwater overextraction manifests itself is in the form of loss of base flows, which means either loss to agri/domestic users downstream or loss to instream/ocean uses. Neither of which is captured here. Scarcity can be the outcome of distributional issues unrelated to absolute availability. So one definition of scarcity could have been the fraction of the population (in each sector) facing water shortages. More generally, 'scarcity' is a social construct, and if the research is to be useful to policy-makers in the region, the 'outcome variable' in the modelling must reflect local, multiple understandings of scarcity.*

The influence of groundwater (over-)abstraction on the amount of baseflow and subsequent availability for downstream agricultural, domestic, and industrial users are captured in the model. In the LPJmL model groundwater reservoirs are replenished by seepage from the bottom soil layers and contribute to the river network by means of baseflow. Baseflow is calculated by means of a linear reservoir function, where groundwater only adds to baseflow when groundwater recharge is larger than groundwater withdrawal. When groundwater recharge is smaller than groundwater withdrawal, no baseflow does occur, which results in a loss of streamflow. This will eventually have an impact on downstream water availability. We will add an extra sentence to the model description of LPJmL to clarify the relation between groundwater bodies and the river network.

We agree with the reviewer that water scarcity can indeed be understood as the outcome of distributional issues unrelated to absolute water availability and therefore can be defined as the lack of access to adequate quantities of water that are needed to fulfil water requirements. The blue water gap as defined in our study is a way to measure the water scarcity by means of unsustainable groundwater withdrawal, which in the LPJmL model can only occur when surface water or renewable groundwater is not available. That surface water or renewable groundwater is not available locally makes that there are no adequate quantities of water and is thus an indication for water scarcity. The main advantage of using the blue water gap as indicator is that we can account for all spatial and temporal mismatches between water demand and supply, which is therefore a way to show the heterogeneity in water scarcity throughout the basins. The magnitude of the water gap is highly depending on the presence of local reservoirs and canal systems, and on the area where the water gap occurs. Figure 9 illustrates very well that the water gap is especially an issue in urban areas, whereas in rural areas the water gap is limited. In combination with the identification on which drivers and processes are responsible for the development of the water gap, this can provide valuable information for policy makers, and shows that the water gap similar to water scarcity can be interpreted as a social construct. We agree with the reviewer that the fraction of the population facing water shortages could have been a way to measure water scarcity. However, according to Liu et al. (2017) there are also other indicators that can be used to measure water scarcity, which can lead to different outcomes. The large variety in indicators makes it therefore difficult to compare the outcomes of one study with the other. To have a robust representation of water scarcity future studies might be needed that assess water scarcity by using a set of multiple indicators. We will add this point to the discussion. Further we will change the manuscript to put more emphasis on assessing the future evolution of the blue water gap and not the future blue water scarcity, which is a broader term.

3. *Contribution: The need to model the impact of multiple stressors rather than of climate change in isolation has now been recognized in the water resources community for a while. In a well-known coarse-scale analysis, Vorosmarty et al. (2000) pointed out that rising human demand for water will outweigh the impacts of climate change on water resources in the south Asian region. [The authors appear to have misinterpreted this study in p.2 line 30: Vorosmarty et al conclude "that impending global-scale changes in population and economic development over the next 25 years will dictate the future relation between water supply and demand to a much greater degree than will changes*

in mean climate.”]. So the question is in what way does this study deepen our understanding of this broad trend or likely responses?

My assessment is “not much, given the uncertainties involved and the limitations of the approach used” [uncertainties are also discussed below]. That climate change is predicted to increase water availability in all 3 basins is clear, once one reads the CC predictions for this region from the GCM runs chosen. That socio-economic developments will (in the absence of any adaptive responses) lead to increases in water demand is obvious to anyone who knows the region. The net result is that “The combination of climate change and socio-economic development is expected to result in increasing water gaps with relative increases up to 7% and 11% in the Indus and Ganges, respectively” [p.18, line 27]”. To my mind, this small change is well within the errors/uncertainties of all the modelling that has been done. (Since these results are not presented in tabular form but only in the bar charts in Figure 8, it is even hard to see that the water gap has actually increased vis-à-vis the reference scenario.) So one is unable to see the value of such a coarse result. The lack of endogeneity in the modelling framework (i.e., the fixed nature of landuse predictions driven by population growth and economic change and the lack of any adaptive response by any water user to water scarcity) means that we are unable to see to what extent adaptive actions might ameliorate the problem. And the lack of information on “who actually suffers because of the scarcity” prevents the analysis from throwing up any interesting social impact information.

We agree with the reviewer that we misinterpreted the outcomes of Vörösmarty et al. (2000). We have corrected this accordingly. We also agree with the reviewer that the need to model the impact of multiple drivers rather than climate change in isolation has been recognized in the water resources community. There have been several global studies, including those from Vörösmarty et al. (2000) and Hanasaki et al. (2013), that have investigated the impacts of climate change and/or socio-economic development on water scarcity. These studies have concluded that rising water demands as a response to socio-economic developments are a more important driver than climate change. This might also be obvious for the Indus, Ganges, and Brahmaputra river basins. However, there has not been a study so far that conducted a high resolution integrated assessment on the evolution of the future blue water gap in the Indus, Ganges, and Brahmaputra river basins, thereby aiming at quantifying the impacts of climate change and/or socio-economic development on the regional water gap. The main difference with global studies, such as the study of Vörösmarty et al. (2000), is that a) a coupled modelling approach is applied for the entire IGB that includes a high-resolution cryospheric-hydrological model that can simulate upstream water availability (and represents mountain-hydrological processes that are important in the region), and a high-resolution hydrology and crop production model that can simulate the downstream water availability, supply, demand, and gap; b) the hydrology and crop production model that is applied for downstream domains has specially been developed for this region by including human interventions, such as the extensive irrigation canal systems of the Indus and Ganges river basins, and multiple cropping systems; c) the high resolution models are forced with an ensemble of downscaled and bias-corrected GCMs, that represents a wide range of possible futures in terms of regional climate change for RCP4.5 and RCP8.5, in combination with SSP storylines. These novelties are highlighted in the last paragraph of the Introduction.

We made one miscalculation. The ensemble mean of the projected changes in the water gap of the Ganges river basin is 14% instead of 11%. The relative changes of 14% and 7% that are projected for the Ganges and Indus river basins, respectively are indeed within the uncertainty range of model outcomes that are generated for the different climate models in combination with SSP storylines. We agree with the reviewer that it is difficult to read the changes in the water gap from Figure 8. We will include an extra table that lists the ensemble means and standard deviations of the projected changes in the future blue water gap at the end of the 21st century.

We are aware that the lacking endogeneity of land use and adaptive responses of water users in the modelling framework are likely to introduce uncertainties in the outcomes of the model. This study aims however at providing a first comprehensive integrated assessment that identifies the main processes and drivers that are responsible for changes in the future water gap. Investigating the impact of adaptation strategies on the future water gap is beyond the scope of this study and needs further investigation in the future by assessing the potentials of well-informed realistic adaptation strategies (i.e. that have been

developed by means of piloting) in closing the water gap. We will add a paragraph to the discussion on the uncertainties that can emerge due to the lacking adaptive response. The uncertainties due to lacking endogeneity are mentioned in the discussion on uncertainties and limitations.

4. *Modelling: There are some concerns with the manner in which the modelling has been done. They may not all affect the results seriously, but need to be tabled and discussed:*

a) *Groundwater is treated as being separate from surface water. E.g., page 2, line 3 says the 3 sources of water are rainfall-runoff, groundwater and meltwater. This would be true if runoff did not include baseflows, which is groundwater returning to the surface as discharge (see Ponce, V.M., 2007. Sustainable yield of groundwater. http://ponce.sdsu.edu/groundwater_sustainable_yield.html, and Sophocleous, M., 2000. experience. Journal of Hydrology 235, 27–43.). But then on page 7, line 2, the authors say total runoff is sum of glacier & snow runoff (presumably melt), surface runoff, lateral flow and baseflow. This then leads to double counting, since “water for irrigation and other uses can be drawn from surface water in the grid cell [which would include baseflows], etc etc. and groundwater bodies” (page 8, line 10-12).*

We categorize groundwater and surface water according to definitions that are consistent with commonly used definitions of the FAO and other water use studies, such as Siebert et al. (2010). Thereby, groundwater is defined as water that is abstracted from groundwater bodies (i.e. shallow/deep aquifers) by using (artificial) wells, and surface water as water that is abstracted directly from rivers, lakes, and reservoirs. Groundwater that has not been withdrawn locally will add to baseflow and enters surface water by means of drainage. From the moment baseflow enters surface water it is considered as surface water when it is used for downstream water supply. We listed these definitions in Section 3.1 Definitions, but will update the definitions to clarify what we define as groundwater and as surface water.

On page 2, line 3 we indeed mention that the water supply has 3 main components: (monsoon) rainfall-runoff, groundwater, and meltwater. The (monsoon) rainfall-runoff as mentioned in this sentence does not include baseflow, but is defined as the surface component of the total runoff that result from rainfall. We are however aware that this sentence may lead to confusion. Therefore, we will change this sentence and mention that water supply is dominated by two different components: locally pumped groundwater and surface water supplied by irrigation canals. Thereby surface water supplied by irrigation canals that are diverted from rivers and reservoirs has three main constituents: direct rainfall runoff, meltwater from upstream located ice and snow reserves, and baseflow.

The total runoff as described on page 7, line 2 is calculated by the SPHY model, which only simulates upstream water supply and does not include the effects of agriculture/irrigation on water supply. In SPHY, surface runoff is not the same as the baseflow runoff, and are both separate components of the total runoff, which means in SPHY baseflow can be a component of surface water. In downstream domains, we apply the LPJmL model (as described on page 7 line 21-33, and page 8 line 1-14). In LPJmL, the contribution from groundwater to surface water is simulated by means of drainage, which means baseflow is a component of surface water as well. As long groundwater is withdrawn from a grid cell it is not added to the baseflow, which means upstream groundwater withdrawals can affect downstream water availability by decreasing the baseflow contribution. Because of this groundwater and surface water can be treated separately, and double counting does not occur.

b) *This treatment of GW as separate from SW also enables the authors to talk of the blue water gap in terms of unsustainable withdrawal of GW (i.e., withdrawal more than recharge) without realizing that the first impact of such over-withdrawal is the loss of baseflows, which will affect downstream grid cells. GW depletion is not a separate/separable phenomenon, unless one is talking about depleting non-renewable forms of GW.*

In our model, the over-abstraction of groundwater does influence the amount of baseflow and thus the amount of water available for downstream grid cells. As mentioned under comment 4a, groundwater

that is withdrawn cannot be added to the baseflow, which means groundwater withdrawals result in a baseflow reduction and subsequently will affect downstream water availability.

- c) *The 'daily timestep' is clearly a case of spurious precision. Water use is definitely not known/predictable at such a fine temporal scale.*

We agree with the reviewer that it is difficult to predict water scarcity on daily basis. However, to predict water scarcity accurately in river basins that highly depend on upstream (mountain) water resources it is important to have a robust representation of mountain-hydrological processes that are highly variable in space and time. In particular, glacier and snow melt processes are not sufficiently captured at larger time steps. For this reason, it is needed to use hydrological models on a high temporal resolution (i.e. daily). The outcomes however, are aggregated to monthly time steps to assess the monthly and seasonal variations in the water availability, supply, demand, and gap.

- d) *The assumption that 'water availability in upstream regions' (the Himalayan catchments) is dependent upon natural factors' may be true for the Indus and the Brahmaputra, but questionable for the Ganga basin. Uttarakhand and Nepal are witnessing massive interventions in hydrology in the form of dams (large and small) as well as traditional uses for agriculture these regions in a dense network of community-scale irrigation systems.*

We are aware that in the upstream domains also human interventions (such as dams, reservoirs, and irrigation) take place and that this also can influence the hydrological cycle, which means water availability is not fully dependent on 'natural factors'. However, we assume the (current) impact of dams/reservoirs and agriculture to be low in comparison with the influence dams/reservoirs and agriculture have in the downstream domains. For instance, compared to the downstream domains the number of dams/reservoirs is limited. The province the reviewer mentioned as example (i.e. Uttarakhand) is among the upstream areas the area with the most dams and capacity (i.e. 15 dams with a total capacity of about 5 km³) (FAO, 2016). In other upstream areas, the number of dams is rather small and the total capacity is low compared to the larger dams in downstream domains. For instance, Tarbela dam has a total capacity of 12 km³, whereas the total capacity of dams in the upstream domains reach up to about 5.5 km³ distributed over about 50 dams (FAO, 2016). Furthermore, most dams are designed as hydropower dams with limited storage or as run-off-the-river hydropower plants, which have a low degree of regulation in the upstream domains of the IGB (Lehner et al., 2011; FAO, 2016). Further it has been found in earlier studies (Biemans et al., 2016) that the irrigation water demand (and cropping intensity) in upstream areas is rather low (i.e. <100 mm yr⁻¹) in comparison with the irrigation water demand (and cropping intensity) in downstream areas (i.e. >500 mm yr⁻¹). We agree with the reviewer that the absence of human interventions in the SPHY model introduces uncertainties in the amount of water that is available for downstream areas. Therefore, we will add a point to the discussion on to point out this drawback. Further we will also point out that future planned infrastructure need to be included in future work to assess the impact on the blue water gap.

- e) *To the best of my knowledge, the SPHY model has very little stream gauge/river gauge data available (at least in the Ganga basin) to validate itself. So there must be major uncertainties just with the flow predictions for the 'upstream' model.*

We have calibrated and validated the model by means of a three-step systematic approach on upstream and downstream located gauging stations in the three consecutive upstream domains of the IGB (Wijngaard et al., 2017). This approach comprised of the following steps: 1) a calibration on geodetically derived glacier mass balances, 2) MODIS-derived snow cover maps, and 3) a calibration on observed discharge of six gauging stations, namely Dainyor Bridge (upstream UIB), Besham Quila (downstream UIB), Bimalnagar (upstream UGB), Devghat (downstream UGB), Wangdirapids (upstream UBB), and Sunkosh (downstream UBB). This three-step calibration approach was implemented to reduce calibration problems of equifinality (Pellicciotti et al., 2012). The calibration and validation of SPHY resulted in model performances with Nash Sutcliffe Efficiency values between 0.60 ("satisfactory") for

Dainyor Bridge and 0.84 (“very good”) for Devghat. We agree with the reviewer that there can be uncertainties in the streamflow for some of the outflow points of the upstream domains due to different basin characteristics. For a more detailed discussion on uncertainties that are potentially included in the streamflow data, we refer to Wijngaard et al. (2017).

f) *The predictions under climate change and SSP are compared with the ‘reference’ period results, which seem to be the average of the period 1981-2010. This is a lengthy period over which major changes have taken place in the water resource use in this region, and using an average for this whole period makes it unusable as a ‘reference’.*

We are aware that a 30-year period is a lengthy period over which major changes can occur in water use in this region. We have decided to use a 30-year period, because this is common and recommended when investigating climate change impacts. Also in other high impact studies (e.g. Hanasaki et al., 2013; Wada et al., 2013) that investigated current and future water scarcity a period of 30 years is used in the analysis of outcomes, also for the calculation of single averages.

Minor technical and editorial comments are given in the marked up pdf attached herewith.

Minor and Technical Comments

1. P2 L1: What about conservation purposes? Cultural purposes?

According to the FAO AQUASTAT Database (FAO, 2016), the agricultural, domestic, and industrial sectors are the largest water consumers. Cultural water use is related to the amount of water used per capita in each country specifically, and can therefore be interpreted to be part of domestic water use. Requirements for conservation activities have a very low rate of water consumption (FAO, 2016) and have therefore a very low share in the total water consumption in comparison with the agricultural, domestic, and industrial water sectors. To mention that these sectors are the dominant water users, but are not the only water users, we have adapted the sentence to clarify that water is *mainly* used for agricultural, domestic, and industrial purposes.

2. P2 L3: Not separate from surface water. Unless one is talking about non-renewable sources...

We refer to comment 4a.

3. P2 L18: CC will also affect GW when rainfall changes

We agree with the reviewer that climate change will also affect groundwater when rainfall changes. We will add an extra sentence to the manuscript to clarify that long-term precipitation changes may lead to changes in groundwater recharge and storage, and thus may affect groundwater availability. These processes are all included in our modelling system.

4. P2 L23: Mentioning only one possible driver (demographic pressure) makes the approach sound very Malthusian. Economic growth/industrialisation, urbanization, shifting agricultural patterns and trade, and governance issues (including inter-nation conflict) can be as big or bigger drivers as population. These in turn result in human interventions on a variety of scales, including large dam projects and interlinking of rivers-type mega-projects. Since later on in the paper you have taken a broader approach in talking about the multiple stressors, I suggest doing so consistently from the beginning.

We agree with the reviewer that multiple drivers need to be mentioned in the Introduction since the paper also focusses on multiple drivers. Therefore, we will add a few extra sentences to the Introduction that also points out the future changes that are related to the other drivers: economic growth, industrialization, urbanization, and intensification of water use in food production resulting from changes in agriculture.

5. P2 L34: May depend upon how scarcity is defined and measured, rather than difference in prediction quality or rigour.

We refer to comment 2

6. *P3 L9: What about all the other drivers mentioned above? (And some not mentioned?) The real source of uncertainty is because of uncertainty in development pathways and outcomes*

This part of the introduction points out a few examples of the drawbacks of the approaches used in the other studies. We agree with the reviewer that drawbacks related to other drivers also should be mentioned. Therefore, we will include this point into the Introduction to mention drawbacks related to socio-economic drivers. Further, the study of Arnell & Lloyd-Hughes (2014), who investigated the relative contribution of SSPs, RCPs, and climate models to the regional and global impact on absolute exposure to increased water resources scarcity, found that in South Asia the uncertainty related to climate models has the largest relative contribution in comparison with the uncertainty related to RCPs and SSPs. To cover the uncertainties related to the climate models, RCPs and SSPs, we have selected climate models that represent a wide range of possible futures in terms of climate change, and we have included two contrasting RCPs and SSPs.

