Responses to Reviewer 2- E. Ansink

This paper is on the interconnectedness of water withdrawals and water scarcity in transboundary basins. A method is presented to formally analyze this interconnectedness. This method is subsequently applied to a global hydrological model. The results show that (in my interpretation), interconnectedness is generally low. The implication is that water scarcity is mostly a local problem, which is new to me. My overall assessment is that this paper is a solid piece of work with a new result that has changed my perspective on the management of transboundary rivers, and I thank the authors for this contribution. I do have some comments. Most of them relate to a lack of precision in the use and application of definitions and terminology. My comments may have implications for (the presentation of) both analysis and results.

Response: We sincerely thank you for your supportive words and constructive comments. We have taken all your comments and suggestions into account when revising the paper. Detailed answers to the specific comments are given below.

Major Comments

Comment 1 (a): The definitions of dependency in Table 1 are not mutually exclusive, although they should be. A visual representation of the authors' definitions and my proposal to adjust them are displayed in Figure 1 below. Adjustment would probably have some consequences for the analysis, which I hope/expect are easy to incorporate. If not, one simplification would be to merge the 'dep' and 'oops' categories. Perhaps the resulting categorization is the one intended by the authors. An even simpler, and perhaps more relevant categorization is to not only merge 'dep' and 'oops', but also merge 'no dep' and 'still no dep'. Results and insights will stay the same but the presentation will be easier.

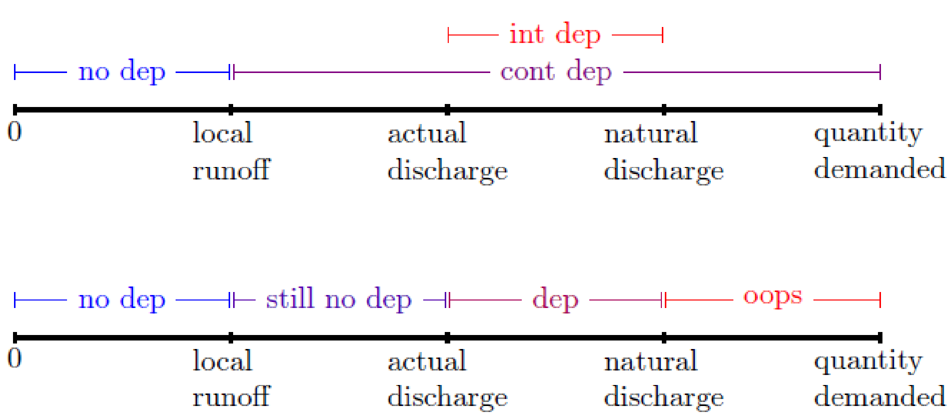

Figure 1: Dependency. Top plot according to Table 1. Bottom plot proposed by reviewer.

Response 1: We thank the referee for pointing this out, and showing that we need to further clarify our definitions. In the revised submission, the definition of dependency is now (described in updated Table 1; see reply to Reviewer 1 comment 1)*: ''Upstream inflows influence whether a region experiences scarcity or not, i.e. how water is managed upstream can change the type of water management regime needed downstream.''* This means, upstream water dependency occurs if water from upstream is needed to avoid scarcity and by scarcity category (NNN, SNO, SNS, SSS) we mean (described in updated Fig 4; see response to Editor comment 1) ''the *stress or shortage condition of a sub-basin under different water availability (local, natural & actual)*''.

Our definition of "No dependency" now states "*Upstream inflows do not influence whether or not a region experiences scarcity, i.e. if a region experiences scarcity (or not) with only local runoff, additional water from upstream does not change this situation*". With our simplified analysis, this includes only two cases: NNN and SSS. The first experiences no scarcity regardless of whether upstream inflows are available. The second does experience scarcity, again, regardless of whether upstream inflows are available.

