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 gratefully 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. The manuscript will be modified accordingly to the responses that are given to the comments.

I have gone through the revised paper carefully.

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

1. *The authors have clarified the doubts raised about the modelling. No problem there.*

Thank you.

2. *Regarding blue water gap (BWG) versus blue water scarcity (BWS): the authors have revised the manuscript to emphasize that they are really estimating the 'blue water gap' (with the assumption that there is no adaptive response to water shortages). But the text is now rather inconsistent—switching between the two terms. There is no real discussion (either in the para starting on p3 line23, or later in the methods section) of the implications of using BWG as a proxy for BWS—so no real recognition of the socially constructed nature of this outcome variable. The authors say that Figure 9 shows how BWG is especially significant in urban areas. But this actually illustrates the risk in using BWG as a proxy for scarcity: because in urban areas, whenever there is a 'gap', it will get addressed through more imports (because the quantities required are still relatively small and drinking water is a political priority). So in fact it is not much of an issue in urban areas!*

We agree that the use of both blue water gap and blue water scarcity is confusing, and in the revised manuscript we will only refer to blue water gap. The focus of this study is on assessing the combined impacts of climate change and socio-economic developments on the future blue water gap. The blue water gap as defined in our study is the amount of unsustainable groundwater that is withdrawn to fulfil the blue water demand. This means the blue water gap is only present when renewable or sustainable blue water resources (i.e. surface water and renewable groundwater) are not available (locally), which means that the blue water gap can be an indicator for a scarcity in renewable water resources. Within the LPJmL model the blue water gap is closed by (unsustainable) groundwater withdrawals. As a result of this model concept water scarcity, in stricto sensu, does not occur, because the demand is always met. We realize that we have not stated this clearly in our last response to the reviewer. Also, we realize that due to the use of the two terms "blue water gap" and "blue water scarcity" throughout the manuscript, the text has become inconsistent and unclear. To avoid the inconsistencies between the two terms we will rephrase the paragraphs in Section 1 Introduction, Section 4.6 Comparison with other studies, and Section 4.7 Uncertainties and Limitations and we will systematically refer to blue water gap only.

3. *The authors have taken pains to include the issue of Environmental Flows as an outcome variable and added a whole analysis there. This is laudable and has made the article potentially more interesting. Their definition of EFR for low flow season as being 60% of the mean monthly flow during that season is, however, quite stringent: this makes even the Brahmaputra as 'not meeting EFR needs even in current/reference scenario. This seems rather extreme and needs to be checked.*

Thank you, we also consider it as a valuable addition and we thank you for this suggestion. We use the well accepted Variable Month Flow (VMF) method of Pastor et al. (2014) to estimate environmental flow requirements (EFRs). This method enables to calculate monthly EFRs depending on the season (low, intermediate and high flow seasons). During the low flow season the EFR is 60% of the mean monthly flow (MMF), 45% of MMF during the intermediate flow season and 30% during the high flow season. Pastor et al. (2014) also compared five methods for assessing EFRs on global and local scales: the Smakhtin, Tennant, Tessmann, VMF, and $Q_{90}\_Q_{50}$ methods. Their review showed that the VMF and the Tessmann methods perform best. The difference between these two methods is that the Tessmann method allocates all water to EFRs in low flow seasons, whereas the VMF method allocates 60% of the MMF to EFRs in low flow seasons. Since the Tessmann method does not allow water withdrawals during the low flow season it is therefore less valid in a region like the IGB. Using the Tessmann method would result in an even more stringent EFR.

In the Brahmaputra River Basin, the low flow season coincides with the rabi season. During this season, the water consumption is significantly higher at most irrigated croplands than during the kharif season (Figure 5, 7, and 8). The combination of higher water consumptions and lower water availability explains why EFRs are not met during the low flow seasons and we therefore think this is realistic, and the VMF method is valid to use here.

4. *The biggest problem I continue have with the paper is "what does the paper contribute to our understanding?". The authors' response has been "we are doing more novel modelling with finer spatial scale, better modelling of many of the processes involved, etc. than anyone else has done". So here we are facing a fundamental difference in our understanding of what constitutes 'contribution' to scientific knowledge: I believe that a 'better' model is one which gives either more precise predictions of changes in some outcome variable(s) or counter-intuitive results on the 'sign' of change in the outcome variable. In other words, 'better' has to be judged not by modelling sophistication per se, but whether the sophistication generates results that are different (and robustly so) from what we already know.*

   When I look at their results carefully, the uncertainties are even higher and the non-results even sharper: In 3 out of 4 scenarios, the blue-water gap actually DECREASES across all 3 basins and all seasons. But these decrease estimates have a high standard deviation, making most of them no different from zero. In the 4th scenario (greatest climate change & highest economic/demographic growth rate) we see that socio-economic growth outstrips effects of CC and there is an INCREASE in the blue-water gap. HOWEVER, this increase is not statistically significant: it is 14% with a standard deviation of 43 (% points I presume). Which means it is not statistically different from 0 (the NO CHANGE scenario). So after all this effort, they are not able to tell us even what the SIGN on the net change is going to be, let alone give us a robust estimate of the magnitude of net change. So why is this whole (very technically competent) exercise useful?