7. *P3 L15: How can daily scarcity be predicted if even utilities don't know what it is on a daily basis? infrastructure mediates between daily fluctuations in runoff or rainfall and creates delayed and ameliorated effects.*

We refer to comment 4c

8. *P3 L22 & 26: Huge amount of human intervention now happening in upstream (such as Uttarakhand) makes this distinction less tenable? Uttarakhand alone has 15 dams in Gangetic basin, and many more planned/under construction. In addition, there is substantial amount of agriculture in the upstream domain, the impact on which also needs to be understood.*

We refer to comment 4d.

9. *P4 L1: Projections from whom?*

The projections are from the study of Gain and Wada (2014). We have added a reference to this sentence.

10. *P5 L5: Valid point. But a) daily timestep is unrealistic (false precision), and b) only high temporal resolution without comparable spatial resolution is not very useful*

For comment a) we refer to comment 4c. We decided to set up a model on 5 x 5 arc-min, which is a decision based on the spatial resolution of the available datasets. The climate forcings have a spatial resolution of 10 x 10 km, the water demand fields have a spatial resolution of 5 x 5 arc-min. We are aware that with a higher resolution model more accurate outcomes can be achieved. The disadvantage of a higher resolution model is however that model calculation times become larger, which is therefore considered to be less feasible. In addition, higher resolution models would create a false precision since some of the datasets (e.g. the MIRCA2000 dataset) are only available at a 5 x 5 arc-min spatial resolution. Further, the spatial resolution that has been used for our model set-up is already high compared to the spatial resolution that has been used in other (global) studies, which often use a spatial resolution of 0.5° x 0.5° (i.e. ~50 x 50 km) for their model set-ups (e.g. Vörösmarty et al., 2000; Hanasaki et al., 2013; Gain and Wada, 2014).

11. *P4 L16: Needs clarification*

We have changed the sentence for clarification.

12. *P4 L21: This is 1.8km x 5 = 9km N-S and variable width: is this adequately 'high-res' for such a densely populated region with high spatial variability?*

We refer to minor comment 10.

13. *P4 L22: WHY MODEL ENTIRE IGB together? What is the connectivity between I & GB? Or even between G & B?*

We investigate future water scarcity for the Indus, Ganges, and Brahmaputra river basins, because these river basins are the three major river basins of South Asia that have a direct connectivity with the Hindu-Kush Himalayan mountain range and therefore are interesting to study because of their dependency on mountain water resources. The three basins are investigated because of the contrasting differences in

basin characteristics (hydro-climatic and socio-economic) and the way how basins respond to future climate change and socio-economic developments. The Indus basin for instance a very dry arid downstream climate and a large dependency on upstream water resources. The climate is dominated by westerly disturbances and monsoon systems, bringing precipitation in winter and summer. The climate of Ganges and Brahmaputra basins are dominated by the monsoon bringing large amounts of precipitation during summer. The dependency on upstream water resources is large in the Ganges basin and smaller in the Brahmaputra basin. Further, socio-economic developments are expected to be strong in the Indus and Ganges, whereas in the Brahmaputra it is expected to be moderate. We will add a sentence to Section 2 Study Area to clarify why we selected the entire IGB as study domain.

14. P5 L11: What about Tehri Dam, or various large dams in Arunachal?

Tehri Dam and the various dams in Arunachal are located in the upstream domains.

15. P8 L7: Meaning flood irrigation (as a technique), or surface water irrigation? Because surely large parts are irrigated from ground water (as a source).

We mean flood irrigation. We have changed the text of the manuscript according to this comment.

16. P8 L24: About 6 km

A grid cell size of 5 arc-min corresponds with a grid cell size of ~ 9 km in the IGB.

17. P9 L12: Water 'availability' also influenced by pollution. Return flows pollute rivers, and make the water unavailable?

We agree with the reviewer that water availability can be influenced by pollution and that once it is polluted it makes the water unavailable for use. In our approach, we did not take the effects of water pollution on water availability into account. This can be considered as a limitation and might also introduce uncertainties in the outcomes. Therefore, we will add this point to the discussion.

18. P10 L6: Please indicate the spatial resolution of IMAGE

The spatial resolution of IMAGE is 5 x 5 arc-min. However we did not use this information since we only use land use change information at regional level (i.e. for India and the other parts of South Asia).

19. P10 L9: What about the endogeneity of landuse? If water becomes scarce, landuse will change. Maybe 2nd order effect, but should be mentioned.

Endogeneity of land use has been considered in our model approach. In the IMAGE model, the aim is to fulfil the food demand at regional level. If water scarcity limits the yield, land use change occurs by allocating more (rainfed) land to meet the food production needs. We assume however that both the crop production and crop types remain as they are, whereas, in reality, farmers can decide to switch to other crop types or crop varieties when crop growth conditions are not favourable any more (i.e. due to the higher risk for heat stress that is a consequence of increased temperature (extremes)). This will most likely influence the irrigation water requirements and subsequently the projected amount of water scarcity. We will add an extra sentence to clarify that we make assumptions on the crop distributions and the crop types and we will add this point to the discussion to highlight the uncertainties that can emerge from these assumptions.

20. P11 L2: This is too lengthy a period, during which water resource use in this region has undergone huge changes. To quote a single average for this entire period (for any variable) is highly problematic.

We refer to comment 4f.

21. P11 L3: No way to confirm that this represents reality.

Both the SPHY and LPJmL models have been validated in previous studies. The SPHY model has been calibrated and validated for the upstream domains in Wijngaard et al. (2017). The LPJmL model has been validated and tested for global applications, such as river discharge (Biemans et al., 2009), irrigation requirements (Rost et al., 2008), crop yields (Fader et al., 2010) and sowing dates (Waha et al., 2012). For South Asia, the model has been applied to study the adaptation potential of increased

dam capacity and improved irrigation efficiency under changing climate conditions (Biemans et al., 2013), and for the estimation of crop-specific seasonal irrigation water requirements (Biemans et al., 2016). In both studies the irrigation withdrawals have been validated for India and Pakistan. We will include this information in the Data and Methods section of the manuscript.

22. P13 L2: Is this realistic at all?

We stated erroneous values corresponding with relative changes in blue water consumption. The values listed (i.e. 24%/ 42%/ 107%) represent relative increases in blue water consumption that are projected for the mid of the 21st century (i.e. 2041-2070). The relative increases that are projected for the end of the 21st century (2071-2100) correspond with the following values: 36% for the Lower Indus Basin, 60% for the Lower Ganges Basin, and 147% for the Lower Brahmaputra Basin. We will update the manuscript by replacing the old values with new values.

The values are difficult to compare with those from other studies, because regional studies investigating future changes in water consumption, using the RCP/SSP combinations, are lacking. To the authors' knowledge the only regional study implemented is the study of Gain and Wada (2014) in the Brahmaputra River Basin. Nevertheless, the authors of the cited study used the SRES A2 scenario framework to assess changes. The authors of the cited study project an approximate doubling of the blue water consumption in the Lower Brahmaputra between 2000 and 2050 under the SRES A2 scenario, which is often seen as similar to the RCP8.5-SSP3 scenario. These projected changes are in line with the projected changes for the Lower Brahmaputra in our study.

23. P14 L15: This involves the value loaded assumption that all surface water can be abstracted and consumed, leaving nothing for instream flows and flows to the ocean. And to say that 'sustainable gw' is something in addition to surface flows is to forget that all GW recharge would normally (i.e. in the absence of abstraction) end up as discharge (=baseflow in rivers or in coastal aquifers as discharge directly to oceans). In other words, to count both is to double count.

As mentioned under comment 4a, double counting does not occur, because groundwater withdrawals (i.e. abstraction from groundwater reservoirs, using (artificial) wells) prevent groundwater to be discharged as baseflow in rivers. This also implies that in the integrated modelling approach we use groundwater and surface water are not disconnected. When upstream groundwater withdrawals occur, baseflow reduces, which eventually affect downstream surface water availability. Further, in the LPJmL model it is possible to abstract all the available surface water locally, from neighbouring grid cells, the upstream located reservoirs or the canals before groundwater can be withdrawn. However, not all the water that is abstracted is also consumed. Water can be lost during conveyance by open water evaporation or as a return flow into the river network. After the application to the field, again only a part of the water will be used for evapotranspiration (i.e. blue water consumption). The remaining part will recharge groundwater or will discharge as a return flow to the river. We will update the model description to clarify that not all withdrawn water is consumed, and that a part of the withdrawn water is discharged in the river as a return flow.

24. P16 L6: Will farming actually adapt to the shorter growing season or will it try to compensate for the higher temperature through extra irrigation?

In LPJmL, the phenology of a crop (i.e. represented by a single period between sowing and crop maturity) is defined by the accumulated amount of growing degree days (GDD) a crop needs to reach physiological maturity. Thereby, the daily number of GDD is highly depending on temperature, and is defined as the difference between the daily average temperature and a crop-specific base temperature. This means under higher temperatures, the daily number of GDD is higher, and the accumulated amount of GDD (or heat units) necessary for crop maturity is reached earlier, but with lower yields. This means that the growing season for a specific crop becomes shorter. This will not necessarily influence the farmer decision to adapt. However higher temperatures also mean a higher risk for heat stress, which is therefore a likely reason for the farmer to adapt by compensating higher temperature through extra irrigation. We will add this point to the discussion.

25. P16 L16: Unless the other studies used some 'maximum limit' on C as a fraction of A, the fact that they use C/A and this study uses C-A should make no difference to the results.

We agree with the reviewer that the difference in water scarcity indicators among different studies should not make a difference in the water scarcity trends that are projected. However, in terms of absolute numbers the use of different water scarcity indicators among different studies can hamper the comparison of outcomes between those studies. Therefore, we emphasized that the differences between our study and other studies are related to the use of different modelling approaches and scenarios or the use of different water scarcity indicators.

26. P17 L23: More generally, the cropping decisions in this model are not endogenously determined, which in fact they would be

We refer to minor comment 19.

27. P18 L15: Downstream DEPENDENCY would be large only if there is high use of the water that comes from the upstream. The fact that downstream AVAILABILITY is much higher than upstream availability is due to the terrain and rainfall pattern: I & G catchments in the Himalayas get high rain, whereas catchment of B which is in Tibet does not.

Figure 3 of the manuscript shows the surface water availability for the four seasons that prevail in South Asia. It shows that especially during the melt season and the monsoon season the water availability is higher in the upstream regions of the Indus and Ganges basins than in the respective downstream regions (i.e. which can be less than 100 mm/year in the downstream regions of the Indus basin). This can mainly be attributed to the high melt contributions in the upstream Indus (more than 80% at Besham Qila; Wijngaard et al., 2017) and the high precipitation in the upstream Ganges. In the Brahmaputra basin, the difference in water availability between upstream and downstream domains is smaller, but still the upstream part receives over 3000 mm precipitation per year. It indicates that the downstream dependency on upstream water resources is large, especially in the Indus and Ganges basins. This is also indicated by the relative contributions of mountain water to the total discharge at the river outlets of the Indus, Ganges, and Brahmaputra. Relative contributions can reach up to about 80% at the outlets of the Indus and Brahmaputra, and up to about 60% at the outlet of the Ganges (Biemans et al., in prep.).

28. P18 L16: Could this simply be an artefact of glaciers melting, thereby generating much more rapid runoff in the Himalayas?

This cannot be seen as an artefact. The projections for the upstream domains show increases in ice melting and precipitation in the Indus river basins, and an increase in precipitation in the Ganges river basin. The increased ice melting and precipitation eventually result in increased runoff in the Himalayas.

29. P18 L26: Isn't this within the uncertainty of the models?

We refer to comment 3.

30. P18 L29: Shouldn't this have been fairly obvious, the moment one considers the climate predictions for this region, and knowing the socio-economic trends in this region?

Yes, it should be obvious that socio-economic development is a key driver in the evolution of the South Asian water gap, whereas climate change works as a decelerator. Though it is obvious, there has not been a study so far, quantifying the impacts of climate change and/or socio-economic development on the evolution of the water gap in the IGB by using a high-resolution modelling approach that considers seasonal variations and which is forced by a set of (combined) climate change and socio-economic scenarios.

31. P23 L5: Cannot find this reference. Is it published? Or submitted?

The reference of Lutz et al. (under review) belongs to a publication that is currently under review.

32. P28: Please indicate the source of this data.

To derive this map, we have extracted data from the MIRCA2000 dataset (Biemans et al., 2016; Portmann et al., 2010). We will add a reference to the caption of the figure.

References

Biemans, H., Siderius, C., Lutz, A. F., Nepal, S., Ahmad, B., Hassan, T., von Bloh, W., Wijngaard, R. R., Wester, P., Shrestha, A. B. and Immerzeel, W. W.: Himalayan mountain water resources crucial for downstream agriculture, in prep.

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Response to Editor

Interactive Comment on “Climate change vs. Socio-economic development: Understanding the future South Asian water gap” by René R. Wijngaard et al.

We greatly acknowledge the editor for his/her remarks and suggestions, which improved the quality of the manuscript significantly. We have carefully considered the suggestions of the editor and we provide a point-by-point response to the editor's comments. For clarity, the editor's comments are given in italics and the responses are given in plain text. The manuscript will be modified accordingly to the responses that are given to the comments.

I agree with the major comments and concerns of the anonymous reviewer. In addition, I would like the authors to add a brief discussion in the "Uncertainties and Limitations" section on the possible non-stationarity in the hydrologic model parameters because of the change in climate and landuse.

Thank you. We have added a brief discussion on the possible non-stationarity in the hydrological model parameters in the section “Uncertainties and Limitations”.

Climate change vs. socio-economic development: Understanding the future South Asian water gap

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Abstract. The Indus, Ganges, and Brahmaputra (IGB) river basins provide about 900 million people with water resources used for agricultural, domestic, and industrial purposes. These river basins are marked as “climate change hotspot”, where

15 climate change is expected to affect monsoon dynamics and the amount of meltwater from snow and ice, and thus the amount of water available. Simultaneously, rapid and continuous population growth, and strong economic development will

likely result in a rapid increase in water demand. Since quantification of these future trends is missing, it is rather uncertain how the future South Asian water gap will develop. To this end, we assess the combined impacts of climate change and socio-economic development on the future “blue” water gapsearcity infor the IGB until the end of the 21st century. We apply a coupled modelling approach consisting of the distributed cryospheric-hydrological model SPHY, which simulates current

20 and future upstream water supply, and the hydrology and crop production model LPJmL, which simulates current and future downstream water supply and demand. We force the coupled models with an ensemble of eight representative downscaled

General Circulation Models (GCMs) that are selected from the RCP4.5 and RCP8.5 scenarios, and a set of land use and socio-economic scenarios that are consistent with the Shared Socio-economic Pathway (SSP) marker scenarios 1 and 3. The

25 simulation outputs are used to analyse changes in the water availability, supply, demand, and gapsearcity. The outcomes show an increase in surface water availability towards the end of the 21st century, which can mainly be attributed to increases

in monsoon precipitation. However, despite the increase in surface water availability, the strong socio-economic development and associated increase in water demand will likely lead to an increase in the water gap during the 21st century.

30 This indicates that socio-economic development is the key driver in the evolution of the future South Asian water gap. The transgression of future environmental flows will likely be limited with sustained environmental flow requirements during the monsoon season and unmet environmental flow requirements during the low flow season in the Indus and Ganges river basins.

1. Introduction

Freshwater resources are essential for hundreds of millions of people living in South Asian river basins. The Indus, Ganges, and Brahmaputra (IGB) river systems provide about 900 million people and the world's largest irrigation scheme (i.e. Indus Basin Irrigation System's (IBIS)) with water, which is mainly used for agricultural (e.g. irrigation), domestic (e.g. drinking water supply), and industrial purposes, (FAO, 2012; Klein Goldewijk et al., 2010; Rasul, 2014; Shrestha et al., 2013).

The water supply in the IGB is mainly dominated by ~~two~~^{three} different components: locally pumped groundwater and surface water supplied by irrigation canals, ~~-, (monsoon) rainfall runoff and meltwater from ice and snow reserves that feed the headwaters~~. Groundwater is an important water supplier for the agricultural sector with contributions of about 64% and 33% to the total irrigation water supply in India and Pakistan, respectively (Biemans et al., 2016; Siebert et al., 2010).

Surface water is supplied by irrigation canals that are diverted from rivers and reservoirs, and constitute of direct rainfall runoff, meltwater from upstream located ice and snow reserves, and baseflow. Meltwater is the largest constituent of the total annual surface flow in the western part of the IGB, where the amount of winter precipitation is substantial and the largest ice reserves are present (Bookhagen and Burbank, 2010; Immerzeel, 2008; Lutz et al., 2014; Rees and Collins, 2006).