As a result, the graphical representation of Table 1 by reviewer 2 does not quite reflect the key distinctions in our analysis, as the 'no dependency' condition can happen under all kinds of water availability. Sufficiency of local runoff is a special case corresponding to the category NNN. Exceeding local runoff does not necessarily mean a region is dependent.

We note that the definitions in Table 1 were not clear enough in the original submission, and inconsistent with usage elsewhere in the paper. We have rectified this confusion. In our revised manuscript, the definitions in Table 1 and elsewhere are updated to be accurate and consistent with the analysis. The updated definitions of dependency are presented in response to Reviewer 1 comment 1. At the same time, we have now simplified our analysis taken into account only scarcity and no scarcity, which reduces the number of definitions and categories as well as simplifying the transition map, as presented in response to Editor Comment 1.

Comment 2: The terms used in Table 1 are not used consistently in the text.

a) The authors use the terms runoff and discharge interchangeably (even in Table 1), which is confusing.

Response 2a: We used both the terms runoff and discharge depending on context. By runoff, we mean that part of the precipitation, snowmelt, or irrigation water that appears in surface streams, while discharge refers to flow (accounting for routing of runoff). We now use the term 'local runoff' for this. As noted in the paper, we approximate discharge as the sum of local runoff in local and upstream sub-basins, such that there is an arithmetic relationship between the two. We used the local runoff data for every SBA to calculate their own water availability, while in natural discharge the local runoff from each upstream SBA was added to the SBA's local runoff. Actual discharge was calculated from this by subtracting the water withdrawals in upstream SBAs.

With respect to Table 1 specifically, local runoff is not discharge because it excludes upstream inflows, upstream inflows are the sum of upstream runoff, so the two terms are indeed interchangeable, natural discharge is calculated as the sum of local and upstream runoff, so is defined as such. Actual discharge is local + upstream runoff - upstream withdrawals, but is more easily defined by comparison to natural discharge. This is now better explained in the revised manuscript, with explicit definitions.

b) The terms 'water withdrawals', 'need' and 'demand' are introduced as different concepts (L129) but they lack proper definitions. Perhaps 'demand' should be replaced by 'quantity demanded', which is something different, or 'use'.

Response 2b: Thanks – we agree these concepts needed clarification. These terms are used in three different contexts within the paper, for calculation of water availability after upstream withdrawals, water stress, and water shortage. Water withdrawal is water withdrawn from a surface water or groundwater source for domestic, industrial and agricultural use. Calculation of water stress uses water withdrawal data to reflect impacts from high use of water. Calculation of water shortage focuses on need for water, in terms of per capita water availability. "Demand" was used as a high-level umbrella term covering both actual withdrawals and need for water (as understood by the water shortage indicator). We believe "quantity demanded" would be too specific in this case (and more cumbersome), and "use" would not cover the idea of "need". Explicit definitions have now been given in the text.

c) In L164 the term 'discharge after upstream WW' is used where authors probably refer to 'actual discharge' from Table 1. In the same paragraph, variable 'avail.afterup' is 1st introduced to reflect the same term, so that we now have three terms for the same concept. More variables are then introduced that face the same problem. This is really confusing and obscures the line of argumentation in the main text.

Response 2c: We agree with the reviewer regarding this issue. These three terms (discharge after upstream WW, actual discharge, *avail.afterup*) refer to the same type of discharge. We used *avail.afterup* as the short form to fit in the transition map. So, *avail.afterup* can be consider as the symbolic representation of actual discharge. 'Discharge after upstream WW', in turn, was used to explain what 'actual discharge' means. In the revised manuscript, we make sure that this term is explained only once at the beginning and we use the term consistently for the rest of the manuscript.

Comment 3(a) another comment on Table 1. The order of presentation is illogical and should be reversed. Start with water stress/shortage, which you need to understand scarcity, then runoff/discharge, both of which you need to understand dependency.

Response 3(a): Thank you for the suggestion. We will revise the order of presentation in Table 1 to improve the logic.