Novelty

In the last decades, several climate change impact assessments have been conducted in the mountainous regions and surrounding lowlands of river basins in South and Central Asia. For instance, Barnett et al. (2005) concluded by means of a global study that in the HKH region future water availability will most likely decrease during the dry season mainly due to vanishing glaciers and snow. Immerzeel et al. (2010) found that the importance of glaciers and snow is highly variable, and that projections in future river flow do not reveal a consistent pattern. A later study of Lutz et al. (2014) projected runoff increases in the upstream domains of the Ganges, Brahmaputra, Salween, Mekong, and Indus until 2050, which were primarily attributed to increases in precipitation and accelerated melt (i.e. only in the upstream domain of the Indus). The assessments indicate that the understanding on the impacts of climate change on upstream water availability in the HKH region has improved over the last decades, despite the large uncertainties that are mainly related to climate change projections. Although scientific research in this field has clearly advanced, there are still large unknowns. For instance, to what extent the climate-induced changes in upstream hydrology will affect the downstream domains of the South Asian river basins, and how it relates to the anticipated socio-economic developments and related changes in water demand. The relevance and novelty of this study is therefore in understanding the link between climate change and socio-economic development with the aim to quantify how the future South Asian blue water gap will develop.

In addition, there are also clear disciplinary novel components of our study:

- For the first time a model is applied that integrates both fundamental cryospheric processes in the upstream part of the basins with an advanced water distribution model that includes reservoirs, multiple cropping cycles and irrigation that integrates extensive canal systems and groundwater. This model takes upstream-downstream links and lateral transport into consideration, which enables the possibility to assess the effects of changes in upstream water supply on downstream water availability and to improve analyses on the regional “blue” water gap.
- Further, the novelty is in the use of gridded socio-economic and land use scenarios, combined with an ensemble of downscaled and bias-corrected GCMs, to assess the combined impacts of climate change and socio-economic development on the future South Asian water gap.

We will emphasize these novelties more explicitly in the introduction.

Uncertainties

The outcomes of this study are prone to large uncertainties that are mainly originating from the uncertainties in climate change projections. This is the case for almost all hydrological impact studies and it is not something that is unique to our case. We consider it a strength of our study that we show the full range of possible futures including uncertainty in both climate change and socio-economic projections. GCMs have a limited skill in simulating the complex mountainous climate regimes of Central and South Asia (Lutz et al., 2016b; Seneviratne et al., 2012). We do the best currently possible by using an advanced envelope-based selection approach to select climate models also based on their skill to simulate the regional climate. For each RCP, we selected four GCMs that represent the four corner points of possible climate conditions (i.e. warm-wet, warm-dry, cold-wet, and cold-dry) and thus cover a wide range of possible future climate conditions. The variation in climate change projections between different GCMs is however large, which results in a large spread among the climate models. This spread propagates subsequently to the hydrological model outcomes. This is a general problem in many studies that are conducted in the region (e.g. Arnell and Lloyd-Hughes, 2014; Lutz et al., 2014; Moors et al., 2011; Wijngaard et al., 2017). The upcoming CMIP6 model archive (Eyring et al., 2016) might improve the outcomes of the studies by reducing the variation in climate change projections between the different GCMs. We will mention this in Section 4.7 Uncertainties and Limitations. Since we only used four climate models per RCP, we realize that the standard deviation is not a suitable proxy for the expression of the uncertainties in Table 2. It is not an uncertainty, but a range of possible futures. For this reason, we replaced the standard deviation values in Table 2 by the min-max range, also for consistency throughout the manuscript. Further, we use a colour scheme to indicate the number of climate-model related outcomes that show the same sign of change as the projected mean change, as an indicator for the trend’s significance.

The updated Table 2 shows that the range of possible futures is indeed large, but this is the spread in possible futures the climate models currently project and it is important to provide this message. For the RCP combinations, a clear decreasing trend is projected on annual basis and on seasonal basis as well. For RCP4.5-SSP1, the decreasing trend is still present, although the projected relative decreases are smaller than for the RCP combinations, which can be attributed to the projected increases in domestic and industrial water consumption. For RCP8.5-SSP3 the projected changes in water demand are so large that climate change cannot compensate them anymore. Despite the large range among the model outcomes, the mean of the outcomes for RCP8.5-SSP3 still indicate that the blue water gap will increase. This means, in turn, that socio-economic development can be considered as a key driver in the future South Asian water gap.

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 minimum and maximum projected changes in the blue water gap. The colours indicate the number of model runs (i.e. green: more than 3 runs; yellow: 2 runs; red: 1 run) that project the same sign of change as the projected mean change.

Basin	Scenario	Annual	Winter	Pre-monsoon	Monsoon	Post-monsoon
Indus	REF [km^3]	83	19	27	28	10
	RCP45 EOC [%]	-36 (-59/-19)	-47 (-70/-32)	-35 (-61/-18)	-32 (-53/-13)	-33 (-54/-13)
	RCP85 EOC [%]	-37 (-52/-15)	-52 (-59/-35)	-44 (-49/-35)	-23 (-58/14)	-29 (-44/-10)
	RCP45-SSP1 EOC [%]	-21 (-50/1)	-31 (-60/-11)	-21 (-53/0)	-16 (-42/7)	-15 (-42/9)
	RCP85-SSP3 EOC [%]	7 (-18/42)	-11 (-25/19)	-9 (-16/5)	30 (-27/91)	18 (-8/48)
Ganges	REF [km^3]	35	13	10	6	6
	RCP45 EOC [%]	-52 (-85/-26)	-61 (-89/-41)	-51 (-86/-23)	-44 (-82/-19)	-41 (-81/-8)
	RCP85 EOC [%]	-55 (-73/-23)	-66 (-78/-38)	-63 (-73/-45)	-39 (-72/14)	-34 (-64/10)
	RCP45-SSP1 EOC [%]	-23 (-74/16)	-37 (-79/-4)	-23 (-74/19)	-9 (-66/28)	-8 (-67/41)
	RCP85-SSP3 EOC [%]	14 (-26/82)	-11 (-40/49)	1 (-23/44)	55 (-17/165)	50 (-11/131)