In the eastern part of the IGB, where ~~the~~ monsoon systems are more dominant, the monsoon precipitation is the largest constituent of the total annual surface flow (Immerzeel, 2008). It is expected that due to projected rises in temperature and precipitation changes, glaciers and seasonal snow cover will be affected, eventually affecting the amount of meltwater and thus the amount of surface water supply from upstream mountainous basins, especially in the western part of the IGB (Kraaijenbrink et al., 2017; Viste and Sorteberg, 2015). Further, monsoon dynamics will likely change, resulting in a decreasing number of rainy days, increasing intensity of precipitation, and increasing mean monsoon precipitation (Kumar et

al., 2011; Lutz et al., in review; Sharmila et al., 2015; Turner and Annamalai, 2012). This might eventually affect the water supply patterns in the eastern part of the IGB. On top of that, long-term precipitation changes may lead to changes in groundwater recharge and storage, which in turn will affect groundwater availability (Asoka et al., 2017). There are however large uncertainties in the projected precipitation changes due to the large spread among the different climate model runs (Arnell and Lloyd-Hughes, 2014; Lutz et al., 2016b; Moors et al., 2011), which hampers the projection of future water supply rates. In addition to climate-induced changes in surface and groundwater supply, groundwater depletion is expected to intensify over the next decades due to socio-economic development, ~~which will likely affect groundwater availability~~ (Rodell et al., 2009; Wada, 2016; Wada et al., 2010).

Simultaneous with changes in water supply under climate change, rapid and continuous population growth and strong economic development are expected to result in a rapid increase in water demand over the coming decades (Biemans et al., 2011; Rasul, 2014, 2016; Wada et al., 2016). The population in the IGB is expected to grow from 900 million inhabitants in 2010 to 1.1 - 1.4 billion inhabitants in 2050, which will likely be accompanied with rapid urbanization (Klein Goldewijk et al., 2010; Rasul, 2016). For instance, in countries like India and Pakistan, the expectation is that by 2050 more than 50% of the population will live in urban areas (Mukherji et al., 2018; UN-DESA, 2018). The population growth is also expected to

be accompanied with continuing fast economic growth (i.e. currently between 2.5% and 7.3% per year) (ADB, 2018), rapid industrialization, and an intensification of water use in food production (e.g. due to expansion of irrigated areas) (Biemans et al., 2013; Rasul, 2016). This will likely result in an increasing pressure on water resources, which in turn will affect food security, safe access to drinking water, public health, and environmental well-being (Liu et al., 2017; Taylor, 2009). Over the past decades, blue water scarcity has already become a prominent issue in some parts of the IGB. Hoekstra et al. (2012) found, for instance, that the Indus river basin experiences severe blue water scarcity during eight months a year, whereas the lower parts of the Ganges-Brahmaputra river system face severe blue water scarcity during five months a year.

Towards the future, it is rather uncertain how blue water scarcity will develop in the IGB. Some-Many (global) studies (e.g. Alcamo et al., 2007; Arnell, 2004) found that future blue water scarcity will decline or will be absent, mainly by increasing water availability due to climate change, whereas other studies (e.g. Gain and Wada, 2014; Hanasaki et al., 2013; Vörösmarty et al., 2000) found that future (seasonal) blue water scarcity will increase due to socio-economic changes, mainly resulting from population growth, or due to decreasing water availability. The opposing trends in future blue water scarcity found in the cited studies indicate that the uncertainty in how the future South-Asian blue water gap will develop is large and that an improved understanding on the development of the future (potential) regional blue water gap scarcity in the region is needed. One of the drawbacks in the cited studies is, for example, that, in general, the selection of climate models, RCPs, and SSPs (RCP = Representative Concentration Pathway; SSP = Shared Socio-economic Pathway) was not tailored to the representation of a wide range of possible futures in terms of climate change and socio-economic development. Consequently, the projected blue water scarcity trends may not provide a full picture in how blue water scarcity will develop into the future. Model selection approaches (e.g. Lutz et al., 2016b) with a focus on a wide range of possible futures in terms of climate change, and the selection of contrasting RCP-SSP combinations according to a RCP-SSP Framework (van Vuuren et al., 2014), can for instance be used to eliminate this drawback. Another drawback is that no models were used with a sufficient representation of cryospheric-hydrological processes. Therefore, the lack of proper simulations of the evolution of mountain water resources (e.g. glacier evolution) may have imposed uncertainties in the outcomes of these studies. Models with a sufficient representation of cryospheric-hydrological processes can be used to eliminate this drawback.

(Blue) water scarcity has been assessed by different methodologies over the last decades. One type of assessments relied on statistics of water use (e.g. FAO AQUASTAT) and observations of meteorological and hydrological variables (Bierkens, 2015). Other were conducted by using several model types, such as global hydrological models (e.g. H08 (Hanasaki et al., 2008a, 2008b), LPJmL (Schewe et al., 2014) and PCR-GLOBWB (Van Beek et al., 2011; Wada et al., 2014)) (Veldkamp et al., 2017). There are several advantages of the use of hydrological models above the use of statistics. First, blue water scarcity can be assessed by taking water availability, the main all types of water use (i.e. agricultural, domestic, and industrial), and their relationships and feedbacks into account on a high spatial and temporal resolution (e.g. 5 arc min and daily). Second, models such as the LPJmL model can be used to assess the impacts of human interventions (e.g. reservoirs) on water availability and irrigation water supply (Biemans et al., 2011; Haddeland et al., 2014). Finally, the use

of models contributes to an improved understanding on processes that are relevant in the development of (future) blue water scarcity.

Large scale hydrological models have mostly been applied without making an explicit distinction between up- and downstream domains and their roles in water supply and demand. To make an explicit distinction between the dominant processes in the different domains, different tools are required to simulate the domain-specific processes properly. For instance, in the upstream domains of the IGB, water availability is highly depending on natural factors, such as ice and snowmelt (e.g. Lutz et al., 2014)). Since cryospheric and hydrological processes vary strongly over short distances in the upstream mountainous areas, higher resolution models with a robust representation of mountain-specific cryospheric and hydrological processes are required to simulate water availability and supply in and from the upstream (mountainous) domains accurately. In the downstream domains of the IGB, the human influence on the hydrological cycle is large with large irrigation canal systems and reservoirs (e.g. Tarbela Dam) (Biemans et al., 2013). In addition, agricultural water use is a very important topic in this region, which requires knowledge of related processes, such as crop growth, and relations between water availability and food production, ~~amongst others~~. In these domains, therefore, a high-resolution model is required that a) has an explicit representation of human interventions in the hydrological cycle, and b) can link hydrological processes with vegetation crop processes.

Environmental flow requirements (EFRs) have not been considered in most future water scarcity assessments. EFRs have so far only been applied by Hanasaki et al. (2013) by using an EFR module (i.e. part of the H08 model) that controls the consumptive amount of water that is withdrawn from river systems. This allows the prioritization of maintaining EFRs, but also has the consequence that agricultural production might be affected. According to Jägermeyr et al. (2017) up to ~30% of the agricultural production in South Asia can be lost when EFRs are considered. In the IGB, rapid and continuous population growth is expected, which will most likely be accompanied with an increase in food demand and thus requires a higher agricultural production (Biemans et al., 2013). Therefore, agricultural needs will probably be prioritized at the cost of environmental flows and water use will most likely intensify, which subsequently might alter flow regimes and the ecological health of a river system (Döll et al., 2009; Pastor et al., 2014). To understand the impact of blue water consumption on environmental flow transgressions, it is therefore needed to estimate EFRs and to assess whether (future) EFRs are met or not.

Most studies that have assessed future blue water scarcity have only focussed on the interannual variability without focussing on the intra-annual variability. This can be considered as a disadvantage in regions with dry and wet seasons, such as the IGB. For instance, Gain and Wada, (2014) found that, based on annual projections, future blue water scarcity is projected to be absent in the Brahmaputra river basin over the next decades. Seasonal and monthly projections indicated however that during the dry season blue water scarcity will become more severe in the future (Gain and Wada, 2014). For this reason, it is important to include the intra-annual variability in blue water scarcity projections in areas like the IGB.

The main objective of this study is to assess the combined impacts of climate change and socio-economic development on the future “blue” water gapscarcity for the downstream floodplains of the Indus, Ganges, and Brahmaputra (IGB) river

basins until the end of the 21st century. ~~The IGB river basins are considered as a climate change “hotspot” (Nepal and Shrestha, 2015; De Souza et al., 2015)~~. For the upstream mountainous domains, we apply a distributed model with a strong representation of cryospheric-hydrological processes that explicitly simulates cryospheric changes (i.e. glacier and snow cover) under climate change. For the downstream domains, we apply a distributed hydrology and crop production model with an explicit representation of human interventions in the hydrological cycle to simulate downstream water supply and demand. We use the RCP – SSP framework (~~RCP = Representative Concentration Pathway; SSP = Shared Socio-economic Pathway~~) to include a wide range of possible futures in terms of climate change and socio-economic development (van Vuuren et al., 2014). Both models are forced with outputs of ~~eight~~ downscaled General Circulation Models (GCMs) representing a region-specific wide range of possible climate conditions (i.e. representing RCP4.5 and RCP8.5) (Lutz et al., 2016b). In addition, we use a set of regional land use scenarios and socio-economic scenarios (derived from SSP1 and SSP3 (Riahi et al., 2017)) to force the hydrology and crop production model. Water demand and consumption are estimated in terms of the amount of water that is required for withdrawal and that is consumed, respectively, by the agricultural, domestic, and industrial sectors. The blue water gap is estimated as the amount of unsustainable groundwater that is withdrawn to fulfil the blue water demand. Water demand is estimated in terms of water withdrawal and water consumption, and water scarcity is estimated by calculating the blue water gap between sectoral water demands and water supply from renewable sources. Finally, EFRs are estimated according to the Variable Monthly Flow (VMF) method (Pastor et al., 2014) to assess the impact of (future) blue water consumption on environmental flow transgressions, assuming that meeting EFRs have the lowest priority.

This study stands out in comparison with previous work in the region (e.g. (Gain and Wada, 2014) by means of multiple a few novelties. First, the novelty of this study lies in the application of a coupled modelling approach, including a high-resolution cryospheric-hydrological model (5 x 5 km) and a high-resolution hydrology and crop production model (5 x 5 arc min), that can simulate up- and downstream water availability, and the downstream water supply, demand, and gap scarcity in the entire IGB. Second, the hydrology and crop production model applied for downstream domains, has specially been developed for this region in that it is able to a) simulate water distribution through extensive irrigation canal systems of the Indus and Ganges river basins, b) make improved simulations of the timing of water demand for agriculture due to an explicit representation of a multiple cropping system (Biemans et al., 2016), and c) simulate groundwater withdrawal and depletion rates. ThirdFinally, the high-resolution models are forced with an ensemble of downscaled and bias-corrected GCMs that were selected by using an advanced selection approach and represent a wide range of possible futures in terms of climate change for RCP4.5 and RCP8.5. FourthIn addition, the hydrology and crop production model is forced with a set of socio-economic and land use scenarios that are most likely linked with the RCPs (i.e. according to the RCP-SSP framework). Finally, the outcomes of the hydrology and crop production model are used to assess the impact of (future) blue water consumption on environmental flow transgressions.

2. Study Area

The future blue water gapseareity is examined for three major South-Asian river basins, which are considered as a “hotspot” of climate and socio-economic changes: the Indus, Ganges, and Brahmaputra (De Souza et al., 2015) (Figure 1). The Indus, Ganges, and Brahmaputra river basins are selected as study area because these South Asian river basins depend to varying degrees on water generated in the Hindu-Kush Himalayan mountain ranges and at the same time have contrasting differences in terms of hydro-climatic and socio-economic characteristics. In a geopolitically complex region, the Indus (I), Ganges (G), and Brahmaputra (B) drain surface areas of around 1,116,000 km², 1,001,000 km², and 528,000 km², respectively, and traverse Afghanistan (I), Pakistan (I), India (I, G, B), China (I, G, B), Nepal (G), Bhutan (B), and Bangladesh (G, B). In this study, the IGB river system is subdivided in several upstream and downstream domains: the Upper Indus Basin (UIB), Upper Ganges Basin (UGB), Upper Brahmaputra Basin (UBB), Lower Indus Basin (LIB), Lower Ganges Basin (LGB), and Lower Brahmaputra Basin (LBB). Thereby, the upstream domains are dominated by the mountainous terrains of the Tibetan Plateau and Hindu Kush – Himalayan (HKH) mountain ranges with elevations up to 8850 m above sea level, and the downstream domains are dominated by hilly regions and floodplains that are part of the Indo-Gangetic plains. The boundary between upstream and downstream domains is located at the southern margins of the Himalayan foothills and directly upstream of large reservoirs, such as the Tarbela and Mangla Dam reservoirs.

The Ganges river basin is the most densely populated basin with a population density of about 580 inhabitants/km², and the Brahmaputra river basin is the least populated basin with 131 inhabitants/km² (2016; Klein Goldewijk et al., 2010). India has the largest economy with a nominal GDP per capita of 1604 US\$ yr⁻¹, whereas Nepal has the smallest economy with a nominal GDP per capita of 748 US\$ yr⁻¹ (International Monetary Fund, 2016). Water withdrawal (i.e. in South Asia) is highest in the agricultural sector (91%, corresponding with 913 km³/year), followed by the domestic (7%, corresponding with 70 km³/year) and industrial sectors (2%, corresponding with 20 km³/year) (FAO, 2012). Much of the water withdrawn is used for the irrigated agricultural areas that are present in the IGB. Among the three river basins, the Ganges river basin has the largest irrigated area with 257,000 km² (i.e. situation in 2000), followed by the Indus river basin (213,000 km²) and the Brahmaputra river basin (27,000 km²) (Biemans et al., 2013). In the irrigated areas of the Indus and Ganges river basins, mainly cash crops, such as sugarcane, wheat, and rice are cultivated (FAO, 2012). Thereby, the annual production of sugarcane is highest with 431 Mt, followed by rice (233 Mt), and wheat (138 Mt) (2016; FAO, 2017).

The climate of the IGB river systems is mainly dominated by the East-Asian and Indian monsoon systems, and the Westerlies. Westerlies are most dominant in the western part of the IGB with significant precipitation during the winter period. The East-Asian and Indian monsoon systems become increasingly dominant when moving eastward causing most of the precipitation to occur during the monsoon season (June-September). In the Brahmaputra river basin, where the climate is mainly driven by the monsoon systems, 60-70% of the annual precipitation occurs during the monsoon season (Immerzeel, 2008). Annual precipitation amounts vary from less than 200 mm in the Thar desert (LIB) and the Tibetan Plateau (UIB) to more than 5000 mm in the floodplains of the LBB (Lutz et al., in review). The high-altitude regions of the HKH experience a

5 cold climate with annual average temperatures down to -19 °C in the Karakoram (UIB), whereas the downstream domains experience mild winters and hot summers with annual average temperatures up to 28 °C at the southern margins of the LGB (Cheema and Bastiaanssen, 2010; Lutz et al., in review; Wijngaard et al., 2017). Within the IGB two growing seasons are prevailing: the rabi season (November – April) and the kharif season (May – October) (Cheema et al., 2014; Portmann et al., 2010).

3. Data and Methods

3.1 Definitions

Throughout this study, we use several terms, which we define as follows:

- 10 • Blue water: water that is withdrawn from surface water and groundwater bodies. Surface water is defined as water withdrawn directly from (rivers, lakes, and reservoirs), and groundwater is defined as water withdrawn from bodies (both shallow groundwater and aquifers and deep aquifers, using (artificial) wells).
- 15 • Green water: water that is infiltrated into soils and that originated directly from precipitation.
- Blue water availability: the total amount of water available in rivers, reservoirs, and groundwater.
- Blue water demand: the total amount of blue water that is required for withdrawal by the agricultural, domestic, and industrial sectors.
- Blue water consumption: the total amount of blue water that is consumed (evapotranspiration in agriculture) by the agricultural (evapotranspiration), domestic, and industrial sectors (withdrawal minus return flows).
- 20 • Blue water gap: the amount of unsustainable groundwater that is withdrawn to fulfil the blue water demand. The blue water gap occurs when the mean annual groundwater withdrawal exceeds the mean annual groundwater recharge.

3.2 Modelling Framework

We use a coupled modelling approach to simulate upstream water availability and downstream water supply- and demand. To this end, two physically-based fully-distributed models are used: the cryospheric-hydrological Spatial Processes in HYdrology (SPHY) model (Terink et al., 2015) and an adjusted version of the (eco-)hydrological Lund-Potsdam-Jena-25 managed-Land (LPJmL) model (Biemans et al., 2013, 2016; Bondeau et al., 2007; Rost et al., 2008). SPHY and LPJmL are set up for a reference period (1981-2010) and a future period (2011-2100), and both run at a daily time step.

3.2.1 Upstream: SPHY

We use SPHY to simulate water availability from the upstream mountainous domains of the IGB. The SPHY model is developed specifically for the high mountain environment in Asia. The model runs at a spatial resolution of 5 x 5 km and

reports on a daily time step. SPHY has been used to assess climate change impacts for high mountain hydrology [in Asia](#) before (Lutz et al., 2014, 2016a; Wijngaard et al., 2017). The used set up was calibrated and validated using IceSat glacier mass balance data (Kääb et al., 2012), MODIS snow cover data (Hall et al., 2002; Hall and Riggs, 2015) and observed discharge in a study on the impacts of climate change on hydrological extremes in the upstream domains of the IGB (Wijngaard et al., 2017). The model simulates daily discharge by calculating the amount of total runoff for each grid cell, and subsequently by routing the total runoff downstream by means of a simplified routing scheme that requires a digital elevation model (DEM) and a recession coefficient. Thereby, the total runoff is the sum of glacier runoff, snow runoff, surface runoff, lateral flow, and baseflow.

For the estimation of the contribution of glacier runoff, sub-grid variability (i.e. 1 km²) is applied by determining the fractional ice cover in each cell, where fractional ice cover can range between 0 (no ice cover) and 1 (complete ice cover). Changes in fractional ice cover over time are modelled using an approach that considers mass conservation and ice-redistribution (Terink et al., 2017). In addition to the determination of fractional ice cover, other information, such as initial ice thickness and the type of glacier (i.e. debris-free or debris-covered) is attributed to a unique identifier that is created for (a part of) each glacier within a model cell. The degree-day approach of *Hock* (2003) is used to simulate glacier melt, which is subsequently subdivided over the surface runoff and baseflow pathways by a calibrated glacier runoff fraction.