Comment 3 (b): A more bold suggestion is the following. Since you assign variable names to some of the terms in Table 1, it would perhaps be transparent to introduce a formula for dependency (with shorter variable names), which would make it much easier to understand the definitions. For example,

if qi denotes water use in sub-basin i, ei denotes local runoff, and Pi denotes the set of i's predecessors (i.e. sub-basins strictly upstream of i) we can write:

- $\hat{e}_i = e_i + \sum_{j \in P_i}(e_j)$ as the total water available after upstream withdrawal;
- $\bar{e}_i = e_i + \sum_{j \in P_i}(e_j - q_j)$ as the total water available after upstream withdrawal.

Subsequently, when we denote x_i as the measure of water needed to avoid water scarcity (be it from stress or shortage), we have:

- $x_i \leq e_i \quad \rightarrow$ no dependency;
- $e_i < x_i \leq \hat{e}_i \quad \rightarrow$ still no dependency (see bottom plot of Figure 1);
- $\hat{e}_i < x_i \leq \bar{e}_i \quad \rightarrow$ dependency.

These formalizations of the definitions may also assist in discussing e.g. the typology of dependence categories in Section 2.2.4. I realize that I might be pushing this point too far. If this is the case then at least sharpen and streamline the definitions and terms used in the paper in a consistent way.

Response 3(b): As we mentioned in our response to Reviewer 2 comment 1, upstream water dependency occurs if upstream inflows influence whether a region experiences scarcity or not. Currently, the definitions in the manuscript are creating confusion and as also mentioned in our reply to Reviewer 2 comment 1, that dependency is not captured by the diagram suggested by the reviewer, such that the suggested variables would likely be insufficient.

Even though we agree that the symbols would provide shorter variable names, use of symbols would increase the level of abstraction and might make it more difficult to understand. We have now modified the definitions of dependencies, which we believe will further clarify the concept.

Comment 4: While you mention treaties on transboundary river water in the discussion, they seem to be ignored in the analysis. Dependencies may not be as severe when they are mitigated by treaties that provide security of continuous upstream inflow. Such treaties may even feature well-designed (flexible) sharing rules able to mitigate the impacts of e.g. climate change. We could even have reversed dependency when a treaty stipulates that local runoff should be shared with downstream riparians. In this case, even if local runoff would be sufficient to satisfy demand, the upstream country would be dependent on the downstream country(/-ies). An example would be Ethiopia's position in the Blue Nile basin.

Response 4: The main focus of our analysis is to identify physical upstream water dependency and explain its direct drivers. The effectiveness of possible treaties was not analysed; instead, our aim was to briefly discuss how this analysis could help treaties to better address water scarcity problems. Treaties have only an indirect effect on physical upstream water dependency, as we define it. They affect development of water resources locally and upstream, which may change the dependency status. It is not the dependency status that would be less severe with a treaty rather than without one, rather a well-designed treaty would attempt to provide interventions that influence the stability of the dependency and hence prevent scarcity from occurring.

The idea of reverse dependencies would be interesting to pursue in future work. Rather than taking a purely physical view of the river system, we can consider a binding downstream allocation as a form of water use that reduces availability, in similar terms to upstream withdrawals. At the same time, the allocation can be considered to increase downstream local availability – the water might be considered to have an equivalent status to local runoff. Discussion will be revised to reflect these links with treaties.

Minor Comments:

Comment 5 L53: Please define 'sub-basin' upon first use.

Response 5: The manuscript will be corrected.

Comment 6. L53: 'experiences' → 'may experience'.

Response 6: The manuscript will be corrected.

Comment 7. L55: 'Parts of basins' do not 'realise' much.

