Response to Reviewer 2

We thank the reviewer for the concise and constructive comments. After careful consideration we provide a point-by-point reply to each of the comments in the text below. We are confident that the reviewers comments and corresponding suggested changes will improve the quality of the paper. The reviewer's original comments are numbered and in italics for clarity. References which do not appear yet in the main manuscript are listed at the end of this document We will modify the manuscript according to our responses.

1.) *The paper provides a comparative analysis of the impact of upper Indus water usage on downstream water availability under future climate change and socio-economic development. The analysis was done in sub-basin scale and under seasonal variability which is potentially interesting. Though the analysis is done on transboundary basin, there is no discussion how the results can add value on transboundary water management.*

Author response: The results of our study show several novel implications for future transboundary water management in the Indus basin. Foremost, previous quantitative studies on transboundary upstream-downstream linkages (Munia et al., 2016; Munia et al., 2017; Munia et al., 2020; Viviroli et al., 2020) evaluated the upper Indus as one aggregated sub-basin. These coarser assessments only provided insight into the development of such trends for the Indus basin at large. Instead, our regional assessment makes a disaggregated assessment for each major Indus tributary in the upper Indus and corresponding downstream areas. This allows our study to look at the trends of future upstream-downstream linkages within the Indus basin. Our approach is especially commendable for providing new quantitative insights into the development of upstream-downstream linkages for Indus sub-basins that are shared between multiple states. Our study thus looks for the first time at the scale of individual tributaries, where transboundary upstream-downstream tensions occur and should be addressed. This method allows for the identification of hotspots within the Indus basin where future transboundary upstream-downstream issues are likely to occur and ensuing hydropolitical tensions are likely to arise between basin countries.

Within the present discussion we highlight such sub-basin level transboundary implications specifically for the Kabul and Jhelum subbasins (largely administered by Afghanistan and India, respectively) and the increasingly populous downstream plains of the Pakistani Punjab (see line 353-370). In addition, we use this discussion to reflect on the future of the Indus Water Treaty. Nonetheless, upon revisiting our document, we acknowledge that the reflection on the larger transboundary implications of the patterns found in our study (line 342-370) can be made more explicit.

To highlight the value added by our novel approach to transboundary water management in the Indus and beyond, we suggest the following changes to the manuscript:

- First of all, we will expand the discussion section dedicated to the new insight provided by our disaggregated approach versus previous lumped approach (line 342-352). We will do so by linking this segment explicitly to new insights gained in our study on transboundary upstream-downstream linkages, as compared to insights provided by previous studies at coarser resolution.
- Second, both the Jhelum and Kabul sub-basins are shared between multiple riparian states. The consequences of changing upstream water use in the upper Indus and the emergence of impact hotspots in the lower Indus (discussed in line 342-360) are thus transboundary in character. However, these changing upstream-downstream linkages are currently described only in geographical terms and an explicit link to the riparian states involved is not made in this segment of the discussion. We will therefore add context on the relevant riparian states here, similar to the way in which we did in line 361-370.

- Third, we will expand the discussion on the consequences that changing upstream consumption and downstream water availability will have for water management and water sharing treaties between the riparian states (line 367-370), such as the Indus Water Treaty. This reflection will be aided by the inclusion of an overview of present water management practices and treaties in the 'Methods and Materials' section (see the response to comment 3).
- Lastly, we think that the tail section of our discussion and conclusion largely reflects on lessons learnt for adaptation towards water and food SDGs and for future hydrological modelling (line 371-375 and 393-402). We will revise these sections to also provide key highlights for transboundary water management. These highlights will be based on the discussion in lines 342-370, expanded with the changes mentioned above.

2.) *I found the method and material section complex and difficult to follow. May be using separate sections for data and scenarios will help.*

Author response: This point was also raised by Reviewer #1. The present 'Materials & Methods' section contains a separate section for the scenarios, while most data is introduction within the 'Analysis and data sources' segment. However, the scenarios that we use in our study are quantitative and spatially explicit and this has caused some overlap to occur between the 'narrative' side of the scenario and 'forcing data' side of the scenarios. Upon revisiting the document we do understand that the current blended introduction of scenario narratives and forcing data makes it more difficult to understand our methodology.

In light of both reviewer comments, we suggest the following changes:

- Primarily, we will restructure the 'Methods & Materials' section. We will split the 'Spatially explicit scenario context' section (line 84-100) to only contain the qualitative, narrative-related information of the scenarios. The forcing data information of the scenarios will be moved to a new sub-section '2.3.1. Scenario forcing data' at the start of the 'Analysis and data sources' section. Here we will explain the input/forcing data that was used to generate the hydrological and water consumption data used directly in our water accounting assessment.
- Additionally, we will add references to Table 1 within the 'Analysis and data sources' section to better clarify what data was exactly used in each part of the analysis. We will also adapt the terminology in this table to be consistent with that used in the text.
- Lastly, we will revise the general overview of the overall approach of our methodology (lines 78-83) to more clearly outline the division between scenario, data and analysis.

3.) *In the discussion section the current water management needs to be discussed. Moreover, the novelty of this analysis needs to discuss clearly.*

Author response: We agree that in our manuscript the discussion on present day water management practices, especially from a transboundary perspective, is limited. A similar concern was raised by reviewer #1, who suggested adding a 'case study' sub-section in the 'Methods and Materials' section to provide an overview of current transboundary water management practices and the role of water sharing accords, such as the Indus Water Treaty. We will implement this suggestion and use this overview to also expand the current reflection (see line 367-370) on the implications of our results for present and future water sharing treaties and water management in the Indus basin (also see response to comment 1).