Those parts that are not covered by glaciers are covered by snow, bare soil, vegetation, or open water. For the snow-covered parts, the model of *Kokkonen et al.* (2006) is used to simulate snow storage dynamics. Snow accumulation and melt is simulated by the degree-day approach of *Hock* (2003), whereas snow sublimation is estimated by a simple elevation-dependent potential sublimation function (Lutz et al., 2016a). Besides snow melt, accumulation, and sublimation, refreezing of snowmelt and rain are included as well. Rainfall runoff processes are simulated for those parts that are free of snow. Rain is subdivided over two pathways: i) a direct transport to the river network by surface runoff, or ii) an indirect transport to the river network via lateral flow or baseflow. For the simulation of soil water processes, processes as evapotranspiration, infiltration, and percolation are included. These processes are simulated for a topsoil and subsoil layer. For a more detailed description of SPHY we refer to *Terink et al.* (2015).

3.2.2 Downstream: LPJmL

The outflows of upstream domains that are simulated by SPHY are input to the hydrology and crop production model LPJmL, where [mountain](#)-water is withdrawn by users or continues its way downstream towards the Arabian Sea or the Bay of Bengal. LPJmL has an explicit representation of human interventions in the hydrological cycle that are relevant in the downstream domain, such as dynamic calculations of irrigation demand, withdrawal and supply (Rost et al., 2008), and the operation of large reservoirs (Biemans et al., 2011). LPJmL has been applied to South Asia before (Biemans et al., 2013), but has recently been updated to represent the agricultural practice of multiple cropping with monsoon-dependent sowing dates (Biemans et al., 2016) and the distinction between different irrigation systems (Jägermeyr et al., 2015). [The LPJmL model has been tested and validated for global applications, such as river discharge](#) (Biemans et al., 2009), [irrigation requirements](#)

(Rost et al., 2008), crop yields (Fader et al., 2010), and sowing dates (Waha et al., 2012). On regional level, irrigation water withdrawals have been validated for India and Pakistan (Biemans et al., 2013, 2016). In this study, the model was further improved to represent groundwater withdrawal and depletion and the distribution of irrigation water through the extensive canal systems in the Indus and Ganges basins. Moreover, the resolution was increased to 5 x 5 arc-min.

5 LPJmL simulates daily discharge by i) calculating the total amount of runoff generated for each grid cell as the sum of surface runoff, subsurface runoff, and baseflow, and ii) routing the total runoff downstream along a river network. Water enters a grid cell by precipitation and/or irrigation water and can be subdivided over two pathways: direct transport to the river network by surface runoff and indirect transport via infiltration and subsurface runoff or baseflow (Schaphoff et al., 2017). Groundwater reservoirs are recharged from the bottom soil layers. Water can be withdrawn from the groundwater reservoirs directly, or they contribute to baseflow through a delayed outflow parameterized by a linear reservoir model. During transport Water can be removed from the grid cell by soil evaporation, plant transpiration, canopy interception, and percolation. Water can also be removed from the river network by lake or canal evaporation. For a more detailed description of LPJmL we refer to Rost et al. (2008) and Schaphoff et al. (2017).

10 In LPJmL, the daily irrigation water consumption is calculated for each grid cell as the minimum amount of additional water needed to fill the upper two soil layers to field capacity and the amount needed to fulfil the atmospheric evaporative demand (Rost et al., 2008). The gross irrigation demand (i.e. withdrawal) depends on the soil and the type of irrigation system that is installed. We assume that all irrigated areas in the IGB rely on surface-flood irrigation (AQUASTAT; FAO, 2014) which is less efficient than sprinkler or drip irrigation systems (Jägermeyr et al., 2015). Daily water demand for other users (i.e. households and industry) is assumed to be constant throughout the year.

15 20 Water for irrigation and other users can be withdrawn from surface water in a irrigated grid cell, surface water from a neighbouring grid cell or a canal system (i.e. if connected), an upstream reservoir build for water supply (i.e. if in place), and groundwater bodies, respectively. If long-term groundwater withdrawals exceed long-term groundwater recharge, the withdrawal is defined as unsustainable. In this study, we define the blue water gap as the mean annual groundwater depletion rate. Not all water that is withdrawn is consumed. Water can be lost during conveyance, by open water evaporation or as a return flow into the river network. After application to the field, again only part of the water will be used for evapotranspiration (blue water consumption), and the remaining part will recharge groundwater or discharge as return flow to the river.

3.3 Data

SPHY and LPJmL are forced with daily air temperature and precipitation fields from a dataset that is developed for the 30 Indus, Ganges, and Brahmaputra river basins (Lutz and Immerzeel, 2015), which accounts for the underestimate of high altitude precipitation, which is common for gridded meteorological forcing datasets in the region (Immerzeel et al., 2015). The datasets are based on the Watch Forcing ERA-Interim (WFDEI) dataset (Weedon et al., 2014), and are bias-corrected and downscaled from a resolution of 0.5° x 0.5° to a resolution of 5 x 5 km and 10 x 10 km for the upstream and downstream

domains, respectively. The LPJmL model is also forced with downward longwave and shortwave radiation, besides daily air temperature and precipitation fields. Downward shortwave radiation is not bias-corrected, since these datasets are corrected to observed cloud cover and by means of corrections for aerosol loadings (Weedon et al., 2010, 2011, 2014). For the application of the meteorological forcings in LPJmL the datasets were resampled to a resolution of 5 arc-min.

5 We use the 15-arc-second void-filled and hydrologically conditioned HydroSHEDS DEM (Lehner et al., 2008). For the use of the DEMs in SPHY the DEMs are resampled to 5 x 5 km. LPJmL uses the stream network from HydroSHEDS at 5 x 5 arc-min. Land use information in SPHY is extracted from the MERIS Globcover product (Defourny et al., 2007). In LPJmL, gridded crop fractions of 13 rainfed and irrigated crop classes for the 2 cropping seasons were derived from the MIRCA2000 dataset (Biemans et al., 2016; Portmann et al., 2010). For SPHY, soil information from the HiHydroSoil 10 database (De Boer, 2016), which is a dataset of soil hydraulic properties derived from the Harmonized World Soil Database (FAO/IIASA/ISRIC/ISSCAS/JRC, 2012) using pedotransfer functions (Sarmadian and Keshavarzi, 2010). LPJmL soil classes were derived from the HWSD (Schaphoff et al., 2013).

15 Current 5-arc-min domestic and industrial water demand datasets are extracted from the PCR-GLOBWB model. In these datasets, water demands were estimated based on methods developed by (Wada et al., 2011b, 2014). Domestic water withdrawals were derived by combining decadal and yearly population data (i.e. extracted from the HYDE v3.2. database (Klein Goldewijk et al., 2010) and the FAOSTAT database, respectively), country-specific per capita domestic withdrawal data (i.e. extracted from the FAO AQUASTAT database), and water use intensities. The water use intensities take country-specific economic and technological developments into account (Wada et al., 2011b). Hence, economic developments are 20 based on changes in GDP, electricity production, energy and household consumption. Technological developments are derived as the energy consumption per unit electricity production and accounts for domestic/industrial restructuring or improved water use efficiency (Wada et al., 2011b). Water use intensities are also used to derive industrial water withdrawal. Industrial water demands are assumed to remain constant throughout the year, whereas domestic water demands are assumed to vary throughout the year, which is depending on air temperature (Wada et al., 2010, 2011a). Not all the water that is withdrawn is consumed. A part of the water withdrawn for domestic and industrial purposes returns to the river network as 25 return flows. The amount of return flow is calculated by means of recycling ratios that is depending on the country-specific GDP and level of economic development (Wada et al., 2011a).

3.4 Future Climate and Socio-economic Development

To evaluate future changes in the water supply, demand, and gapsearcity due to climate change combined with socio-economic developments we use the RCP-SSP Framework (van Vuuren et al., 2014). We force SPHY and LPJmL with an 30 ensemble of downscaled General Circulation Model (GCM) runs from the medium stabilization scenario RCP4.5 and the very high baseline emission scenario RCP8.5 (van Vuuren et al., 2011). From the CMIP5 multi-model ensemble (Taylor et al., 2012) we select four GCM runs for each RCP that represent the full CMIP5 ensemble in terms of projected ranges in the means and extremes of future air temperature and precipitation over the IGB region, and have sufficient skill to simulate

historical climate conditions in the IGB (Lutz et al., 2016b). Subsequently, the selected models are downscaled using the reference climate data by applying a Quantile Mapping approach, which performs well in downscaling climate model data for floodplains as well as mountainous terrains (Themeßl et al., 2011). This method scales future GCMs down and bias-corrects them by means of empirical cumulative density functions that are calculated for the reference climate dataset and 5 historical GCM runs (1981-2010).

For the representation of future socio-economic development, we select two SSP storylines (O'Neill et al., 2014, 2015; Riahi et al., 2017) that represent a “Sustainability” scenario (SSP1) and a “Fragmentation” scenario (SSP3). We choose to select SSP1 and SSP3, because these SSPs are most likely linked with RCP4.5 (i.e. RCP4.5 – SSP1) and RCP8.5 (i.e. RCP8.5 – SSP3) (van Vuuren and Carter, 2014). Future 5-arc-min domestic and industrial water demand datasets are 10 extracted from the IMAGE [v3.0](#) model (Stehfest et al., 2014). Within the IMAGE model a sub-model (i.e. developed by Bijl et al., (2016)) is included, which calculates the future domestic and industrial water demands based on projections for population growth and economic development (based on GDP per capita) that are consistent with the selected SSPs. The projected population and GDP (PPP) changes for the IGB are summarized in Table 1 for SSP1 and SSP3.

Land use change scenarios that are consistent with the SSP storylines are calculated by Integrated Assessment Models 15 like IMAGE (Stehfest et al., 2014). IMAGE calculates land use change based on a set of SSP-specific assumptions regarding dietary changes and resulting per capita food demand, the level of intensification and potential yield increase on existing cropland, and changes in import and export of commodities. We use the SSP1 and SSP3 [regional scale](#) outcomes of IMAGE 20 (Doelman et al., 2018) to derive changes in rainfed and irrigated cropland extents for Pakistan, India, Nepal, and Bangladesh between 2010 and 2100. Subsequently, we project those changes on our gridded datasets of current kharif and rabi cropped areas to construct transient datasets of land use change in the IGB. These gridded datasets are used in combination with the climate change datasets to estimate future water requirements for irrigation. [We assume that both the crop distribution and crop types remain as they are. This implies that they are not adapted when crop growth conditions become unfavourable \(e.g. due to changing climate conditions\). It is beyond the scope of this study to investigate the impact of climate change adaptation of agricultural practices on irrigation water requirements and related impacts on the blue water gap.](#)

25 [3.5 Analysis of Environmental Flows](#)

[To assess the impacts of \(blue\) water consumption on environmental flow transgressions we estimate environmental flow requirements \(EFRs\) according to the Variable Monthly Flow \(VMF\) method of Pastor et al. \(2014\). The VMF method is a valid method that considers intra-annual variability in streamflow and correlates well with locally calculated EFRs. The EFRs are calculated on monthly basis by using the discharge at the river outlets of the Indus, Ganges, and Brahmaputra under naturalized conditions \(i.e. without withdrawals for irrigation and other users\). First, the mean annual flows \(MAFs\) and mean monthly flows \(MMFs\) are calculated for the reference \(1981-2010\) and far-future periods \(2071-2100\). The MAFs and MMFs are then used to determine low flow \(MMF<0.4·MAF\), high flow \(MMF>0.8·MAF\), and intermediate flow seasons \(MMF>0.4·MAF & MMF < 0.8·MAF\). Based on the seasonal classification, subsequently EFRs are calculated](#)

where the EFR is set equal to 60%, 45%, and 30% of the MMF during low, intermediate and high flow seasons, respectively.
Finally, the discharge impacted by anthropogenic water withdrawals (i.e. with irrigation and full access to groundwater) is compared with the EFRs to assess whether environmental flows are met or not.

4. Results and Discussion

5 4.1 Future Climate Change

In the IGB, both temperature and precipitation are projected to change towards the end of the 21st century. Figure 2 shows the projected annual and seasonal temperature and precipitation changes in the IGB for RCP4.5 and RCP8.5, at the end of the 21st century. On annual basis, temperature is projected to increase with 1.5 – 2.9 °C for RCP4.5 and 2.8 – 5.2 °C for RCP8.5, with respect to the reference period (1981-2010). The largest increases are projected in the western and north-western parts of the Indus river basin (i.e. in the Hindu Kush and Karakoram mountain ranges) and on the Tibetan Plateau. The large temperature increases in these regions can most likely be attributed to elevation-dependent warming, which causes a stronger warming in the high altitude upstream regions in comparison with the lower-lying downstream regions (Palazzi et al., 2016; Pepin et al., 2015). Precipitation is, in general, projected to increase with increases up to about 200% for RCP4.5 and up to about 100% for RCP8.5. Thereby, the largest increases are projected in the southernmost parts of the Indus river basin, which is a region where the amount of precipitation is relatively low (less than 300 mm/year) and thus small absolute increases can result in large relative increases. In the same region, also the range in model projections is large. Besides precipitation increases, also precipitation decreases are projected. These decreases are mainly projected to occur in the westernmost part of the Indus river basin. On seasonal basis, the projected temperature changes do not show large seasonal differences. The main difference can be found between the projections made for RCP4.5 and RCP8.5 with temperature differences up to about 2 °C between RCP4.5 and RCP8.5. The projected precipitation changes show large seasonal differences. For RCP4.5, the largest and smallest increases are, in general, projected during post-monsoon and pre-monsoon/winter, respectively. During the pre-monsoon and winter seasons even a decrease in precipitation is projected in the UIB (~-1%) and UGB (~-5%), respectively. For RCP8.5, precipitation increases are, in general, largest during post-monsoon. During pre-monsoon, also precipitation decreases are projected in the UIB (~-4%). The range in model projections is especially large during the post-monsoon and winter seasons.

4.2 Blue Water Availability

In the IGB, the seasonal and spatial variability of surface water availability is quite large. Figure 3 shows the seasonal surface water availability (i.e. natural runoff) for the reference period (1981-2010) in the upstream and downstream domains of the IGB as simulated by SPHY and LPJmL. The surface water availability is generally largest during the monsoon season (Figure 3c) varying from less than 100 mm/year in the floodplains of the Indus (LIB) to more than 3500 mm/year in the mountainous upstream domains of the Ganges and Brahmaputra. In these domains, the large surface water availability can

mainly be attributed to the combined contributions from ice and snowmelt, and monsoon precipitation that can reach amounts over 3000 mm/year at the southern margins of the UGB and UBB (Wijngaard et al., 2017). During the winter season (see Fig 3a) the surface water availability is generally lowest with rates less than 100 mm/year in most regions of the IGB. Water availability is generally higher than 100 mm/year in the LBB and directly south of the Himalayan arc. The 5 higher surface water availability in these regions can likely be explained by the release of groundwater from aquifers that have been recharged during the monsoon season. A similar pattern can also be recognized for the same regions during the pre-monsoon (Figure 3b) and post-monsoon seasons (Figure 3d). During the pre-monsoon season surface water availability can reach up to about 1000-1500 mm/year in the HKH mountain ranges, which can be attributed to snowmelt.

Future water availability is expected to increase as a result of climate change. Figure 4 shows the current and future 10 monthly surface water availability for the up- and downstream domains of the IGB under current (1981-2010), mid-future (2041-2070; MOC), and far-future (2071-2100; EOC) climate conditions. Surface water availability is projected to increase for, both, RCP4.5 and RCP8.5 in the entire IGB. Similar trends have also been found in other studies conducted in (a part of) the IGB (Immerzeel et al., 2010; Lutz et al., 2014; Masood et al., 2015; Nepal, 2016). The increases in surface water availability are projected to be stronger during the monsoon season, which can likely be attributed to increases in monsoon 15 precipitation (Figure 2) and increases in ice ~~and snow~~melt. The increases in melt (i.e. especially ice melt) are a likely reason that the natural runoff peaks in the upstream domains of the Ganges and Brahmaputra are projected to shift from July to August. Furthermore, increases are stronger for RCP8.5, with exception of the Indus basin, where a opposite trend can be observed. The opposite trend can mainly ~~most likely~~ be attributed to the reduction in ~~snowmelt glacier areas~~ towards the end of the 21st century, which is most likely caused by the stronger temperature increases in the Indus basin (Figure 2), leading to 20 a higher fraction of precipitation to fall as rain (Radié et al., 2014). The range among model runs is large, especially for RCP8.5, which indicates that uncertainty in future water availability projections is large, especially in the upstream mountainous domains. The graphs further show that, under current and future conditions, there is a clear upstream-downstream difference in the amount of water that is available in the Indus and Ganges with significant larger amounts of water available in the upstream domains In the Brahmaputra basin, the upstream-downstream difference is smaller, which 25 can be attributed to the East-Asian monsoon systems that have a high intensity in the floodplains of the Brahmaputra. The upstream-downstream differences in surface water availability indicate the significance of upstream water resources for the floodplains that are located downstream. In the future, it is projected that the upstream-downstream difference will be enhanced, implying that the ~~downstream~~ dependency on upstream mountain water resources will increase.