Response 7: Sentence in the original manuscript: "*We argue that a sub-basin therefore experiences a 'hidden' dependency: a downstream part of a basin might be avoiding water scarcity only thanks to upstream inflows, and may not actually realize it until those inflows are no longer available due to increased upstream withdrawals or lower runoff due to potential climate change impacts.*"

We have reworded to avoid implying presence of an actor. Sentence will be revised as follows: "*We argue that a sub-basin therefore may experience a 'hidden' dependency: a downstream part of a basin might be avoiding water scarcity only thanks to upstream inflows, and may not actually face the scarcity until those inflows are no longer available due to increased upstream withdrawals or lower runoff due to potential climate change impacts.*"

Comment 8. Figure 1 duplicates Table 1 and can be removed.

Response 8: Table 1 provides definitions, whereas Figure 1 provides a graphical overview of contributions of the paper (similar to a graphical abstract). We would prefer to keep both, particularly to address different learning styles of the reader.

Comment 9. L131: The 30yr period is introduced here without any explanation. Why? And how?

Response 9: The 30yr period was used to capture the current hydro climatic characteristics. Explanation and reference will be added in the revised methodology section.

Comment 10. L155–159: Are return flows accounted for?

Response 10: In our analysis, return flows are assumed not to be usable downstream. Withdrawal refers to the total amount of water used for each sector, much of which is returned to the water environment where it may be available to be withdrawn again. However, estimation of return flows is uncertain and they may not necessarily be available to downstream users, for example because of pollution, timing of the flows or infiltration to groundwater (Wada et al. 2011a; Wada et al. 2011b). Thus, the return flows were not included in the paper.

The revised method section explicitly mentions that our analysis provides an extreme case where return flows are not reused (see also Munia et al. 2016). The limitations section of the revised manuscript also explicitly discusses this issue.

Comment 11. L165–166: What if an SBA has multiple downstream SBAs? Possibility of double-counting.

Response 11: The sentence in the original manuscript reads as follows: "*We identified the entire upstream area for each SBA based on the upstream-downstream hierarchy; i.e. in cases when an SBA has more than one upstream SBA, the total upstream water use is summed (WW.upstream).*"

The drainage network used here to identify upstream-downstream has a clear hierarchical relation, with no distributaries, so water only flows to one immediately downstream sub-basin and there is no risk of double counting.

Comment 12. L198–199: What happened to 'persistent' and 'occasional' from Table 1?

Response 12: Occasional scarcity has now been dropped from the analysis (see response to Editor comment 1).

Comment 13. Figure 4: the color code categorizes SSS as featuring 'no dependency' which seems incorrect. In general, I would say that any setting where there is scarcity under actual discharge (i.e. after upstream water use) should be coded as 'intervened dependency', since the upstream water use exacerbates the downstream scarcity. I realize that the authors would probably say that this is a case of 'no dependency' because there would also be scarcity with out upstream water use, but that is a semantic argument since scarcity is coded here as a binary variable.

Response 13: Thank you for sharing your interpretation. Please see our response to Reviewer 1 comment 1. We have updated the definitions in Table 1. All upstream water use affects the severity (or frequency) of downstream scarcity, so all situations would be coded as intervened dependency by that definition, reducing its utility. In our case, we are more interested in the transition between discrete system regimes (also see response to Editor Comment 1), which is why we have not adopted the reviewer's suggestion.

Comment 14. The term ‘ordering’ and the arrows used in Figures 6 and 8 suggest that sub-basins can only develop in one direction, namely from good (NNN) to bad (SSS). You may want to present a more nuanced story, explaining under what circumstances this tendency may be reversed.

Response 14: Thanks for raising this issue. Indeed, we do not want to give the impression that SBAs can only develop in one direction; we do already mention the possibility of changes in the other direction at several points.

The change in dependency category goes backward with the decrease of own and upstream water withdrawal as explained in line 280: “*Over time, this change in dependency category could go forward and backward as water demand of the SBA increases or decreases*” and in L295: “*decrease in demand would have the opposite effect*”.

We have now modified Figure 6 (see Editor Comment 1, updated Figure 6) and added text to Section 2.2.3 to better explain the reversed condition.

Comment 15. Figure 6 is presenting too much at the same time. From the text I understand that there is a natural ordering, but I do not see the added value of presenting all possible pathways through these orders. Same of course for Figure 8. Can you somehow summarize this in an easier way?