4.) *Future of the upper Indus basin's water availability is highly uncertain in the long run, mainly due to the large spread in the future precipitation projections. Despite large uncertainties in the future climate and long-term water availability, basin-wide patterns and trends of seasonal shifts in water availability are consistent across climate change scenarios.*

Author response: We thank the reviewer for this important comment on the consideration of uncertainty in hydroclimatic projection. Previous studies have shown that rising temperatures under climate change will intensify glacial melt in this region and subsequently increase seasonal mountain water discharges for the century to come (Wijngaard et al., 2018; Lutz et al., 2014). Since all climate change projections used in this study assume an increase in regional temperatures (~2°C in RCP4.5 and ~5°C in RCP8.5, see Lutz et al., 2016), the surge in meltwater, and thus the increase in surface water availability across the Indus basin, is also consistent across all climate change scenarios and models, despite the large uncertainty found in regional precipitation projections. We will clarify this important sidenote within the corresponding segments of the result and discussion sections.

5.) *There is no mention of green water and its importance, nor is the capacity of green water to partially substitute for blue water needs ignored. At least in the discussion section this limitation must be discussed, and the possible implications for the findings.*

Author response: The SPHY model from previous research was used to simulate the hydrology of upper Indus sub-basins from a biophysical point-of-view (Wijngaard et al., 2017). The subsequent discharge projections hence do not consider societal water withdrawals/consumption in the upstream areas. Instead, these anthropogenic factors, including the blue water consumption from agriculture, were determined independently using other simulation models and combined with the naturalized SPHY hydrology in our water accounting framework. The LPJmL model that we used to simulate the blue water footprint (i.e. consumptive water use for irrigation) will only apply irrigation water if the crop water requirements cannot be met with the water available through precipitation (Bondeau et al., 2007). Hence, the blue water footprint used in our study is already implicitly corrected for green water availability. However, the SPHY model does simulate a water balance at the grid cell level, in which evapotranspiration from a natural vegetation layer is accounted for (see Terink et al., 2015). A green water footprint is therefore already subtracted from the discharge projections of upper Indus sub-basins provided by the SPHY model. To avoid double accounting for green water, we only take the blue water needs from LPJmL. We acknowledge that in our present document this implicit role of green water is not clear. We will therefore add an explanation to clarify the processes described above in lines 121-124 and lines 144-162.

6.) *In this study Greenhouse emission and socioeconomic development scenarios are decoupled, which can introduce further uncertainty to the results, acknowledging that including SSPs is a strong point of this study. Maybe a discussion can help potential users.*

Author response: Our study considers both climatic and socio-economic drivers. We have therefore used the SSP and the RCP frameworks together. The coupling between the frameworks used in our study (i.e. SSP1-RCP4.5 and SSP3-RCP8.5) has been employed in earlier regional assessments (Wijngaard et al., 2018) and are among the most frequent combinations in global integrated RCP-SSP research (see O'Neill et al., 2020). However, as is stated in line 87-89, these couplings are extreme scenarios (best-case and worst-case) that constrain the bandwidth of plausible future development as indicated by state-of-the-art climate models and regionally downscaled socio-economic projections. Using our decoupled approach, more moderate combinations between the RCPs and SSPs, or asymmetric scenarios (e.g. pessimistic socio-economic development with optimistic climatic development) are also possible at the regional level. Although such scenario choices will lead to different outcomes, it is likely that these would remain within the range of the results found in our current study, as these are based on scenarios that represent the boundaries of plausible future developments. We will acknowledge this uncertainty in the limitations section of the discussion (line 330-342) and reflect on its implications.

7.) *In Table 2 results are presented in number, while in the text it is in percentage. It will be better to adopt one method to avoid confusion.*

Author response: This point was also raised by reviewer #1. Table 2 indeed contains absolute numbers in terms of population totals, future discharges and water consumption at the sub-basin level for three timesteps. In the text related to Table 2, we discuss the changes between these timesteps in terms of growth percentages, as it is the relative changes that allow us to compare between big and small sub-basins. In the end, this relative comparison is valuable to explain why some sub-basins have similar trends in Figure 3, despite the vast differences between them in terms of total population and discharge. Nonetheless, we do understand that this inconsistency in unit notation between Table 2 and the text can cause confusion. We will therefore add the relative change compared to the reference period (between parenthesis) after the absolute numbers in Table 2.

8.) *In the discussion section a separate section on limitation of the analysis will be benefited.*

Author response: The current version of the discussion first discusses the limitations of our approach and subsequent opportunities for future research (line 310-342) and then discusses the implications of the work (line 343-375). We will make this distinction clearer by adding sub-section headers.

References

1.) Terink, W., Lutz, A. F., Simons, G. W. H., Immerzeel, W. W., & Droogers, P. (2015). SPHY v2. 0: Spatial processes in Hydrology. Geoscientific Model Development, 8(7), 2009-2034.
2.) O'Neill, B. C., Carter, T. R., Ebi, K., Harrison, P. A., Kemp-Benedict, E., Kok, K., ... & Pichs-Madruga, R. (2020). Achievements and needs for the climate change scenario framework. Nature climate change, 10(12), 1074-1084.