4.3 Blue Water Consumption

30 Irrigation is by far the largest water consumer in the IGB. Figure 5 shows the annual and seasonal blue water consumption for irrigated croplands and the combined blue water consumption for domestic and industrial sectors. The maps indicate that the irrigation water consumption is largest in the Punjab and Haryana provinces (i.e. in northern part of the LIB/western part of the LGB) with consumption rates that reach over 600 mm/year on an annual basis. Also in the Sindh province (i.e. located

in the delta plains of the Indus) and along the Ganges river consumption rates are high. The difference in water consumption between the rabi (winter) and kharif (monsoon) seasons is limited in the Indus river basin, whereas in the Ganges and Brahmaputra river basins the water consumption during the rabi season is significantly higher at most of the croplands than during the kharif season. The seasonal differences are a result of rainfall patterns in the IGB. In the Ganges and Brahmaputra 5 river basins, the Indian and East-Asian monsoon systems prevail, which means that sufficient green water is available and thus (blue water) irrigation is less concentrated during the kharif season (Biemans et al., 2016). In the Indus river basin, the influence of monsoon systems is smaller, which means more irrigation is required to fulfil the crop demands. However, during the rabi seasons the amount of precipitation is limited, which means also (blue water) irrigation is required in the Ganges and Brahmaputra river basins. In comparison to irrigation, the water consumption in the domestic and industrial 10 sectors is almost negligible. In most areas, the consumption rates are less than 100 mm per year. Only in the larger urban areas, such as New Delhi, Islamabad, Lucknow, and Jaipur (location, Figure 1), the consumption rates can reach up to 380 mm/year.

As a result of climate change and/or socio-economic developments, blue water consumption is projected to change into the future. Figure 6 shows the projected changes in the annual blue water consumption for irrigated croplands and other users 15 (i.e. domestic and industrial sectors) for RCP4.5, RCP8.5, RCP4.5 – SSP1, and RCP8.5 – SSP3. Under current conditions (i.e. REF, 1981–2010), the total blue water consumption is largest in the Indus river basin with a total rate of 145 km³/year, of which 138 km³/year (~95%) is consumed on irrigated croplands and 7 km³/year (~5%) is consumed by domestic and industrial sectors. The total blue water consumption is smallest in the Brahmaputra river basin, with a total rate of 5 km³/year 20 of which 4 km³/year (~80%) is consumed on irrigated croplands and 1 km³/year (~20%) is consumed by domestic and industrial sectors. The differences in total water consumption among the basins, is that in the Indus river basin agriculture is dominated by irrigated croplands (see Fig 1d), whereas in the Brahmaputra river basin agriculture is dominated by rainfed croplands. In addition, the LIB covers a larger area than the LBB, which eventually result in larger consumption rates when aggregating the grid values within a basin. Future total water consumption is projected to change. When only considering 25 climate change, there will be no change in domestic and industrial water consumption. Irrigation water consumption is projected to decrease from 138 km³/ 91 km³/ 4 km³ per year up to about 116 km³/ 69 km³/ 3 km³ per year in the LIB/ LGB/ LBB for RCP8.5, at the end of the 21st century. This trend can be explained by growing seasons that become shorter for most crops due to temperature increases. The shorter growing seasons mean that less water is demanded and thus less water is consumed. In addition, precipitation is projected to increase (Figure 2), which means more green water will be available and less (blue water) irrigation is required. When considering future climate change and socio-economic developments, an 30 increase in the total water consumption is projected with mean relative increases up to about 3624% / 6042% / 147407% per year in the LIB/ LGB/ LBB for RCP8.5 – SSP3, at the end of the 21st century. The increasing total water consumption can mainly be attributed to increasing domestic and industrial water consumption that emerge from population growth and economic development. Their increase ranges from 283% to 311% for RCP4.5 – SSP1 and from 586% to 715% for RCP8.5 – SSP3, at the end of the 21st century, indicating that domestic and industrial water consumption will be a significant

component of the South Asian future water balance. Compared to the reference period there is however a slight decrease in irrigation water consumption projected, although the decreases are smaller than those for the runs considering climate change only, which is due to the expansion of irrigated croplands under the SSPs. Only for RCP8.5 – SSP3 a slight increase in the irrigation water consumption is projected at the end of the 21st century.

5 | Figure 7 shows the monthly projected changes in the total blue water consumption for RCP4.5, RCP8.5, RCP4.5 – SSP1, and RCP8.5 – SSP3. Under current climate conditions, two peaks in the total water consumption can be recognized in the Indus river basin, which coincide with the rabi and kharif crop seasons. In the Ganges and Brahmaputra river basins, the total water consumption is highest during the rabi season, but also smaller peaks can be recognized that coincide with the kharif season. Considering climate change only, the total water consumption is projected to decrease slightly throughout the 10 entire year in the Indus river basin, with exception of the post-monsoon season, when a slight increase is projected. In the Ganges river basin, the total water consumption is projected to decrease during the second half of the rabi season, whereas during the first half of the rabi and kharif seasons the total water consumption is projected to increase slightly. These trends are also projected for the Brahmaputra river basin, with exception of the second half of the kharif season, where also a slight 15 increase in total water consumption is projected, though the projected increases are smaller than for the first half of the kharif season. The projected increases can most likely be explained by increasing temperatures (Figure 2) that enhances the atmospheric evaporative demand. The increasing atmospheric evaporative demand result into higher crop evapotranspiration and thus higher irrigation water consumption. Because growing seasons are projected to become shorter in the IGB and precipitation is projected to increase (see Fig 2), total water consumption will eventually decrease in the second half of the rabi season, and for RCP8.5 also in second half of the kharif season. The projected increases during the second half of the 20 kharif season in the Brahmaputra river basin can likely be explained by increasing temperatures that are smaller in the downstream domains of the Brahmaputra river basin than in other downstream domains (Figure 2). Due to the smaller temperature increases, the growing seasons show a smaller decline, and therefore the higher evapotranspiration rates emerging from temperature increases as well might outweigh the effect of shorter growing seasons, which eventually results in a slight increase in total water consumption. In the entire IGB, the water consumption for RCP8.5 is projected to be lower 25 than for RCP4.5, which can most likely be attributed to the precipitation increases that are larger for RCP8.5, and thus cause blue water irrigation to be lower for RCP8.5 than for RCP4.5. When considering both climate change and socio-economic development, the total water consumption is projected to increase, where the largest increases are projected for RCP8.5 - SSP3. Thereby, the difference in projected increases between the mid of the 21st century (MOC) and the end of the 21st 30 century (EOC) are especially large for RCP8.5 - SSP3, which can be explained by the extensive population growth that is projected at the end of the 21st century for SSP3 (Table 1). This eventually results in a larger increase in domestic water consumption. Further, the difference in projected increases between the RCP – SSP model runs and the reference model runs is especially large in the Brahmaputra river basin, which can be explained by the strong increases in domestic and industrial water consumption. For instance, for RCP8.5 – SSP3 a relative increase of 619% is projected in domestic and industrial water consumption at the end of the 21st century. Although the difference with projected relative increases in the Indus and

Ganges river basins (i.e. 715% and 586%, respectively) is not large, the impact is however higher since the domestic and industrial sectors have a higher contribution in the total water consumption (i.e. ~20% for the reference period) in comparison with the Indus and Ganges river basins (i.e. ~5% and ~12%, respectively).

4.4 Blue Water Gap

5 Climate change is projected to have a mitigating effect on the future South Asian water gap, whereas socio-economic development is projected to have an enhancing effect on the water gap. Figure 8 shows the projected changes in the annual and seasonal blue water demand and supply for RCP4.5, RCP8.5, RCP4.5 – SSP1, and RCP8.5 – SSP3. In addition, Table 2 lists the ensemble mean and standard deviation of the projected relative changes in the annual and seasonal blue water gap for the end of the 21st century (i.e. EOC). Under current climate conditions, the total demand is largest in the Indus river basin with 767 km³/year and smallest in the Brahmaputra river basin with 15 km³/year. Most of the blue water supply consists of surface water (~67% in the Indus, and ~93% in the Brahmaputra). The other part consists of sustainable and unsustainable groundwater. The latter is defined as the blue water gap or the unmet demand, assuming that any unmet demand is covered by additional groundwater abstractions. The unmet demand is largest in the Indus river basin with 83 km³/year (~11% of total demand), followed by the Ganges river basin with an unmet demand of 35 km³/year (~11% of total demand) (Table 2). The simulated unmet demand in the Ganges river basin fall in range with reported historical values in other studies (Jacob et al., 2012; Richey et al., 2015; Rodell et al., 2009; Tiwari et al., 2009). The simulated unmet demand in the Indus river basin is more difficult to compare due to the limited amount of studies reporting groundwater depletion. Cheema et al., (2014) reports a groundwater depletion rate (i.e. unmet demand) of 31 km³/year, which is lower than the simulated groundwater depletion rate in our study. The difference can mainly be explained by the fact that in our study the domestic and industrial sectors are also able to abstract groundwater, which consequently result in larger depletion rates. In the Brahmaputra river basin, no blue water gap is simulated, because all demands can be sustained by surface water and renewable groundwater. In the Indus river basin, the seasonal demand, supply, and gap are largest during the monsoon and melting season which coincides with the prevailing growing season, the kharif. In the Ganges and Brahmaputra river basins, the seasonal demand, supply, and gap (i.e. only in the Ganges river basin) are largest during the winter, which coincides with the rabi season. Assuming climate change without socio-economic development, demand and supply are projected to decrease in all basins on annual basis, and in general during the winter, pre-monsoon and monsoon seasons for RCP4.5 and RCP8.5. During the monsoon (i.e. only in the Brahmaputra river basin) and post-monsoon seasons, demand and supply are projected to increase. The water gap is projected to decrease under all circumstances with mean annual relative decreases up to 37% and 5560% (Table 2), in the Indus and Ganges river basins, respectively, for RCP8.5, at the end of the 21st century. On seasonal basis, the largest relative decreases are projected during the winter season with relative decreases up to 47% (RCP4.5; EOC) and 64% (RCP8.5; EOC) (Table 2) in the Indus and Ganges river basins, respectively. The decreasing demand (met and unmet), and supply can mainly be explained by shorter growing seasons that emerge from temperature increases, and increasing precipitation that result in a shift from blue water irrigation to green water or rainfed irrigation. The

increases in monsoon and post-monsoon (i.e. first half of the kharif (monsoon) and rabi (post-monsoon) seasons) can likely be explained by enhanced atmospheric evaporative demands and resulting increases in crop evapotranspiration that emerge from temperature increases. Despite the increases in demand, the water gap is projected to decrease, which can mainly be explained by the higher surface water availability (Figure 4) that eventually result in lower unsustainable groundwater withdrawals and thus a smaller water gap. Climate change and socio-economic developments combined result, on annual base, in increasing water supply and demand in the Brahmaputra and Ganges river basins for all RCP - SSP scenarios. In the Indus river basin, only increases are projected for RCP8.5 - SSP3. For RCP4.5 - SSP1, demand and supply slightly decrease. The reason for the decreasing trend is that the (relative) increase in domestic and industrial water consumption is limited in comparison with those projected under RCP8.5 - SSP3 and other basins, which in combination with declining irrigation 10 water demand, eventually results in decreasing water demand and supply. The future water gap tends to increase for RCP8.5 - SSP3 in the Indus and Ganges river basins with annual relative increases up to 7% and 14%, respectively, at the end of the 21st century (Table 2). On seasonal basis, the relative increases are largest during the monsoon season with increases up to 30% and 55% in the Indus and Ganges river basin, respectively. For RCP4.5 - SSP1 the gap decreases, since the declining irrigation water withdrawals are not outweighed by the increases in domestic and industrial water consumption. This might 15 also explain why the water gap for RCP8.5-SSP3 is projected to decline during the winter season. Finally, the changing water demands result in changing shares of the different sectors in the total water demand, which is especially striking during the pre-monsoon season in the Brahmaputra river basin. Due to a combination of increasing domestic and industrial water demand, and declining irrigation water demand (which is especially large during pre-monsoon in this basin) the domestic and industrial sectors are eventually projected to become the largest contributors to the total water demand. The uncertainties 20 that are accompanied with the relative changes are especially large for the RCP-SSP combinations (Table 2), which can be attributed to the large range in model outcomes that are generated for the different climate models in combination with SSP projections. For instance, the combination of RCP8.5 climate models and SSP3 projections result in an increasing water gap for some GCM-SSP combinations, whereas for others a declining water gap is projected. The combination of these changes eventually result in low ensemble means, but large standard deviations.

25 Figure 9 shows the spatial distribution of current groundwater depletion (i.e. indicator for the blue water gap) and future absolute changes in groundwater depletion for RCP4.5, RCP8.5, RCP4.5 – SSP1, and RCP8.5 – SSP3. Under current conditions, groundwater depletion is largest in the Punjab and Haryana provinces with depletion rates of around 1000 mm/year in the irrigated areas. In urban areas, such as New Delhi, depletion rates can even reach up to about 2000-2500 mm/year. Also in the Sindh province, the water gap is large with depletion rates in the range 300-350 mm/year. The 30 simulated depletion rates in the irrigated areas of the Indus river basin are similar with those that were found by Cheema et al. (2014). For RCP4.5 and RCP8.5, in general less groundwater depletion is projected, which is mainly caused by the declining irrigation blue water withdrawal and consumption. For both RCP – SSP combinations, depletion is expected to decrease in the irrigated croplands, whereas in the urban areas (e.g. New Delhi) depletion is projected to increase with more than 200 mm/year (i.e. corresponding with a relative increase of more than 150%). For RCP8.5 – SSP3, also areas located in

the Sindh province, and west of the Indus river are expected to experience more depletion, due to population growth and economic development.

4.5 Environmental Flows

The future socio-economic developments and associated increases in blue water consumption are expected to have a limited impact on environmental flow transgressions. Figure 10 shows the ensemble mean and range of the projected changes in EFRs and anthropogenic influenced discharge at the outlets of the Indus, Ganges and Brahmaputra under present and far-future (EOC) RCP-SSP conditions. Under current conditions, EFRs in the Indus, Ganges, and Brahmaputra are generally not met during the low flow season (i.e. winter, pre-monsoon, and post-monsoon), whereas during the monsoon season EFRs are met. The combination of high unmet demands in the Indus river basin (Figure 8) on the one hand and sustained EFRs on the other, can be explained by the absence of water shortage during the monsoon season due to the higher surface water availability. During the low flow season, however, the surface water availability is low, which eventually causes that EFRs and water demands cannot be met, and that high competition between different water users occur. Future projections indicate that both EFRs and anthropogenic influenced discharge will increase, which can most likely be attributed to the increase in surface water availability (Figure 4). Future EFRs are projected to be sustained during high flow seasons, whereas during low flow seasons EFRs remain unmet. However, due to low withdrawals in the Brahmaputra river basin it is projected that EFRs can be sustained all-year round. Further, the large uncertainty bands in the model projections of the Indus indicate that, especially for RCP8.5-SSP3, there is a probability that EFRs will not be met either during the second half of the monsoon season.

4.6 Comparison with other studies

The projected changes in the future water demand are, in general, in line with reported trends in other studies, although different processes can be responsible for the changes. In their global scale study, Wada et al., (2013) projects for instance also decreases in the irrigation water demand for RCP4.5 in the irrigated croplands of South Asia. Nevertheless, the authors project an increase in irrigation water demand for RCP8.5. According to the authors, increases in precipitation are responsible for the decrease in irrigation water demand for RCP4.5, and are outweighed by increases in temperature for RCP8.5, which cause atmospheric evaporative demand to enhance, eventually resulting in increasing irrigation water demands. In our study, the seasonal increases in irrigation water demand (i.e. during the monsoon (partly) and post-monsoon seasons) can also be attributed to enhanced atmospheric evaporative demands emerging from temperature increases. Nevertheless, other processes are responsible for the decreases in irrigation water demand. Besides increases in precipitation, shorter growing seasons as a response to temperature increases, which are larger for RCP8.5, lead to decreasing irrigation water demands. Another study of Hanasaki et al., (2013) show similar trends with decreasing irrigation water demands that are the result of increasing precipitation too. The cited study is also in line with the projected changes in water scarcity in our study with projected increases in water scarcity due to population growth and economic developments.

There are also studies that show opposite trends. For instance, Alcamo et al., (2007) show that water scarcity will decrease in South Asia due to increasing water availability that outweigh the increases in water demand. Another study of Gain and Wada (2014), show that future water scarcity will increase in the Brahmaputra basin during the dry season (i.e. November – May), whereas in our study no water gap has been simulated or projected. The differences between the 5 outcomes of the cited studies and those that are simulated or projected in our study is that a) different indicators were used to assess water scarcity, and b) different models and scenarios were used to assess future water scarcity. In both cited studies, the ratio between availability and consumption and or demand were used as indicator for water scarcity, whereas in our study the unsustainable groundwater withdrawal was used as an indicator for to estimate water scarcity. Since in the Brahmaputra, blue water availability is high, and blue water demand is relatively low in comparison with other basins, it means that 10 unsustainable groundwater withdrawal is not needed to fulfil the water demands, and that therefore no water scarcity appears. Further, the use of different models and scenarios can result in ~~the~~ different water availability projections, which 15 can make ~~at the~~ difference in whether water scarcity will appear or not. In our study, the increasing water availability cannot outweigh the increases in water demand, whereas this is the case in the study of Alcamo et al. (2007). The use of different water scarcity indicators and modelling approaches hampers the comparison of outcomes with those that are reported in other studies.

4.7 Uncertainties and Limitations

The projections of future water availability, demand, and supply are subject to several uncertainties and limitations that are 20 mainly related to the climate change projections, the representation of ~~(physical)~~ processes and non-stationarity in the used hydrological models, and the land use change and socio-economic scenarios.