Response 15: As noted in response to Reviewer 1 comment 5 & Editor Comment 1, we agree that the original typology of transitions was complex, but this was what emerged from our simple set of assumptions when trying to map out system regimes and potential transitions between them. We have now simplified the analysis by taking into account only scarcity and no scarcity conditions (i.e. not considering occasional scarcity) and using average discharge instead of min and max discharges. This simplification now results in four system regimes (see updated Figure 4 under response to Editor Comment 1), connected by a one simple map of transitions. We also aimed to further motivate within the paper why we are interested in looking at a transition map in the first place by connecting the study with the concept of resilience (see also Editor comment 1).

Comment 16. The numbers in Table 3 surprise me. To me, the category ‘intervened dependency’ is the most relevant since in both other categories there is not really a scarcity problem, right? Less than 2% are in this category. Oh wait, you include SSS in the ‘no dependency’ categoy, see my comment 9. If I include this, the number becomes 11%. This is still a low percentage in light of (my interpretation) of the literature on water scarcity. It implies that water scarcity is mostly a local problem so that not much can be expected from transboundary cooperation.

Response 16: It’s important to distinguish between dependency and scarcity and recognize that dependency is primarily about potential for future scarcity, which transboundary cooperation aims to mitigate. The “intervened dependency” category and SSS only include cases where institutional arrangements have failed to prevent scarcity from occurring – that it is a low percentage is reassuring, because it suggests that transboundary cooperation has not too frequently failed. It is, however, debatable whether 11% is a low percentage from that point of view.

To judge the importance of transboundary cooperation, it is more important to look at areas with no scarcity who are dependent on upstream inflows. The original manuscript stated in the abstract that "*Our results show that almost 932 million people (33% of the total transboundary population) live in SBAs that are dependent on upstream water to avoid stress because of their own water use, while 464 million people (17% of the total transboundary population) live in SBAs dependent on upstream water to avoid possible shortage*". While our analysis does not consider how close these basins are to scarcity (as pointed out by Reviewer 1 comment 2), it is clear that transboundary cooperation is widely important for avoiding deterioration of the current status quo – it is not just a local problem.

We do, however, agree that it is more of a local problem than the literature often recognizes. Our analysis highlights the importance of local demand in causing scarcity and dependency. If local demand stays low enough, neither scarcity nor dependency occurs, and transboundary cooperation is not needed. This point has been made in existing literature (e.g. related to social construction of scarcity).

We also have now revised the discussion to reflect the above-mentioned implications of our results for transboundary cooperation.

Comment 17. I find that Section 3.2 is very speculative and could perhaps be shortened.

Response 17: Section 3.2 has been substantially shortened as a result of leaving out occasional scarcity from the analysis – the full typology no longer needs to be described.

For the record, we note that the old Section 3.2 was already acknowledged in the manuscript as speculative, with the aim of providing possible implications of the ordering and most importantly its connection with water demand and water availability. The section was trying to make suggestions for how negotiation in upstream-downstream relationships might be influenced, which was important to understand the significance of the transition maps identified in the analysis.

References

Munia, H., Guillaume, J., Mirumachi, N., Porkka, M., Wada, Y., Kummu, M. (2016). "Water Stress in Global Transboundary River Basins: Significance of Upstream Water use on Downstream Stress." Environmental Research Letters, 11(1), 014002.

Wada, Y., van Beek, L P H, Bierkens, M. F. P. (2011a). "Modelling Global Water Stress of the Recent Past: On the Relative Importance of Trends in Water Demand and Climate Variability." Hydrology and Earth System Sciences, 15, 3785-3808.

Wada, Y., Van Beek, L., Viviroli, D., Dürr, H. H., Weingartner, R., Bierkens, M. F. (2011b). "Global Monthly Water Stress: 2. Water Demand and Severity of Water Stress." Water Resour. Res., 47(7).