To assess the impacts of climate change on ~~the~~ future water ~~gap~~ scarcity, an ensemble of 8 downscaled and bias-corrected GCMs were used that cover the full range of climate conditions representative for RCP4.5 and RCP8.5. The GCMs have a poor skill in simulating the regional climate in the complex (mountainous) terrains of Central and South Asia (Lutz et al., 2016b; Seneviratne et al., 2012). Despite the selection of GCMs based on their skill in simulating the regional climate by 25 using an advanced envelope based selection approach (Lutz et al., 2016b), still uncertainties can be introduced in the water scarcity assessments. In addition, uncertainties can be introduced in the way how GCM runs were selected. The models were selected in three consecutive steps that are based on changes in climatic means and extremes, and the skill in simulating the historical regional climate. Which method is chosen to select the climate models dictates which models are selected and therefore largely determine the outcomes of climate change impact study like ours.

There is wide variety in approaches that can be used to assess water scarcity (Liu et al., 2017). Some approaches focus 30 only on blue water scarcity, whereas other approaches focus on the green water scarcity or the combination of blue and green water scarcity. To assess the blue and/or green water scarcity there is wide variety of indicators that can be used, where each indicator can result in a different trend. Further, the use of different models can result in different outcomes. In our study, we focus only on the blue water gap~~blue water scarcity~~ and assess blue water scarcity by using unsustainable water withdrawal

as an indicator ~~for unmet demand~~. The confidence in the trends we found by using our approach of two coupled models could be increased by including more hydrological models in a multi-model approach in combination with multiple water scarcity indicators that can increase the robustness of these trends (e.g. Alcamo et al., 2007, Wada et al., 2016).

The LPJmL model version we used for our assessments has a limitation in simulating domestic and industrial water demand. In the current version, only annual values of domestic and industrial demand could be included. Since domestic water demand varies on monthly basis with higher demands during the summer/monsoon season (i.e. higher temperatures during summer/monsoon result in higher demand) and lower demands during the winter season. This means that on seasonal base, the domestic water demand and consequently the water gap ~~searcity~~ can be overestimated during the winter season, and underestimated during the summer/monsoon season. Further, the model has the limitation that the impact of water pollution on water availability cannot be simulated. This means that surface water and sustainable groundwater withdrawals can be overestimated and unsustainable groundwater withdrawals (i.e. the water gap) to be underestimated.

Whereas the LPJmL model includes human interventions, such as dam operations, and irrigation withdrawals and distribution through canals, the SPHY model that has been used for our upstream assessments does not include them. Since human interventions can influence the hydrological cycle, uncertainties might be introduced in the outflows of the upstream domains. Current impacts of dams and irrigation withdrawals are however assumed to be small due to the relative low number and total capacity of dams in the upstream domains compared to the number and total capacity of dams in the downstream domains. For instance, Tarbela Dam has a total capacity of 12 km³, whereas the total capacity of dams in the upstream domains reach up to about 5.5 km³ distributed over about 50 dams (FAO, 2016). Furthermore, most dams are designed as hydropower dams with limited storage or for run-off-the-river hydropower operations, which have a low degree of regulation in the upstream domains of the IGB (FAO, 2016; Lehner et al., 2011). The impact of agriculture is also assumed to be small due to the rather low irrigation water demands (and cropping intensity) in upstream domains (i.e. <100 mm yr⁻¹) compared to the irrigation water demands (and cropping intensity) in downstream domains (Biemans et al., 2016).

The parameterization of the SPHY and LPJmL models are based on present climatology, land use and other physical catchment characteristics, and is assumed to be stationary. Many hydrological parameters, such as parameters controlling snow processes, are however non-stationary, and can change due to possible changes in climate, land use or other characteristics (Brigode et al., 2013; Merz et al., 2011; Westra et al., 2014). According to several studies (e.g. Brigode et al., 2013; Vaze et al., 2010; Westra et al., 2014) the impact of non-stationarity is highly dependent on several factors, including the length and variability of the period of parameterization, which are decisive for the robustness of the models and thus the magnitude of uncertainty in the model outcomes. For instance, Vaze et al. (2010) indicated that models can be used for climate impact studies when parameterizations are based on data records of 20 years and longer, and for areas where future annual precipitation is not more than 15% dryer or 20% wetter than the mean annual precipitation that is derived from the data records. Other studies (e.g. Brigode et al., 2013) have indicated that shorter periods (e.g. 3 years) also can result in acceptable parameter sets. The disadvantage remains however that in the IGB long data records are scarce and future changes in climate and land use can be more extreme, especially in the southern part of the IGB, where precipitation

increases over 100% are projected for the end of the 21st century (Figure 2). This indicates that the non-stationarity of hydrological parameters can result in uncertainties in the (future) model outcomes, such as hydrological flow predictions. To reduce the impact of non-stationarity other calibration strategies, such as the Generalized Split Sample Test procedure (Coron et al., 2012), are recommended, which aims at testing several possible combinations of calibration-validation periods to test the model's performance under different climate conditions.

Land use change scenarios that are consistent with SSP1 and SSP3 were extracted from the IMAGE model (Doelman et al., 2018), and represent future changes in rainfed and irrigated cropland extents. One limitation is that only outcomes on future cropland extents were used as a representative for the land use change scenarios, whereas outcomes on future intensification of current croplands were not considered. Consequently, the projected yield increases and related increase in irrigation water consumption, though not linearly related, were not accounted for. This might eventually result in an underestimation of irrigation water demand. Further, future irrigation water demand can be overestimated since any future increases in irrigation efficiency were not included in our modelling approach. Another limitation that might influence the projections on irrigation water demand is the way how irrigation practices are reflected within our modelling approach. In our approach, it is assumed that crop types ~~are not adapted remain constant~~ over time, which consequently results in decreasing irrigation water demands when growing seasons shorten, ~~and crops cannot be grown fully until the moment of harvesting~~. The reality however is that farmers may adapt to changing climate conditions ~~(e.g. due to the higher risk for heat stress that is a consequence of increased temperature (extremes))~~ by switching to different crop types that are more suitable for the changed climate. This might eventually influence projections on future irrigation water demand.

Finally, ~~T~~he SSP storylines that are used to project future changes in water demand do not account for potential feedbacks between climate change and socio-economic changes. For instance, the impacts of climate change on the land system are not included (Doelman et al., 2018). According to Nelson et al. (2014), climate change has an impact on agro-economic variables, such as agricultural area and production. The authors found, for example, that under climate change agricultural areas are projected to increase due to intensifying management practices that are induced by climate change. This means that without taking potential feedbacks between climate change and socio-economic changes into account, any future increases in cropland extents might be underestimated.

Finally, future changes in the water demand and gap that have been assessed are based on selected climate change scenarios and SSP storylines. The future changes that are assessed do however not reflect the impact of adaptation strategies. For instance, it is most likely that extra hydropower dams and reservoirs will be developed in the future (Mukherji et al., 2015). In the agricultural sector, it is most likely that irrigation efficiencies will be improved by changing irrigation systems or that crop types will be changed to ones that are more climate-tolerant (e.g. Biemans et al., (2013). Further, future developments, such as regional or transboundary cooperation that improve water and energy sharing and thus optimize water resources use (Molden et al., 2017), and its impact on the water gap have not been assessed. Follow-up studies including the simulation of basin-scale effects of climate change adaptation measures are needed to investigate the impacts of future adaptation strategies and developments on the South Asian water gap and their potential in closing the water gap.

5. Conclusions

The objective of this study is to assess the impacts of climate change and socio-economic developments on the future blue water gapsearcity in the downstream domains of the Indus, Ganges, and Brahmaputra river basins. To this end, we use a coupled modelling system consisting of the cryospheric-hydrological SPHY model, and the global dynamic hydrological and 5 crop production model LPJmL. The models are forced with an ensemble of 8 bias-corrected downscaled GCMs that represent the full range of regional RCP4.5 and RCP8.5 climate conditions in combination with and without two socio-economic development scenarios (SSP1 and SSP3) that are likely linked with these RCPs. The model outcomes are analysed in terms of changes in the water availability, demand and gapsearcity.

The outcomes indicate that surface water availability will increase towards the end of the 21st century with the largest 10 projected increases for RCP8.5. Thereby, increases are projected to be stronger during the monsoon season, which can mainly be attributed to the increases in monsoon precipitation, snowmelt and glacier melt. The upstream – downstream difference in water availability is largest in the Indus and Ganges river basins, whereas in the Brahmaputra river basin this 15 difference is relatively small. This indicates that the downstream dependency on upstream water resources is large, especially in the Indus and Ganges river basins. Future upstream-downstream differences in water availability are projected to be enhanced, implying that the downstream-dependency on upstream water resources will increase.

Annual and seasonal water consumption are projected to decrease when considering climate change only. This is mainly caused by shortening of growing seasons that emerge from temperature increases, and precipitation increases that result in a shift from blue water irrigation to green water or rainfed irrigation and thus cause irrigation water consumption to decline. Only in the monsoon (partly) and post-monsoon, water consumption is expected to increase, which can mainly be attributed 20 to enhanced atmospheric evaporative demand and resulting increases in crop evapotranspiration that emerge from temperature increases. The combination of climate change and socio-economic development result in increasing annual and seasonal water consumption for RCP4.5 – SSP1 and RCP8.5 – SSP3 due to population growth and economic developments.

Due to declining water demand under climate change only, the water gap is also expected to decrease with relative 25 decreases up to 37% and 5560% in the Indus and Ganges, respectively, for RCP8.5, at the end of the 21st century. The combination of climate change and socio-economic development is expected to result in increasing water gaps with relative increases up to 7% and 141% in the Indus and Ganges, respectively, for RCP8.5-SSP3, at the end of the 21st century. Future EFRs are projected to be sustained during high flow seasons, whereas during low flow seasons EFRs cannot be met in the Indus and Ganges river basins. Based on the outcomes it can be concluded that socio-economic development is the key driver in the evolution of the South Asian water gap, whereas climate change plays a role as a decelerator. For the South 30 Asian region, which is already facing water stress in a geopolitically complex situation, our findings provide valuable insights in the future evolution of the regional water gap, providing a scientific basis for the formulation of transboundary climate change adaptation policies.

Code and Data Availability. The code of the SPHY model is publicly available at <https://github.com/FutureWater/SPHY>. The code of the LPJmL model is available upon request. The datasets that are produced in this study are available upon request.

5 *Author Contributions.* The study is designed by A.F. Lutz, H. Biemans, R.R. Wijngaard, and W.W. Immerzeel. The model codes were adjusted by H. Biemans for the LPJmL model. The models were run by R.R. Wijngaard (SPHY) and H. Biemans (LPJmL). The analyses on the simulation outcomes were performed by R.R. Wijngaard. R.R. Wijngaard and H. Biemans prepared the manuscript text. The figures were prepared by R.R. Wijngaard. Finally, the proof-reading was performed by all (co-)authors.

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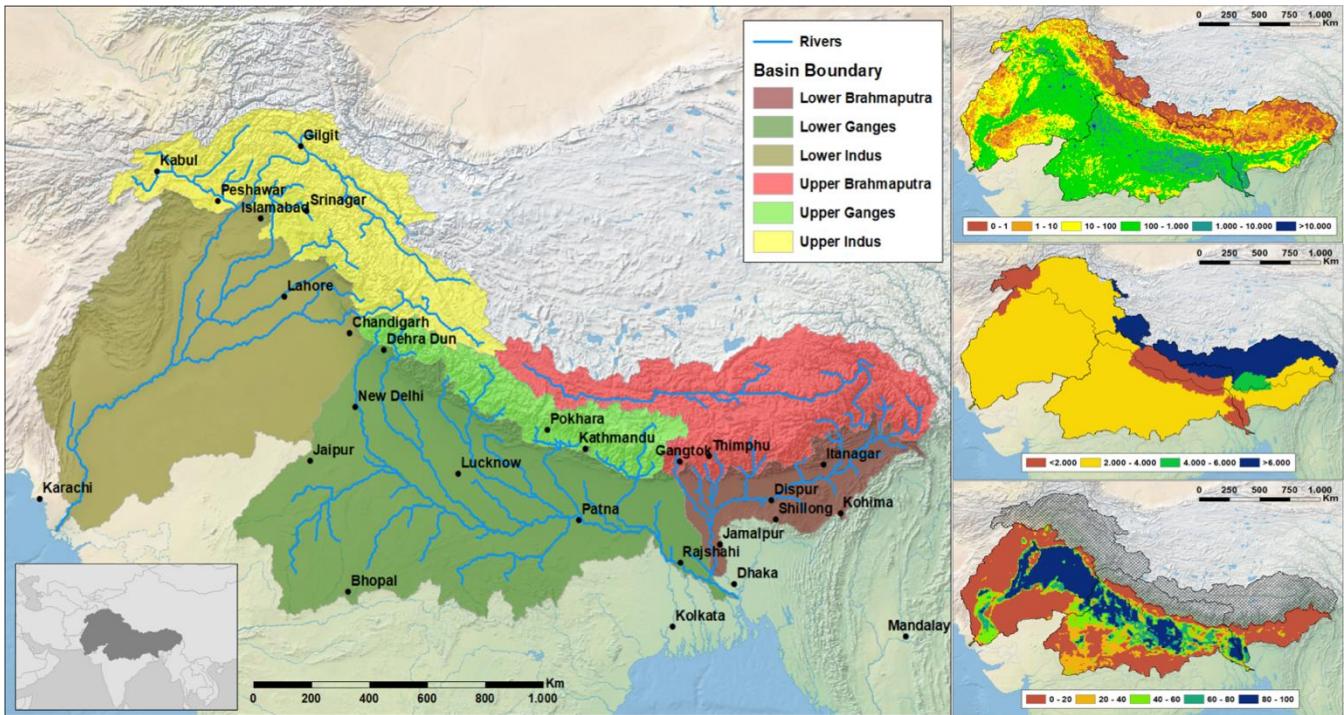


Figure 1. a) Map of study area showing the sub-basins and the largest cities in the region, b) the population density [inhabitants/km²], c) the GDP (PPP) per capita per country [US\$/inhabitant], and d) the fraction of irrigated cropland [%].

5 Source of the background imagery, the cities, and the political borders illustrated in the inset is naturalearthdata.com. Source of the population density data is the HYDE v3.2 database (Klein Goldewijk et al., 2010). The GDP (PPP) per capita is derived from IIASA SSP database (IIASA, 2017). [The fraction of the irrigated cropland is derived from the MIRCA2000 dataset](#) (Biemans et al., 2016; Portmann et al., 2010)

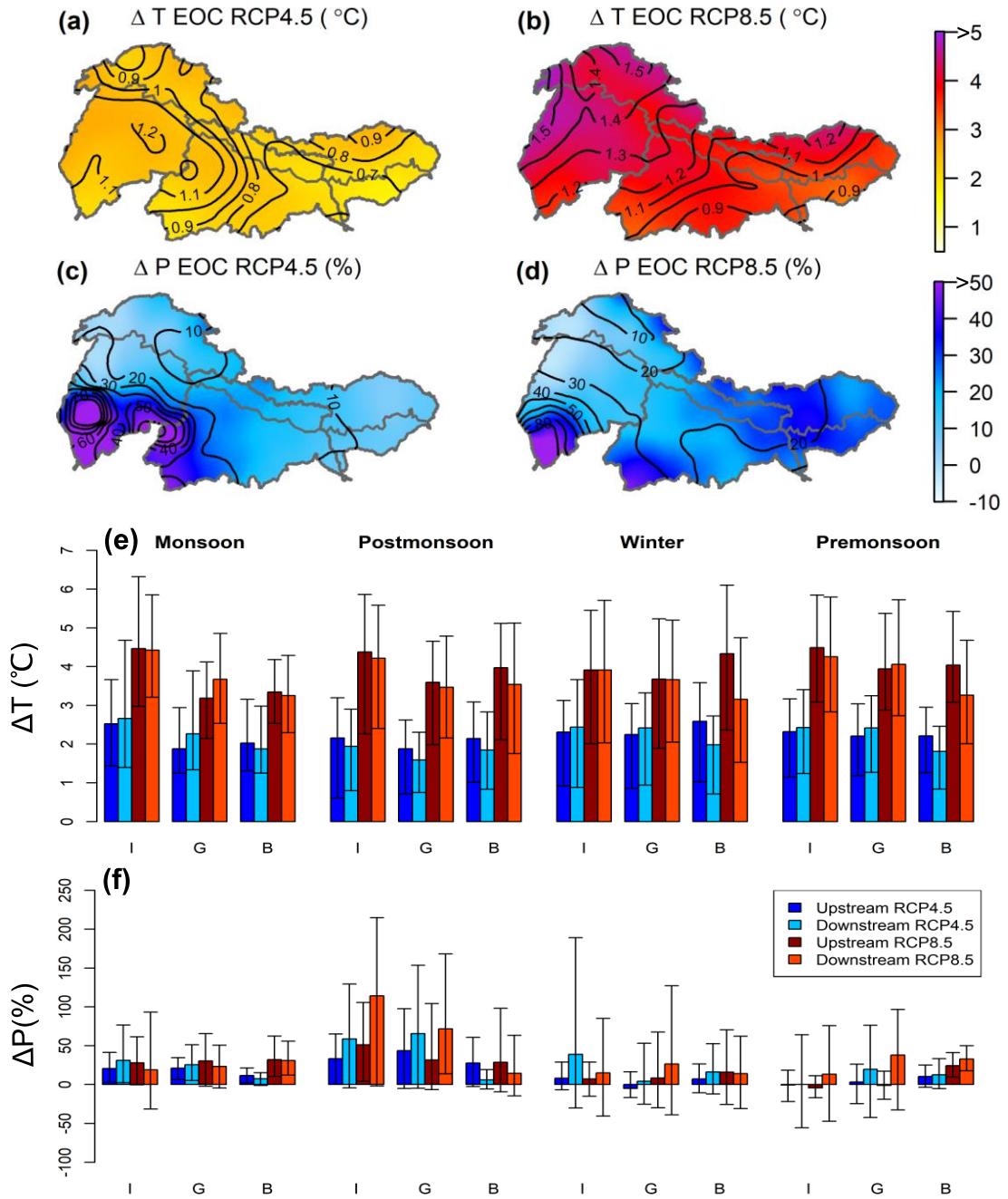


Figure 2. Maps showing the annual changes in temperature (a, b) and precipitation (c, d) between 2071-2100 and 1981-2010 for RCP4.5 and RCP8.5. The bar plots show seasonal changes in temperature (e) and precipitation (f) in the upstream and downstream domains of the IGB for RCP4.5 and RCP8.5. The contour lines within the maps and the error bars within the bar plots denote the ensemble range of the projections.

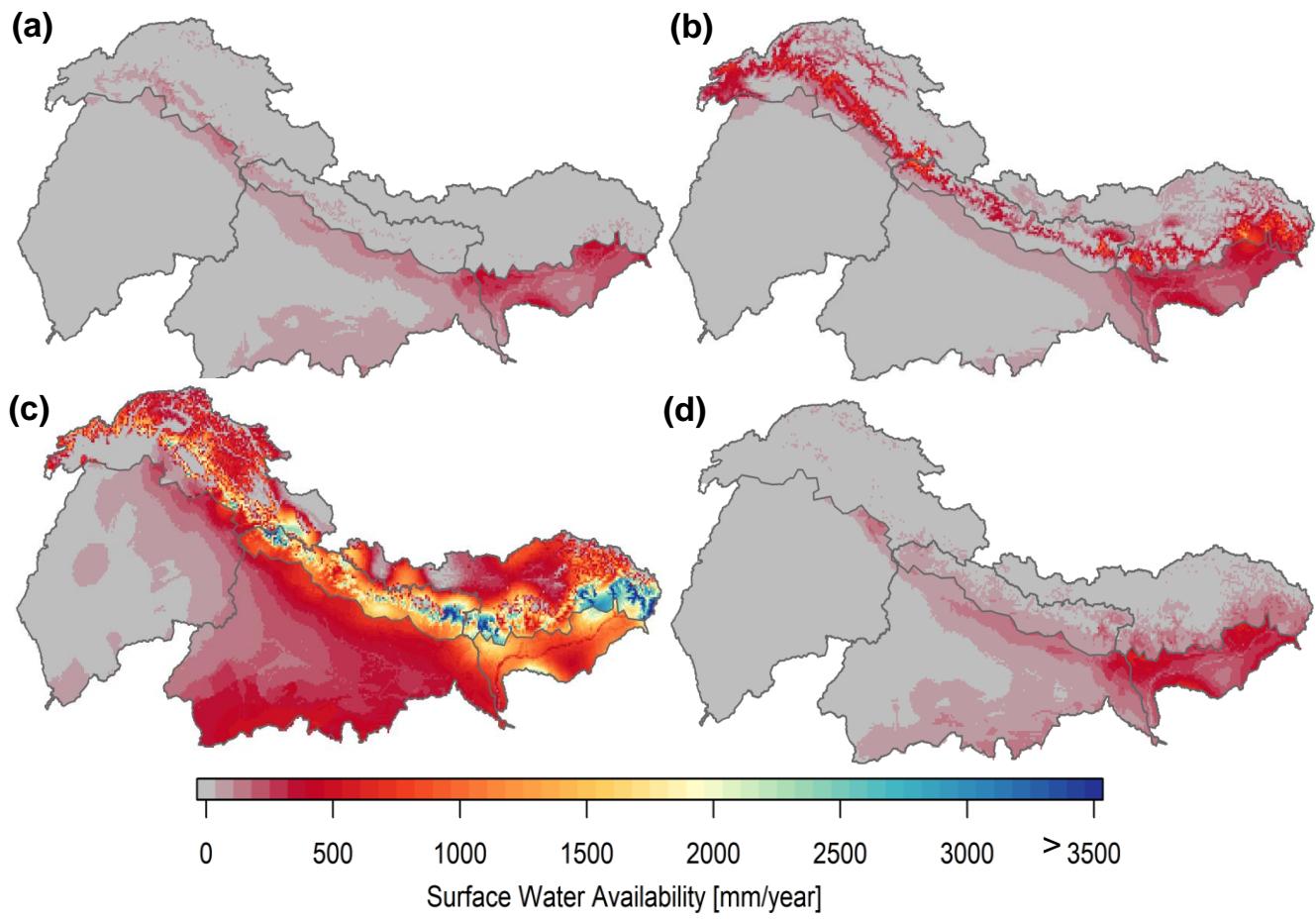


Figure 3. Maps showing the surface water availability in winter (a), pre-monsoon (b), monsoon (c), and post-monsoon(d).

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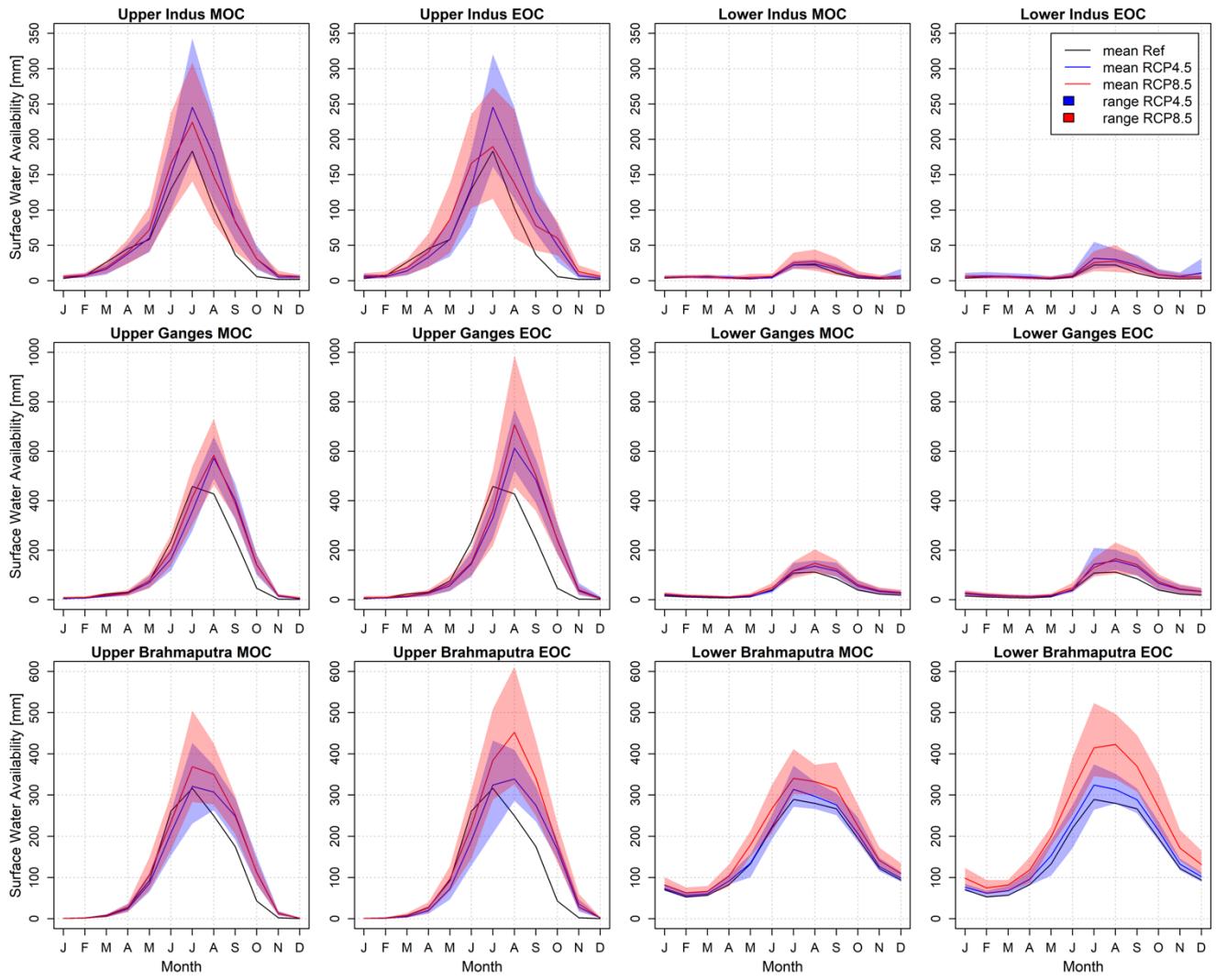


Figure 4. Plots showing the mean monthly blue water availability for the reference (1981-2010) and future periods (mid-of-century (MOC) (2041-2070) and end-of-century (EOC) (2071-2100)) under RCP4.5 (blue) and RCP8.5 (red). The coloured bands represent the range of ensemble projections that are resulting from forcing the SPHY and LPJmL models with the different climate models.

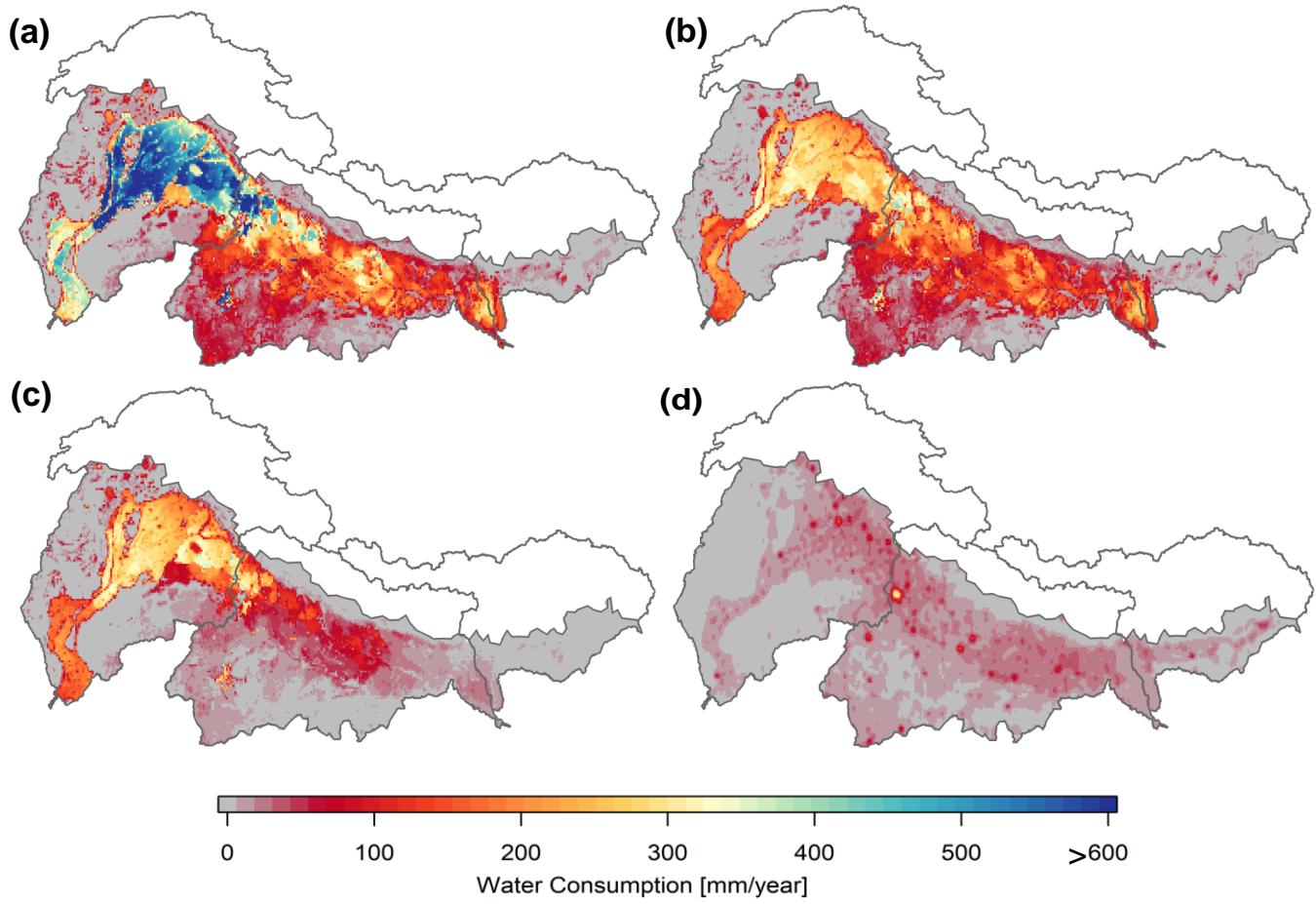


Figure 5. Maps showing the blue water consumption for irrigated croplands (a-c) and other users (i.e. domestic + industrial) (d). The irrigation water consumption is given on annual base (a), and for the rabi (b) and kharif seasons (c). The domestic + industrial water consumption is given on annual base.

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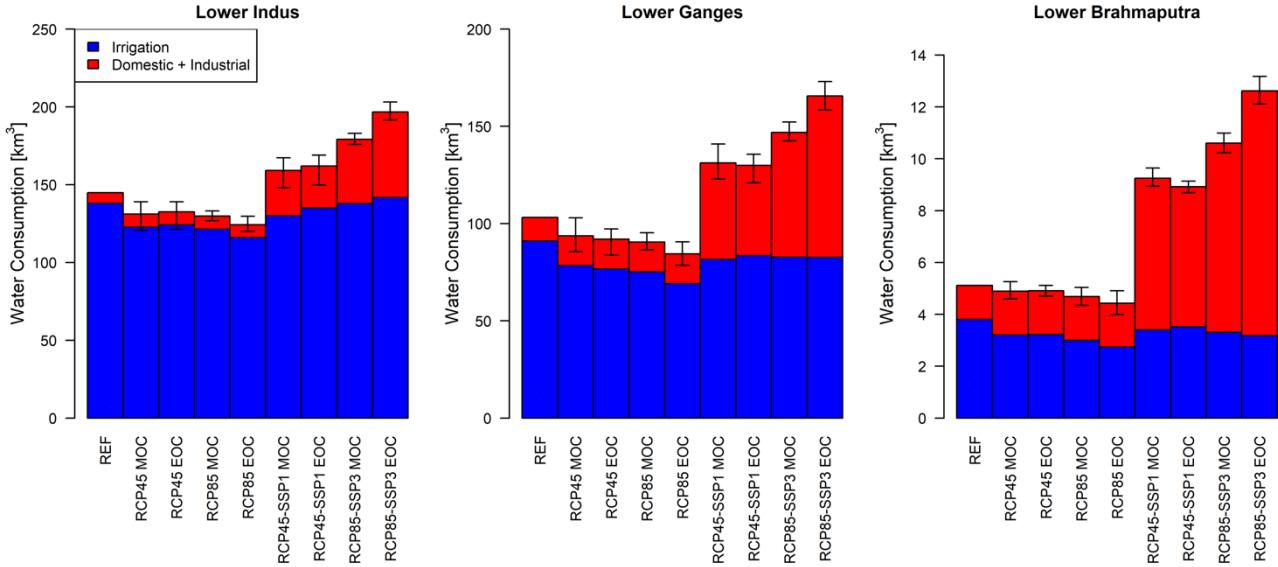


Figure 6. Projected changes in the annual blue water consumption for irrigated croplands and other users (i.e. domestic + industrial) for RCP4.5, RCP8.5, RCP4.5 – SSP1, and RCP8.5 – SSP3. The projected changes are given for the mid and end of the 21st century (MOC and EOC) and represent the ensemble mean. The error bars denote the range of the ensemble

5 projections.

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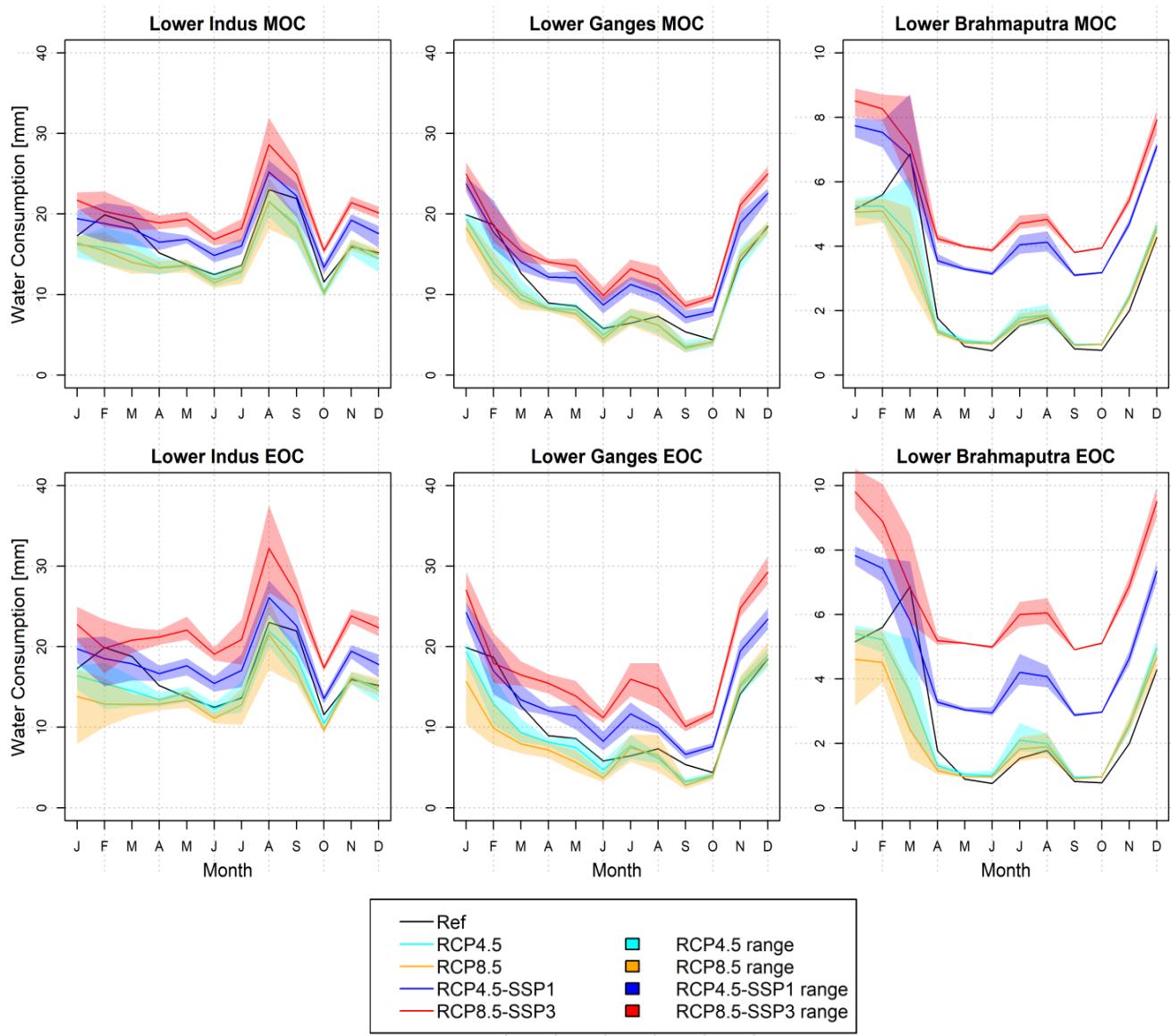


Figure 7. Monthly projected changes in the total water consumption for RCP4.5, RCP8.5, RCP4.5 – SSP1, and RCP8.5 – SSP3. The projected changes are given for the mid and end of the 21st century (MOC and EOC). The coloured bands represent the range of ensemble projections that are resulting from forcing the ~~SPHY and~~ LPJmL models with the different climate models.

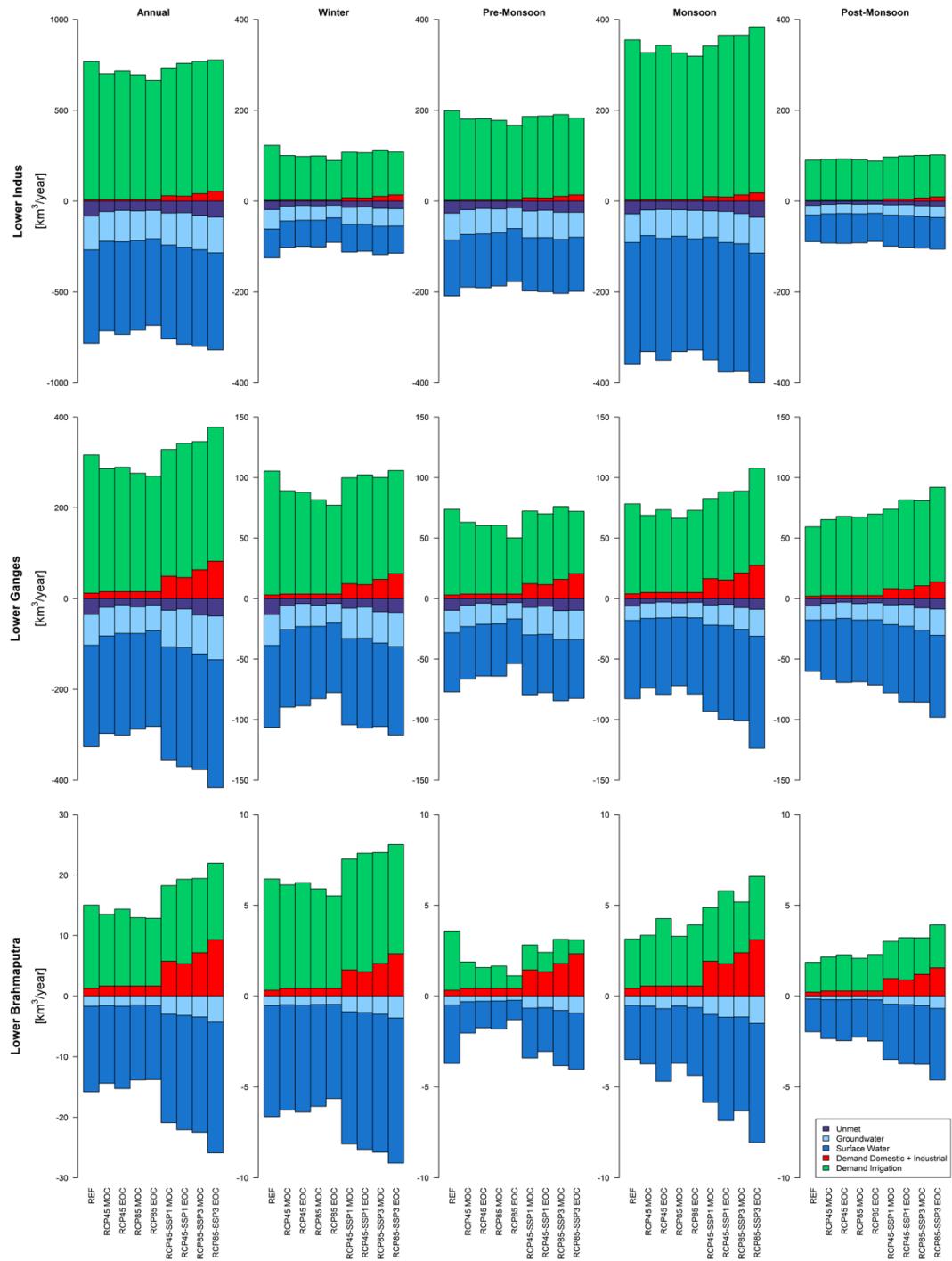


Figure 8. Projected changes in the annual and seasonal blue water demand and supply for RCP4.5, RCP8.5, RCP4.5 – SSP1, and RCP8.5 – SSP3. The projected changes are given for the mid and end of the 21st century (MOC and EOC).

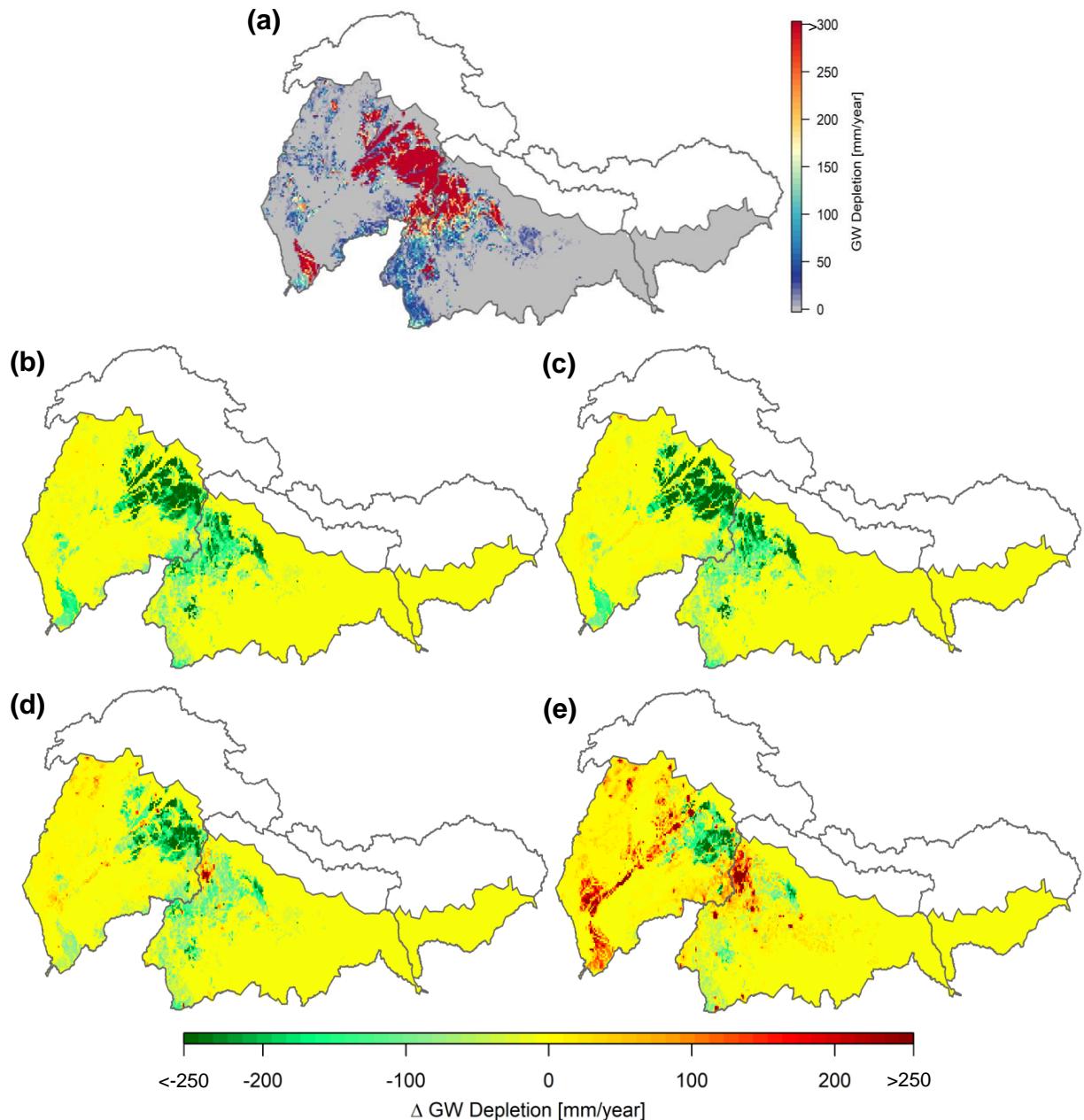
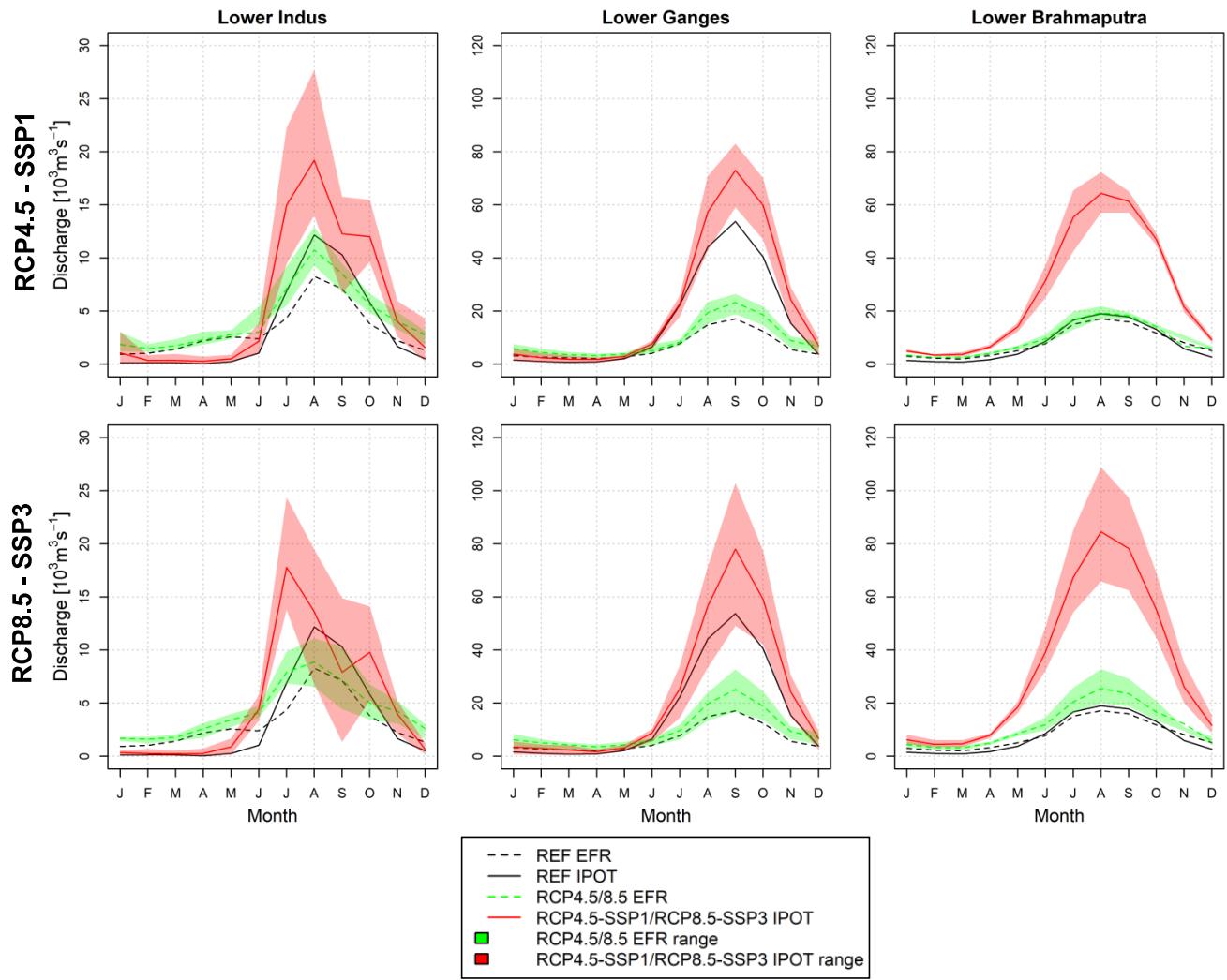


Figure 9. Maps showing the annual groundwater depletion for the reference period (a) and the projected changes in groundwater depletion for RCP4.5 (b), RCP8.5 (c), RCP4.5 – SSP1 (d), and RCP8.5 – SSP3 (e). The projected changes are given for the end of the 21st century. Green indicates less depletion and red indicate more depletion.



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Figure 10. Monthly projected changes in the environmental flow requirements (EFR) and anthropogenic influenced discharge (IPOT) at the outlets of the Indus, Ganges and Brahmaputra rivers for RCP4.5 – SSP1 (upper row) and RCP8.5 – SSP3 (lower row). The projected changes are given for the end of the 21st century (EOC). The coloured bands represent the range of ensemble projections that are resulting from forcing the LPJmL model with the different climate models and SSP storylines.

Table 1. Projected basin-aggregated population counts and GDP (PPP = Purchasing Power Parity) for SSP1 and SSP3. The population counts are extracted from the HYDE v3.2 database (Klein Goldewijk et al., 2010). The GDP (PPP) is a product of the population counts and the country-specific GDP (PPP) per capita, which is derived from the IIASA SSP database 5 (IIASA, 2017) as the ensemble mean of the IIASA GDP and OECD Environmental Growth models.

Basins	Countries	Population (x 10 ⁶)			GDP (PPP) (x 10 ⁹ US\$2005)		
		2010	2050	2100	2010	2050	2100
Indus	AF, CN, IN, PK	245	346/469	289/725	631	5124/2894	14574/7191
Ganges	BD, CN, IN, NP	494	629/804	466/1073	1410	14276/8782	28796/15198
Brahmaputra	BD, BT, CN, IN	65	81/101	58/129	165	1601/952	3299/1689

Table 2. Projected changes in the annual and seasonal blue water gap of the Indus and Ganges river basins under present (1981-2010) and far-future (2071-2100; EOC) conditions for RCP4.5, RCP8.5, RCP4.5-SSP1, and RCP8.5-SSP3. The values between the parentheses represent the standard deviation.

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<u>Basin</u>	<u>Scenario</u>	<u>Annual</u>	<u>Winter</u>	<u>Pre-monsoon</u>	<u>Monsoon</u>	<u>Post-monsoon</u>
<u>Indus</u>	<u>REF [km³]</u>	<u>83</u>	<u>19</u>	<u>27</u>	<u>28</u>	<u>10</u>
	<u>RCP45 EOC [%]</u>	<u>-36 (15)</u>	<u>-47 (14)</u>	<u>-35 (16)</u>	<u>-32 (15)</u>	<u>-33 (15)</u>
	<u>RCP85 EOC [%]</u>	<u>-37 (15)</u>	<u>-46 (11)</u>	<u>-37 (11)</u>	<u>-34 (21)</u>	<u>-30 (18)</u>
	<u>RCP45-SSP1 EOC [%]</u>	<u>-21 (18)</u>	<u>-31 (18)</u>	<u>-21 (20)</u>	<u>-16 (18)</u>	<u>-15 (18)</u>
	<u>RCP85-SSP3 EOC [%]</u>	<u>7 (25)</u>	<u>-11 (18)</u>	<u>-9 (8)</u>	<u>30 (52)</u>	<u>18 (24)</u>
<u>Ganges</u>	<u>REF [km³]</u>	<u>35</u>	<u>13</u>	<u>10</u>	<u>6</u>	<u>6</u>
	<u>RCP45 EOC [%]</u>	<u>-52 (21)</u>	<u>-61 (17)</u>	<u>-51 (23)</u>	<u>-44 (23)</u>	<u>-41 (27)</u>
	<u>RCP85 EOC [%]</u>	<u>-55 (20)</u>	<u>-64 (16)</u>	<u>-54 (19)</u>	<u>-47 (28)</u>	<u>-44 (25)</u>
	<u>RCP45-SSP1 EOC [%]</u>	<u>-23 (32)</u>	<u>-37 (27)</u>	<u>-23 (33)</u>	<u>-9 (35)</u>	<u>-8 (39)</u>
	<u>RCP85-SSP3 EOC [%]</u>	<u>14 (43)</u>	<u>-11 (36)</u>	<u>1 (26)</u>	<u>55 (75)</u>	<u>50 (55)</u>